UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

3D Systems Corporation et al.,

Petitioner

v.

Intrepid Automation, Inc.,
Patent Owner.

Inter Partes Review (IPR) Proceeding Number: 2025-01242
U.S. Patent No. 11,338,511

Exhibit Number: **Exhibit 1003 for Petitioner**

Exhibit Title: Yong Chen, Ph.D. Declaration

Date of Filing: July 18, 2025

Filed By: Petitioner 3D Systems Corporation et al.,

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

3D Systems Corporation et al.,

Petitioner

v.

Intrepid Automation, Inc.,
Patent Owner.

Case No. IPR 2025-01242
U.S. Patent No. 11,338,511

Declaration of Yong Chen
in Support of Petitioner in the
Petition for *Inter Partes* Review of U.S. Patent No. 11,338,511

I, Dr. Yong Chen, do hereby declare as follows:

I. INTRODUCTION

A. Engagement

1. I have been engaged by Petitioner to provide an expert report in the form of this declaration on whether the claims of U.S. Patent No. 11,338,511 ("**the '511 Patent**") (EX1001), are (1) novel and/or (2) non-obvious in light of several prior art references.

B. Summary of Patent and Technology

2. The '511 Patent is concerned with improving printing resolution of additive manufacturing ("**AM**") systems that use light projection to cure photoactive materials such as photocurable polymer resins, for the sake of obtaining faster and/or larger scale additive manufacturing. Digital light processing ("**DLP**") is one example of this type of additive manufacturing technology. In DLP and similar methods, one or more projectors project an image onto the surface of a photocurable resin, causing the resin to cure or solidify in the places where light of sufficient energy strikes the resin surface for a sufficiently long period of time to form a three dimensional ("**3D**") part or product. Such curing or solidification typically forms one 'layer' or cross-section of the article or printed part.

3. To form a complete printed 3D part, this 'selective photocuring' process is repeated many times to form many layers or cross-sections of the article. The layers or cross-sections bond to one another as they are being formed in

sequence, thereby 'building up' the desired three-dimensional article, one layer at a time. The process is 'selective' because solidification of a given layer occurs only where light of sufficient intensity strikes the resin surface for a certain period of time. Therefore, the more precisely and accurately a device such as a DLP device projects an image onto the resin surface, the more precisely and accurately the final three-dimensional article will be printed. The '511 Patent describes systems and methods for improving this precision and accuracy.

C. Summary of Conclusions Formed

4. Based on the legal standards provided to me by the Petitioner's attorneys, the systems and methods described and claimed in the '511 Patent are not novel. Nor are they non-obvious. All of the techniques described in the '511 Patent were already well-known in the industry. The '511 Patent merely addresses well-known problems in the industry and 'solves' those well-known problems through well-known techniques for improvement of printing accuracy in DLP-type additive manufacturing system or 3D printer.[1] For example, the techniques of the '511 Patent—normalizing irradiance, gamma adjustment, warp correction, and edge blending—are all techniques that I have long used in practice and/or in academia, and which are and have been used by those skilled in the art, predating the earliest

[1] For purposes of this analysis, the terms "additive manufacturing" and "3D printing" are used interchangeably.

priority date of the ’511 Patent - July 30, 2018. As described below, these techniques are disclosed in the prior art individually and in combination to accommodate for (1) mechanical and optical non-uniformities/nonlinearities commonly found in DLP-type systems, (2) differences in the reactivity of different resins, as literally taught in additive manufacturing textbooks for decades, (3) geometric distortions commonly associated with projecting images onto two-dimensional surfaces, and (4) problems related to overlapping image projections, as occurs in virtually every multi-projector DLP system.

5. All of the foregoing problems have long been known to potentially cause inaccuracies in the DLP-based 3D printing. And all of the solutions to these problems disclosed and claimed in the ’511 Patent have likewise long been known and implemented in the industry. In short, there is nothing new or non-obvious in the techniques claimed in the ’511 Patent. The ’511 Patent simply repackages known techniques for addressing known problems, invented by others. It has long been a common practice to, in parallel, address many challenges in projection systems by employing broadly-capable technical approaches.

6. Further, nothing in my review of the ’511 Patent suggests that these well-known techniques (individually or in combination) are being used in a new, limited, or improved way. Rather, the techniques claimed are being applied in customary and conventional fashion—operating as they are expected to function

(individually and in combination). In fact, all four of the techniques claimed in the '511 Patent have already been disclosed in full in Shkolnik and, therefore, are anticipated by at least this reference. Moreover, Sekine (which discloses at least three of the four techniques) may be predictably combined with Greene (which discloses the fourth technique) to yield the same invalidity result on obviousness grounds. So, too, does the combination of Shkolnik and Sekine. Further, the skilled artisan would readily combine the teachings of the cited references in the following table for multiple reasons, as further discussed below.[2]

Claim	Limitation	Shkolnik	Sekine + Greene	Shkolnik + Sekine
1[a]	A method comprising:	✓	✓	✓
1[b]	a. providing an additive manufacturing system, comprising:	✓	✓	✓
1[c]	an image projection system comprising a plurality of image projectors; and	✓	✓	✓
1[d]	an image display subsystem;	✓	✓	✓
1[e]	b. projecting a composite image onto a build area within a resin pool using the image projection system, wherein:	✓	✓	✓
1[f]	the image projection system is controlled by the image display subsystem;	✓	✓	✓

[2] Though this table is solely for claim 1, each claim is addressed in my analysis.

1[g]	the composite image comprises a plurality of sub-images arranged in an array;	✓	✓		✓	
1[h]	two or more adjacent sub-images in the array overlap at two or more sub-image edges; and	✓	✓		✓	
1[i]	each sub-image is projected onto a portion of the build area using one of the plurality of image projectors; and	✓	✓		✓	
1[j]	c. adjusting properties and aligning a position of each sub-image in the array using a set of filters comprising:	✓	✓		✓	
1[k]	an irradiance mask that normalizes irradiance;	✓	✓		Shkolnik ✓	Sekine ✓
1[l]	a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool;	✓	Sekine	Greene ✓	Shkolnik ✓	Sekine
1[m]	a warp correction filter that provides geometric correction; and	✓	✓		✓	
1[n]	an edge blending bar at one or more sub-image edges.	✓	✓		✓	

7. In sum, the claims of the ’511 Patent should not have been granted and are invalid based on my analysis below.

D. Background and Qualifications

8. My complete qualifications and professional experience are described in my Curriculum Vitae (“**CV**”), a copy of which can be found in **Appendix A**.

9. The following is a brief summary of my relevant qualifications and professional experience.

10. Among other things, my CV includes a list of publications and my issued patents for at least the last 25 years.

11. I am currently a Professor (with tenure) in the Department of Aerospace and Mechanical Engineering at the University of Southern California, Los Angeles, CA. My current place of business is located at 1115 W. 25th Street, Los Angeles, CA 90007. I am over the age of eighteen, and am a permanent resident of the United States. My research focuses on additive manufacturing and, more specifically, modeling, control, materials, and application of AM technology. I have held the following academic positions:

- 12/18~present: Professor (with tenure), Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA.
- 12/18~present: Professor (joint-25%), Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA.
- 7/18~06/21: Director, Daniel J. Epstein Institute, Viterbi School of Engineering, University of Southern California, Los Angeles, CA.
- 1/14~12/18: Associate Professor (by courtesy), Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA.

- 6/13~12/18: Associate Professor (with tenure), Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA.
- 4/14~6/14: Visiting Professor (on sabbatical), Department of Engineering Design and Production, Aalto University, Espoo, Finland.
- 3/14~4/14: Academic Visitor (on sabbatical), Department of Mechanical Engineering, National University of Singapore, Singapore.
- 1/14~3/14: Visiting Professor (on sabbatical), Department of Mechanical and Automation Engineering, Chinese University of Hong Kong, Hong Kong.
- 7/06~05/13: Assistant Professor, Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA.

12. I am currently directing the Additive Manufacturing Lab in USC's Center for Advanced Manufacturing (CAM), where I lead a diverse research team of around 15 members, consisting of postdoctoral researchers and Ph.D., M.S., and undergraduate students, on projects relating to additive manufacturing technology. I have over 24 years of academic and industry experience in applying, designing, studying, teaching, and writing about additive manufacturing, including 19 years at USC and 5 years at 3D Systems, Inc.

13. I received a Ph.D. degree in Mechanical Engineering in 2001 from Georgia Institute of Technology, Atlanta, Georgia; my thesis was titled "Computer-Aided Design for Rapid Tooling: Methods for Mold Design and Design-for-Manufacture." Before that, I received an M.S. degree in 1996 from Huazhong University of Science and Technology, China, and a B.S. degree in 1993 from Zhejiang University, China, both in Mechanical Engineering.

14. After completing my M.S. degree in 1996, I worked at Huazhong University of Science and Technology, China, as a Lecturer for one and a half years before coming to the U.S. to pursue my Ph.D. degree. During and after completing my Ph.D. degree, I worked with 3D Systems, Inc., Valencia, CA, including as a Senior R&D Engineer (8/01~7/06). I was also a consultant for 3D Systems, Inc., Valencia, CA, for a year 8/06~ 6/07.

15. Through the research and work experience described above, I have significant experience in the area of additive manufacturing, including AM process and machine development, modeling and control techniques for AM processes, and designs and computation methods for AM-enabled applications.

16. I have published 1 edited book, 4 book chapters, over 130 journal papers, and 90 peer-reviewed conference papers related to additive manufacturing. My publications have been recognized by 15 Best/Outstanding Paper Awards in major design and manufacturing conferences and research journals. Many of my

publications are on the development of DLP-based vat photopolymerization, including its calibration/gamma adjustment (e.g., a research paper "Smooth Surface Fabrication Based on Controlled Meniscus and Cure Depth in Microstereolithography" in *Journal of Micro- and Nano-Manufacturing*, Vol. 3, September 2015 (EX1027), printing with a faster speed (e.g., a research paper "Digital Material Fabrication Using Mask-Image-Projection-Based Stereolithography" in *Rapid Prototyping Journal*, Vol. 19(3), 2013 (EX1025)), and achieving a larger printing size with high printing resolution (e.g., a research paper "Hopping Light Vat Photopolymerization for Multiscale Fabrication" in *Small*, Vol. 19(11), 2205784, 2023 (EX1026)). The citations of my publications are over 15,000 and my h-index in Google Scholar is 57. My publication history is detailed in my attached CV. I am also an inventor on several U.S. and non-U.S. patents related to my work.

17. I am a Fellow of the American Society of Mechanical Engineers (ASME). I have served as conference/program chair as well as a keynote speaker in several international design and manufacturing conferences, including the Conference Chair of the 2017 International Manufacturing Research Conference, the Program Co-Chair of the 2019 International Design Engineering Technical Conferences, and the Program Chair and the Program Co-Chair of the 2022 and 2021 Manufacturing Science and Engineering Conferences, respectively. I have also

served on the editorial boards of several international journals on manufacturing, including *Journal of Manufacturing Science and Engineering*, *Computer-aided Design*, *Journal of Computing and Information Science in Engineering*, *Manufacturing Letters*, *Journal of Intelligent Manufacturing*, and *International Journal of Precision Engineering and Manufacturing*.

E. Compensation and Prior Testimony

18. I have been retained on behalf of Petitioner to provide my independent opinions regarding the ’511 Patent.

19. I am being compensated at my standard consulting rate of $300 per hour for my time. My compensation is in no way contingent on the results of this or any other proceedings relating to the ’511 Patent.

20. For ease of understanding, I have added **emphasis in bold** in my discussions and quotations, unless otherwise noted.

F. Documents Considered for Declaration

21. This information can be found in **Appendix B**.

II. LEGAL STANDARDS FOR PATENTABILITY

A. Anticipation

22. I have been informed that a patent claim is anticipated if a single prior art reference, such as a patent or a publication, discloses each and every limitation of the claim expressly or inherently.

23. This includes whether one skilled in the art would reasonably understand or infer from the prior art reference's teaching that every claim limitation was disclosed in that single reference.

24. I understand that testimony concerning anticipation must be testimony from one skilled in the art and must identify each claim element, state the person's interpretation/understanding of the claim element, and explain in detail how each claim element is disclosed in the prior art reference. The testimony is insufficient if it is merely conclusory.

25. I understand that prior art can, however, anticipate a claim even if it **does not expressly 'spell out'** all the limitations arranged or combined as in the claim, if a person of skill in the art, reading the reference, would at once envisage the claimed arrangement or combination, or if the **missing descriptive matter is necessarily present, or inherent, in the reference.**

B. Obviousness

26. I have been informed and understand that a patent claim can be considered to have been obvious to a person of ordinary skill in the art ("**POSITA**") at the time the application was filed. This means that, even if all of the requirements of a claim are not found in a single prior art reference, a claim is still not patentable if the differences between the subject matter in the prior art and the subject matter in the claim would have been obvious to a POSITA at the time the application was

filed. I further understand that the concept of inherency also applies to an obviousness analysis.

27. I understand that a prior art reference may be a pertinent prior art reference (or "analogous art") if it is in the same field of endeavor as the patent or if it is pertinent to the problem that the inventors were trying to solve. A reference is reasonably pertinent if it logically would have commended itself to an inventor's attention in considering the problem at hand. If a reference relates to the same problem as the claimed invention, that supports use of the reference as prior art in an obviousness analysis. Here, all of the references relied on in my obviousness analysis below are in the same field of endeavor as the '511 Patent, e.g., additive manufacturing and ways to improve quality of the final 3D-printed product. The references are also pertinent to a particular problem the inventor was focused on, e.g., improving printing size with high printing resolution using techniques associated with normalizing irradiance, gamma adjustment, warp correction, and edge blending.

28. A claim is deemed obvious "if the differences between the claimed invention and the prior art are such that the subject matter as a whole would have been obvious before the effective filing date to a person having ordinary skill in the art." 35 U.S.C. § 103(a). More specifically, obviousness can be predicated on several factual inquires, including: (1) the level of ordinary skill in the art; (2) the scope and

content of the prior art; (3) the differences between the claimed subject matter and the prior art; and (4) secondary considerations of non-obviousness, such as commercial success, licensing, skepticism, long-felt need, praise by others and unexpected results.

29. I understand that the obviousness analysis entails an expansive and flexible approach assessed by the skilled artisan. To this end, there need not be precise teachings in the art directed to the specific subject matter of the challenged claim; rather, one can take account of the inferences and creative steps that a person of ordinary skill in the art would employ. For situations when the question is whether a patent claiming the combination of elements of prior art is obvious, I understand from Petitioner's attorneys that the Supreme Court has distilled certain principles as instructive for informing the obviousness analysis:

> When a work is available in one field of endeavor, design incentives and other market forces can prompt variations of it, either in the same field or a different one. If a person of ordinary skill can implement a predictable variation, § 103 likely bars its patentability. For the same reason, if a technique has been used to improve one device, and a person of ordinary skill in the art would recognize that it would improve similar devices in the same way, using the technique is obvious unless its actual application is beyond his or her skill.... A court must ask whether the improvement is more than the predictable use of prior art elements according to their established functions.

30. To assist in this process, I understand that a court may look to whether the prior art teaches toward or away from the claimed invention. A reference teaches away when a person of ordinary skill, upon reading the reference, would be

discouraged from following the path set out in the reference, or would be led in a direction divergent from the path that was taken by the applicant.

C. Person of Ordinary Skill in the Art ("POSITA")

31. I understand that in determining the level of ordinary skill in the art, several factors are considered. Those factors may include: (i) the type of problems encountered in the art; (ii) prior art solutions to those problems; (iii) the rapidity with which innovations are made; (iv) the sophistication of the technology; and (v) the educational level of active workers in the field. A person of ordinary skill in the art must have the capability of understanding the scientific and engineering principles applicable to the pertinent art.

32. Based on my review of the specification and claims of the '511 Patent, it is my opinion that a person of ordinary skill in the art in the relevant time period would have had a master's degree in mechanical engineering, industrial engineering, optics, or a similar field, with course work or industry experience in additive manufacturing; or a bachelor's degree with a subset of that course work and 2-3 years of additive manufacturing experience. It is understood in this field that industry experience may compensate for less or unrelated formal educational experience.

33. In light of my experience in Section 1.C., I meet the above definition of a person of ordinary skill in the art, and did so as of 2001. Also, I have worked with

persons of ordinary skill in the art through my professional and academic experiences, and I have an understanding of their skill level related to additive manufacturing, included as related to the '511 Patent.

34. Finally, I understand that, in an *inter partes* review proceeding, as with anticipation, the Petitioner bears the burden of proving obviousness of a challenged patent claim by "a preponderance of the evidence." I understand that the preponderance of the evidence standard requires that a reasonable factfinder could find a material fact is more probable than the nonexistence of that fact. I have applied the "preponderance of the evidence" standard throughout my declaration.

III. OVERVIEW OF TECHNOLOGY & STATE OF THE ART

A. Background

1. Overview of the Technology and Common Problems in the State of the Art – and Well-Known and Conventional Methods to Overcoming These Problems.

35. The concept of 3D printing was first developed by Chuck Hull in 1984, when he was using ultraviolet light to cure tabletop coatings. In 1986, "Hull established the 3D Systems company to market the first machine for rapid prototyping, which he called stereolithography (SLA)." C. Groth *et al*., Three-Dimensional Printing Technology, VOLUME XLVIII NUMBER 8 ©2014 JCO, Inc. ("Groth"), 476. The original SLA apparatus developed by Hull was based on using a laser to photocure layers. As stated above, "photocuring" typically means polymerizing or solidifying a photocurable liquid resin by shining light onto the resin

surface. The light must have sufficient intensity and must strike the resin surface for a sufficiently long period of time to "trigger" the polymerization or otherwise achieve the desired solidification. Additionally, this photocuring is carried out in a spatially selective manner, meaning that the **resin solidifies only in specific locations where the light strikes the resin**. In the original SLA apparatus, **spatial selectivity** was achieved by **carefully controlling a laser** to shine only on certain regions of the photocurable material (e.g., on only certain "spots" on the surface of the liquid resin).

36. Another photocuring method that has been developed for additive manufacturing is digital light processing ("**DLP**"), which was developed beginning in the 1990s. The DLP-based method is "**identical to SLA except for the light source**: a projector is used to cure an entire layer at a time (Fig. 3), in contrast to the [laser-based] SLA, which must draw the entire layer [dot-by-dot] to cure it." *Id*., 478. Figures 1 and 3 from Groth are reproduced below, illustrating this difference between the laser-based SLA and DLP methods. However, it should be noted that Figures 1 and 3 from Groth, and especially Figure 3, are greatly simplified. A DLP projector actually includes thousands or even millions of independently-controlled micromirrors, as described further below.

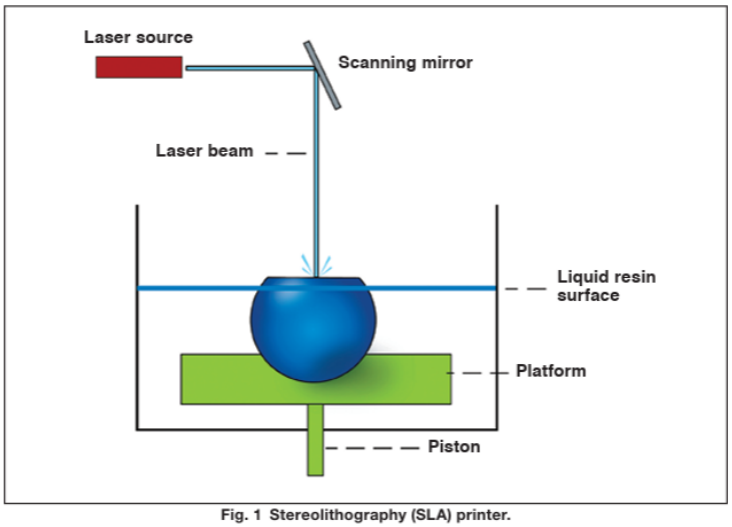


Fig. 1 Stereolithography (SLA) printer.

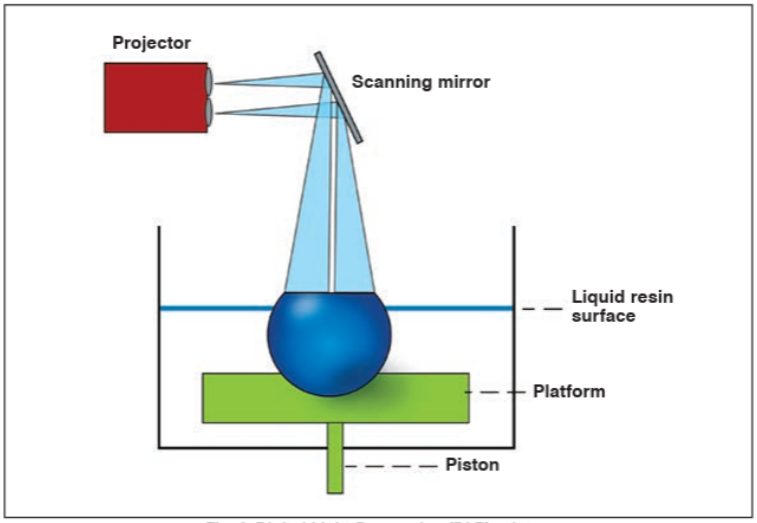


Fig. 3 Digital Light Processing (DLP) printer.

37. In terms of SLA, "the build tray of an SLA printer is immersed in a liquid resin that is curable by a concentrated ultraviolet laser light." Growth (EX1008), 477 (Fig. 1). The laser "draws" or "paints" a cross-section of the object to form each layer, essentially **one pixel at a time**. After the layer is "drawn" by the laser and photocured, "the tray descends by a distance equal to the layer thickness, allowing uncured resin to cover the previous layer" due to gravity or using a recoating device. *Id.* This **process is repeated hundreds or thousands of times** as

the printed object takes shape, "growing" downward as the process continues: cure one layer with a laser, lower the platform, cure the next layer with the laser, lower the platform, cure the next layer with the laser, lower the platform, etc. The layer-by-layer process used by SLA printers is not unique among additive manufacturing techniques. However, SLA printers are "generally **slower** than others because the laser can cure only a small area at a time." *Id.* In other words, the "slow" step is using the laser to "draw" or "paint" each layer or cross-section of the printed object, **one pixel at a time**. The laser must "touch" each pixel to be cured, one at a time. Indeed, the pixel size in an SLA printer is largely defined by the laser spot size (the size of the tiny point of light produced by a laser, such as a laser pointer). Because the laser spot (and thus the pixel size) is very small, it can take a long time for a laser (even a fast laser) to scan an entire layer or cross-section of the printed object, **especially if the printed object is large**.

38. By contrast, **DLP is generally a faster method than SLA**. *Id*., 478. As Groth points out in his article, "[t]he heart of the DLP projector is a chip developed by Texas Instruments (TI)." *Id.* Known as a **digital micromirror device** or "DMD," "the chip contains **hundreds of thousands [or millions] of tiny mirrors** that are able to move in two directions, on and off, thousands of times per second." *Id.* In a DLP projector, a single light source (e.g., a single "light bulb") shines light onto all of those thousands or millions of mirrors at the same time. Each of the mirrors can

then reflect a portion of the light received from the single light source. That is, the thousands or millions of mirrors in the DMD can *each* project light onto a separate pixel of a layer of resin, **all at the same time**. The DMD thus projects an entire image (*all* of the pixels) onto the two-dimensional surface of the curable resin **simultaneously**, as compared to the pixel-by-pixel "scanning" or "painting" the laser of an SLA device must carry out. The result is that the **curing time needed per layer is drastically reduced in DLP printing**, as compared to laser-based printing. A DLP device still cures layer-by-layer just like a laser-based device does (cure, lower, cure, lower, cure, lower, etc.); but the curing step is much faster in the case of DLP, which means the **overall print job is much faster**, especially when printing large objects.

39. Nonetheless, **DLP methods still present technical challenges**.[3] One early challenge was related to its **resolution**. In additive manufacturing, spatial

[3] The '511 Patent outlines some of these well-known problems in the Background section of the patent and elsewhere throughout the specification:

> [O]ne problem that arises with conventional additive manufacturing systems utilizing DLP is that as the layer size increases, the pixel size increases proportionally. The result is a decrease in the resolution of the final part, which will negatively affect part accuracy and surface finish. This also has the negative affect of reducing the projected energy density, which slows down the print process further as each layer needs a longer exposure time. Therefore, as DLP system are used for larger layer sizes, the theoretical advantage that full layer exposing achieves over conventional methods is reduced.

Id., 1:25-36.

"resolution" refers to **how precisely an object is formed**, in terms of the smallest physical feature the user can accurately control. It is analogous to "dots per inch" or "dpi" in two-dimensional printing. A two-dimensional printer, such as a standard laser or inkjet printer found in an office for printing documents, generally has a resolution described in terms of dpi. The higher the dpi, the larger the number of "dots" of ink the printer can accurately and precisely place within each inch of space on a blank sheet of paper. The higher the dpi, the "sharper" and more precise the printed image will be. The concept of resolution in three-dimensional printing or additive manufacturing is analogous. An additive manufacturing system with a "high" resolution can accurately print smaller features than a system with a "low" resolution. For example, a printer with a "high" resolution may be able to print objects having features (e.g., a ridge or depression or any other feature) that are as small as 50 microns (or millionths of a meter). In contrast, a printer with a "low" resolution may be able to print physical features with a precision of only 500 microns. **Higher resolution is preferred** over lower resolution, of course.

40. DLP methods have an inherent resolution limit **due to the way light projectors work**. Just like a light projector in a conference room or movie theater, moving a DLP projector closer to or farther away from a surface (such as the surface of liquid resin) causes the image projected on the surface to be smaller or larger, analogous to the way moving a movie projector **closer** to a wall or screen will cause

the projected image to "**shrink**," while moving the movie projector **farther away** from the wall or screen will cause the projected image to "**expand**." The problem arises because the amount of light produced by the projector is **constant**, no matter how large or small the projected image is. If the projected image is relatively small, then the light is more "concentrated" within the small area—the projected image will appear brighter with a higher resolution. In contrast, if the projected image is relatively large, then the same amount of light is more "spread out" within the larger area—the projected image will appear dimmer with a lower resolution. "Spreading out" a projected image in this way is helpful for **increasing the size of the projected image**, but it also means the **effective pixel size is larger**, and thus the **effective resolution is lower**. In the case of DLP-based additive manufacturing, both **large image size** and **high resolution** are desired. But it's **not possible** to optimize both image size and resolution at the same time, at least not **if only one DLP projector is used**.

41. Therefore, an early solution in the DLP-based additive manufacturing was to **use more than one DLP projector** at the same time, to carry out the same "print job." This allowed multiple projected images to be **"stitched together"** to form a single **composite image**. The figure below illustrates this combination of sub-images. This figure is actually taken from a patent for multi-projector displays more generally, not for 3D printing specifically. But the concept is the same (later I

will address challenges unique to carrying out 3D printing with multiple projectors, particularly challenges related to the chemistry and physics of photocurable resins).

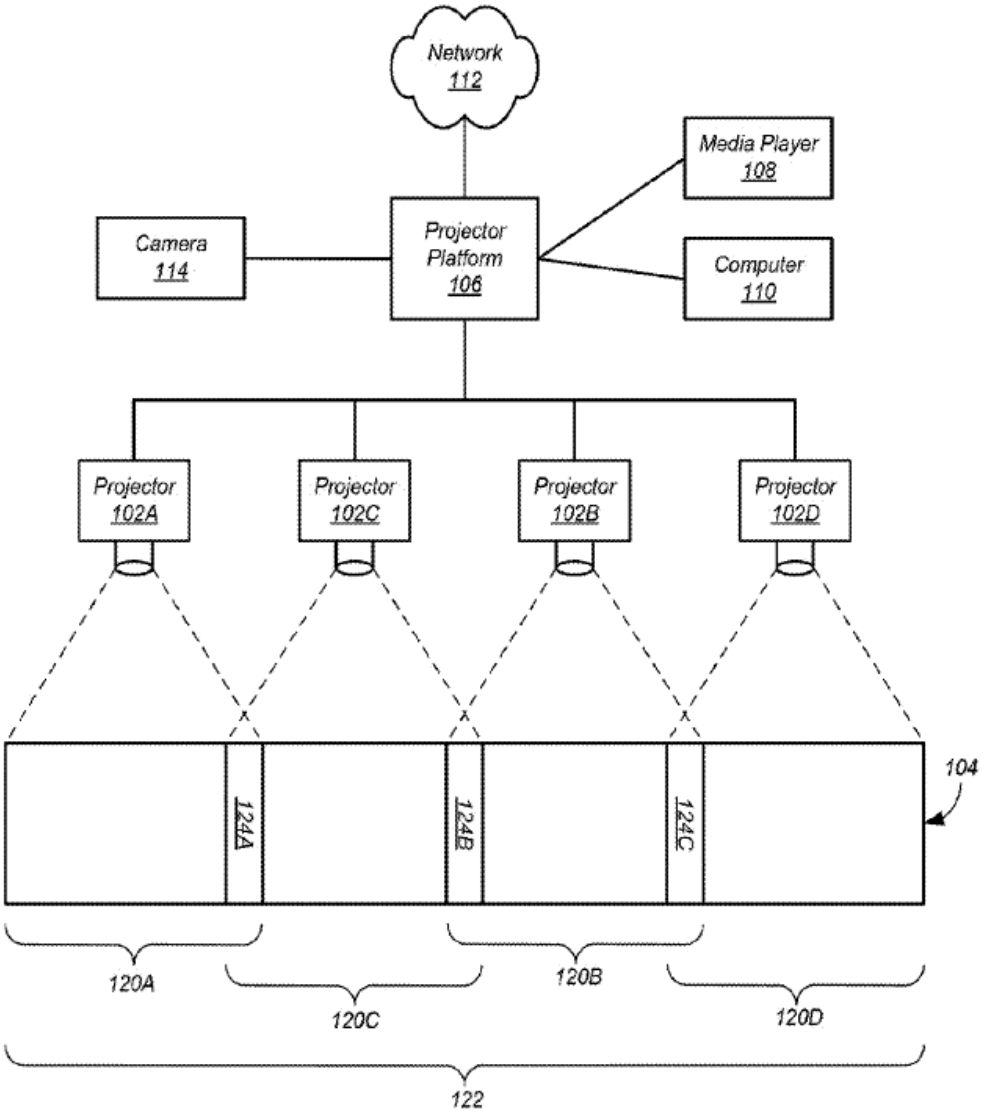


FIG. 1

42. As seen in the above figure from U.S. Patent 8,102,332 assigned to Seiko Epson Corporation and titled "Intensity Scaling for Multi-Projector Displays,"

issued on January 24, 2012, four individual projectors (102A, 102B, 102C, and 102D) produce four sub-images or "component projections" (120A, 120B, 120C, and 120D) that combine to form a "single composite projection" or image (122). See, e.g., U.S. Patent 8,102,332 B2 (EX1009), 7:27-53. **Using multiple projectors** (e.g., as shown in Figure 1 above) **avoids the loss of resolution** associated with "spreading out" the light from only a single projector, but **new challenges are introduced**, including with respect to **differences in brightness** from one individual projector to the next, **"gaps" between sub-images** if the projectors are not aligned correctly, or **"over exposure"** caused by areas where the projected sub-images **overlap** (e.g., in the "overlap regions" 124A, 124B, and 124C in the figure above). Each projector is also individually subject to the ordinary **geometric distortions or warping** such as "pincushioning," "barrel distortions," or "keystoning" familiar to anyone who has tried to use a portable light projector in an unfamiliar room.

43. The movie projector industry and related industries have dealt with these kinds of multi-projector challenges for **many years**, with **many solutions** put forth, such as in U.S. Patent 8,102,332 B2. Indeed, the use of irradiance normalization, gamma adjustment, warp correction, and edge blending have been commonplace throughout the patent and non-patent literature for many years. For example, **edge blending** has been well-known in multi-projector systems for decades. See, e.g., Song *et al.* (EX1010), "A new edge blending paradigm for multi-

projector tiled display wall," *2010 International Conference on Computer Application and System* Modeling (ICCASM 2010), Taiyuan, 2010, pp. V5-349-V5-352, doi: 10.1109/ICCASM.2010.5620133; Brown and Lowe (EX1011), "Automatic panoramic image stitching using invariant features," *International Journal of Computer Vision*, 74 (2007): 59-73; U.S. Patent 6,456,339 B1 (EX1012) ("Super-Resolution Display," issued on Sept. 24, 2002); and U.S. Patent 7,079,157 B2 (EX1013), ("Matching the Edges of Multiple Overlapping Screen Images," issued on July 18, 2006). Likewise, **calibration and geometric alignment or correction** have been well-known in multi-projector systems for decades. See, e.g., Garcia-Dorado and Cooperstock (EX1014), "Fully automatic multi-projector calibration with an uncalibrated camera," *CVPR 2011 WORKSHOPS*, Colorado Springs, CO, USA, 2011, pp. 29-36, doi: 10.1109/CVPRW.2011.5981726; Harville *et al.* (EX1015), "Practical Methods for Geometric and Photometric Correction of Tiled Projector," *2006 Conference on Computer Vision and Pattern Recognition Workshop (CVPRW '06)*, New York, NY, USA, 2006, pp. 5-5, doi: 10.1109/CVPRW.2006.161; U.S. Patent 7,443,364 B2 (EX1016), ("Projection of Overlapping Sub-Frames onto a Surface," issued on Oct. 28, 2008; and U.S. Patent 7,907,792 B2 (EX1017), ("Blend Maps for Rendering an Image Frame," issued on March 15, 2011). Other examples of challenges and solutions related to the **use of multiple projectors to form a single composite image** can be found in the

following: U.S. Patent 7,292,207 B1 (EX1018), ("Computing Blending Functions for the Tiling of Overlapped Video Projectors," issued on Nov. 6, 2007); U.S. Patent 8,427,391 B2 (EX1019), ("Configurable Imaging System," issued April 23, 2013); U.S. Patent 8,446,431 B2 (EX1020), ("DLP Edge Blending Artefact Reduction," issued May 21, 2013); U.S. Patent Application Publication No. 2013/0269882 A1 (EX1021), ("Tiled Display Rotational Assembly," published Oct. 17, 2013); U.S. Patent Application Publication No. 2013/0278840 A1 (EX1022), ("System and Method for Image Aspect Preservation in Multiple Projector Alignment," published Oct. 24, 2013); and U.S. Patent Application Publication No. 2013/0321475 A1 (EX1023), ("Zonal Illumination for High Dynamic Range Projection," published Dec. 5, 2013).

44. The additive manufacturing community began using multiple projectors for DLP-based 3D printing **at least as early as 2008** (see, e.g., U.S. Patent 8,666,142, filed on Nov. 18, 2008), over 10 years before the filing date of the '511 Patent. Moreover, the **additive manufacturing community looked to the more general multi-projector prior art for teachings and suggestions**. For example, U.S. Patent Application Publication No. 2016/0046075 A1 ("Three-Dimensional Printing with Supported Build Plates," published on Feb. 18, 2016) explicitly cites the teachings of 7 of the multi-projector patent documents cited in the immediately preceding paragraphs above. Indeed, this additive manufacturing patent application

from Joseph DeSimone and Carbon3D incorporates these 7 patent documents by reference, including for guidance regarding the "blending" or "smoothing" of overlapped regions from "tiled" sub-images produced by multiple DLP projectors in the same print job. See U.S. Patent Application Publication No. 2016/0046075 A1 (EX1024), at [0217].

45. In recent decades, the additive manufacturing community has addressed a number of **common problems related to multi-projector DLP-type 3D printing**, including the following: **irradiance normalization**, **edge blending** (also known as "pixel blending," "image blending," or "stitching"), **gamma adjustment** or gamma correction, **grayscaling**, **anti-aliasing**, and **warp correction**. These common problems and their common solutions are discussed in more detail below, particularly in the context of the "Prior Art Considered" section and the various "Grounds" for unpatentability of the claims of the '511 Patent. In the immediately following section, I will describe them only briefly as an aid to understanding at a high level.[4]

B. Brief Description of Key Concepts

1. Irradiance and Irradiance Normalization.

[4] This high level understanding is not intended to replace the POSITA's understanding of key limitations in the context of the '511 Patent. That discussion is laid out in Section IV.E. - POSITA Understanding of the Ordinary and Customary Meaning of Core Claim Limitations in the Context of the Entire Patent.

46. "**Irradiance**" refers to the **amount of light that strikes a surface over a given area**, such as a square centimeter (cm^2) of liquid resin. The "amount" of light is essentially **how strong the light is**—it is the "power" of the light, in terms of energy over time (e.g., milliJoules per second or "mJ/s"). The total light "**exposure**" experienced by a specific area or "spot" is equal to the irradiance (power) multiplied by **how long the light shines on that spot**. That is, "exposure" is *power times time* (e.g., in units of mJ/cm^2). This concept of light "exposure" is essentially the same as the total sun "exposure" that may lead to a sunburn when lying out too long on a beach—how bright and how long is a surface exposed to light. This concept is especially important in DLP-based additive manufacturing because the light exposure is what causes the solidification of the liquid resin—where the light strikes the resin, the struck location of the resin selectively solidifies, thereby defining a portion of the 3D object that is being printed. In general, **the higher the light exposure, the more solidification occurs over time**.

47. As noted above, the digital micromirror devices (DMDs) used in DLP-based image projection systems include thousands or even millions of tiny mirrors, each of which reflects light onto a tiny area. That is, each mirror reflects a tiny portion of light it receives from the overall light source—such as a "light bulb" shining onto many tiny mirrors at the same time. Each of those tiny mirrors can be individually controlled by the DMD, such as by tilting it. The "spot" illuminated by

a single micromirror can be considered to be a **single pixel** (the smallest individually addressable area for light illumination and photocuring purposes). Like any opto-mechanical system, DMDs and DLP projectors can have various **flaws or failure modes**. For example, a specific micromirror can be out of alignment or otherwise non-functional, such that it does not reflect light where it is supposed to, even though the other micromirrors in the DMD may still be working properly. Sources of electrical power and sources of light can likewise fail or degrade over time, which may affect all of the mirrors of a given DMD at the same time.

48. For example, the light source (e.g., a simple light bulb) for a one DLP projector may be older than the light source of another DLP projector. The older light source simply may not produce as much light as the newer light source. The result would be that all the pixels associated with the newer light source may be brighter than all the pixels associated with the second light source, even when both DLP projectors are set at "full power," meaning all of the mirrors of the DMD of each DLP projector are "supposed to" reflect full light intensity onto a resin surface.

49. Therefore, when multiple DLP projectors are used (each of which includes its own independent DMD and thus many thousands or millions of its own micromirrors), there is an **almost infinite number of possible variations in performance** from **micromirror-to-micromirror**, or **pixel-to-pixel**. Such variation, if unaccounted for, can cause undesired variations or inaccuracies in

projected sub-images and composite images. For example, a given pixel can be "under exposed" (not enough light, and thus not enough solidification of the resin) or "over exposed" (too much light, and thus too much solidification of the resin).

50. This common problem has been addressed for many years by "**normalizing**" the irradiance provided by the thousands or millions of tiny mirrors of the DMDs, even if a single DLP projector is used in the AM system. Such normalization can be carried out in various ways. One way to conceptualize irradiance normalization is "taking the lowest common denominator." If some pixels are brighter than others when set to "full power" (as is typically the case in multi-projector DLP systems), then normalization can be carried out by "turning down" the brightness of the brightest pixels so that they are only as bright as the dimmest pixel. In other words, the dimmest pixel is used as the baseline for all of the other pixels, such that all pixels (once "normalized") have uniform brightness. This process is precisely what Example 1 ("Irradiance Mask") of the '511 Patent describes. See '511 Patent (EX1001), 23:13-26.

2. **Edge Blending.**

51. "**Edge blending**," in the context of a multi-projector system, describes the process or technique of managing areas of a composite projected image that include light received from multiple different light sources, such as multiple micromirrors or DMDs. Most commonly, these "overlap" areas or regions occur

when multiple projectors project multiple sub-images onto the same surface, as shown above in Figure 1 from U.S. Patent 8,102,332. In that figure, the "overlap regions" are denoted as 124A, 124B, and 124C. Other terms such as "**pixel blending**," "**image blending**," and "**stitching**" can also be used to refer to the management of overlapping regions in a composite image. As stated above, edge blending has been known for a very long time in both the movie projector field and also the additive manufacturing field.

3. Gamma Adjustment, the Photocuring Working Curve, Grayscaling, and Anti-Aliasing.

52. The concept of "**gamma adjustment**" or "gamma correction" in the context of photocuring is best understood with reference to **fundamental principles of chemistry and physics**. In general, photocuring of a resin includes both (a) a **physical process** and also (b) a **chemical process**. The physical process is the penetration of the incident curing light into the resin. The chemical process is the curing or polymerization reaction of the photocurable resin. These two processes (light penetration and chemical reaction) depend on the nature of the specific resin being cured—they are both **material-dependent properties**. One resin may interact differently with light and have different chemical reactivity than another resin. However, all photocurable resins inherently have a so-called "**working curve**" that shows the relationship between light penetration and chemical reaction at a given wavelength of light (e.g., ultraviolet light having a peak wavelength at 385 or 405

nanometers (nm)). These fundamental principles of chemistry and physics are described in detail in Paul F. Jacobs, *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography* (Society of Manufacturing Engineers, McGraw-Hill, 1992). Additionally, the content of Chapter 4 was also published as a standalone article: Paul F. Jacobs, "Fundamentals of Stereolithography," *Proceedings of the 1992 International Solid Freeform Fabrication Symposium*, pages 196-211 ("**Jacobs**"). Jacobs is a standard text in the field of additive manufacturing, particularly for its description of the fundamental physics and chemistry of photocuring, whether using SLA, DLP, or any other kind of photocuring. I, personally, own a copy of the book as would many other persons skilled in the art. I would consider the Jacobs text part of the common storehouse of knowledge for those working in the field of the present AM technology. An example working curve is illustrated in Figure 4 of Jacobs (reproduced below). This working curve is for a specific resin called "XB 5149." See Jacobs (EX1007), p. 204. However, the fundamental features of the working curve are similar for any photocurable resin.[5]

[5] All 3D printing systems that use photocurable resins—such as disclosed in the '511 Patent and the prior art systems—rely upon this relationship as being fundamental to the operation of those systems.

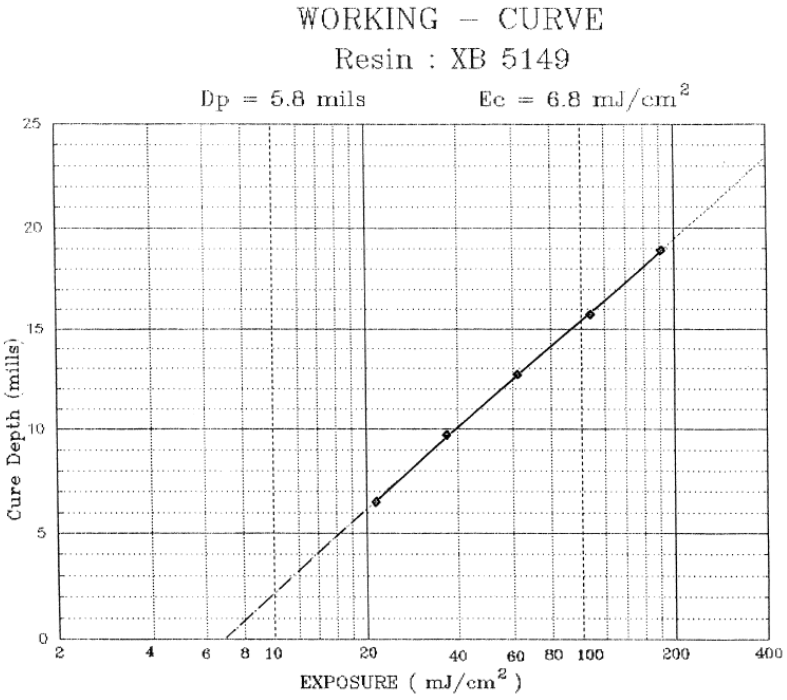


FIGURE 4

53. In a working curve, **cure depth is plotted on the y-axis** (often in "mills" or "mils," where 1 mil equals 1/1000 of an inch, but other units of length can also be used). **Light exposure is plotted on the x-axis** (often in mJ/cm^2, but other units of energy per area may also be used). The "curve" is linear (it appears as a straight line) because the plot is logarithmic—notice the logarithmic scale of the x-axis. The markings on the y-axis are *evenly spaced*, moving from 5 mils to 10 mils to 15 mils, and so on. However, on the x-axis, the markings for 2 mJ/cm^2, 4 mJ/cm^2, 6 mJ/cm^2, 8 mJ/cm^2, 10 mJ/cm^2, 20 mJ/cm^2, and so on are *not* evenly spaced, but are instead plotted *logarithmically*. This type of plot (called a **"semilog" plot**) is used for working curves because there is a **non-linear, logarithmic relationship** between the **cure depth** of the resin and the **light exposure** (energy per unit area) experienced

by the resin. This non-linear, logarithmic relationship arises from the **fundamental physics and chemistry** of photocurable resins, such as methacrylates.

54. With reference once again to Figure 4 from Jacobs, two additional features of the working curve are worth noticing: **penetration depth (D_p)** and **critical energy (E_c)**. Every photocurable resin has a characteristic D_p and E_c at the curing wavelength (e.g., 385 nm), often denoted as lambda (λ). The value D_p is defined as that depth of the resin which results in a reduction of the irradiance to a level equal to 1/*e* of the surface irradiance, where *e* is the base of natural logarithms (equal to 2.7182818…). On the semilog plot of a working curve, D_p is equal to the slope of the line (denoted as "*m*" in the standard mathematical description of a line as $y = mx + b$). E_c is the critical energy, which is the energy needed to obtain the gel point of a resin, as described on page 203 of Jacobs. Moreover, as further described by Jacobs (EX1007), (pages 203-206), the metric E_c is equal to the intercept of a working curve corresponding to a semilog plot (not a linear plot) of cure depth on the ordinate or y-axis and the logarithm of maximum light exposure on the abscissa or x-axis (i.e., a working curve such as Figure 4 above). E_c is assigned to the intercept, at which the cure depth is zero. Therefore, it is common to describe the working curve equation as follows:

$$Cd = D_p \ln (E_{max}/E_c)$$

where Cd is the maximum cure depth, D_p is the penetration depth, E_{max} is the maximum exposure, E_c is the critical energy, and ln is the symbol for natural logarithm. This equation can also be rewritten as $E_{max} = E_c \exp (Cd/D_p)$. At this point it is helpful to observe that the ’511 Patent uses the **same math**, but **different symbols**, to describe the **same fundamental physics and chemistry**. The ’511 Patent uses “D_p” as the abbreviation for “cure depth” (not for “penetration depth,” which is different). Similarly, the ’511 Patent uses E′ to represent “exposure” (“energy per unit area”). The abbreviations used in the ’511 Patent are perhaps unusual, but the **math itself is not**. Figure 5A of the ’511 Patent (reproduced below) is **fundamentally the same** as Figure 4 of Jacobs—both are semilog plots of cure depth on the y-axis and exposure on the x-axis, and both illustrate straight lines with an x-intercept at a non-zero value of exposure (equal to the critical energy E_c of course). Indeed, laying aside the differing abbreviations, Figure 5A of the ’511 Patent is essentially a superimposable copy of Figure 4 of Jacobs.

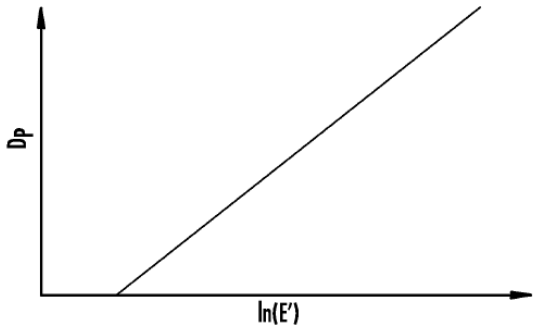


FIG. 5A

55. Turning now to "**gamma adjustment**," "**gray scaling**," and "**anti-aliasing**," the general concept of gamma adjustment/correction/calibration at a high level relates to making adjustments to a photocuring process to account for the unique chemistry and physics of a specific photocurable resin (e.g., with reference to that resin's working curve), particularly with respect to the light exposure. Gamma adjustment or correction thus occurs any time a photocuring process parameter (e.g., curing time or irradiance) is selected based on the specific resin used. It is literally a textbook adjustment known and used in the field for over 30 years by the filing date of the '511 Patent.

56. "Grayscaling" and "anti-aliasing" both relate to **smoothness of surfaces**. Pixels are generally square-shaped or rectangle-shaped. As a result, forming an image from such "building blocks" can result in a "pixelated" appearance. "Anti-aliasing" refers specifically to reducing this effect. "Grayscaling" is one technique that has long been recognized as a way of improving anti-aliasing. In grayscaling, pixels can have values other than **fully "on"** (e.g., assigned as "**white**" or as a "**1**" in a binary system) or **fully "off"** (e.g., assigned as "**black**" or as a "**0**" in a binary system). Pixels can instead have "gray" values in between "black" and "white" or in between fully on and fully off, where these in between "gray" values can represent different intensities of irradiation that are intended to strike a particular area of resin (e.g., a particular pixel).

57. A helpful illustration of both anti-aliasing and grayscaling is provided by U.S. Patent Application Publication 2017/0102679 A1 ("Sub-Pixel Grayscale Three-Dimensional Printing," published on April 13, 2017, and denoted as "**Greene**"). Greene is further discussed in subsequent sections. For present purposes, Figures 10A and 10B are reproduced below.

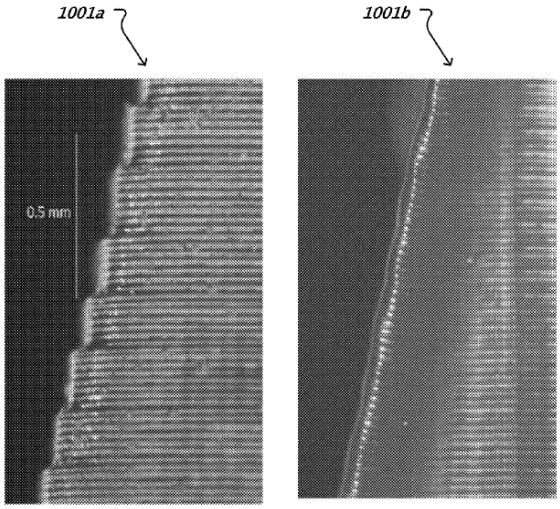


FIG. 10A ***FIG. 10B***

58. Figures 10A and 10B show a cross-section of an example of a 3D structure printed from the same digital model without grayscaling (Figure 10A) and with grayscaling (Figure 10B). See Greene (EX1006), [0053]. In Figure 10A, the cross-sectional image 1001a was printed without using grayscale intensity values (e.g., only "black" and "white" intensity values were used). In Figure 10B, the cross-sectional image 1001b was printed using grayscale intensity values in addition to black and white intensity values. As seen, the grayscale intensity values (Figure

10B) resulted in "sub-pixel" features and a "smoother edge," as compared to the "jagged, stair-stepped edge" shown in Figure 10A.

4. **Warp Correction.**

59. "**Warp correction**" in the context of projector-based 3D printing refers to making various adjustments to ensure that the **actual geometric appearance** of the printed article (or cross-section thereof) **matches the digital "model"** of the article. That is, such geometric correction avoids "keystoning" or other types of distortions.

60. A helpful illustration of such distortions common to projector-based additive manufacturing is provided by U.S. Patent 8,666,142 B2 ("System and Method for Manufacturing," issued on March 2, 2014, denoted as "**Shkolnik**"). Shkolnik is further discussed in subsequent sections. For present purposes, Figures 5A and 5B of Shkolnik are reproduced below. Figure 5A of Shkolnik illustrates an example of a "barrel distortion," Shkolnik (EX1004), 32:64-66. Figure 5B illustrates a "pincushion distortion." Other types of geometric distortion are also possible and have long been known.

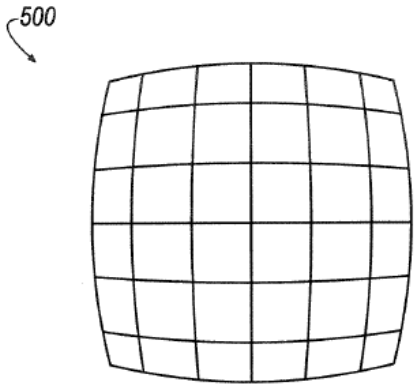


FIG. 5A

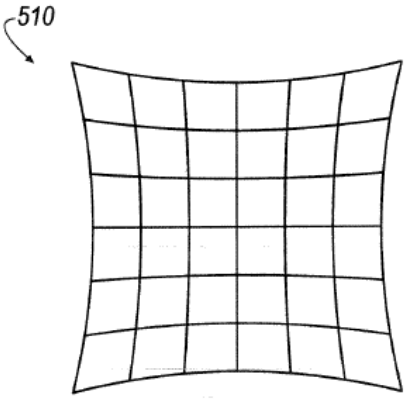


FIG. 5B

IV. THE ’511 PATENT

A. Effective Filing Date of the ’511 Patent

61. The ’511 Patent was filed on March 29, 2021, and purports to claim priority to (a) U.S. Patent Application No. 16/938,298, filed on July 24, 2020, now U.S. Patent 11,014,301; (b) U.S. Patent Application No. 16/370,337, filed on March 29, 2019, now U.S. Patent 10,780,640; (c) U.S. Provisional Patent Application No. 62/734,003, filed on September 20, 2018; and (d) U.S. Provisional Patent Application No. 62/711,719, filed on July 30, 2018. See ’511 Patent (EX1001), cover. For my analysis, I apply an effective filing date or earliest possible priority

date of July 30, 2018, without conceding the ’511 Patent is entitled to claim priority to such a date.

B. Subject Matter of the ’511 Patent

62. The ’511 Patent describes an additive manufacturing system using an image projection system that comprises one or more image projectors that project a composite image onto a build area within a resin pool. ’511 Patent (EX1001), 1:38-46; *see also* FIGS, 1A, 1E-1G. The composite image comprises or is formed from a “plurality of sub-images arranged in an array.” *Id.*, 1:45-46. The system also includes a subsystem that “controls each of the image projectors to **adjust the properties** of each sub-image and the alignment of the position of each sub-image within the composite image.” *Id.*, 4:16-20.

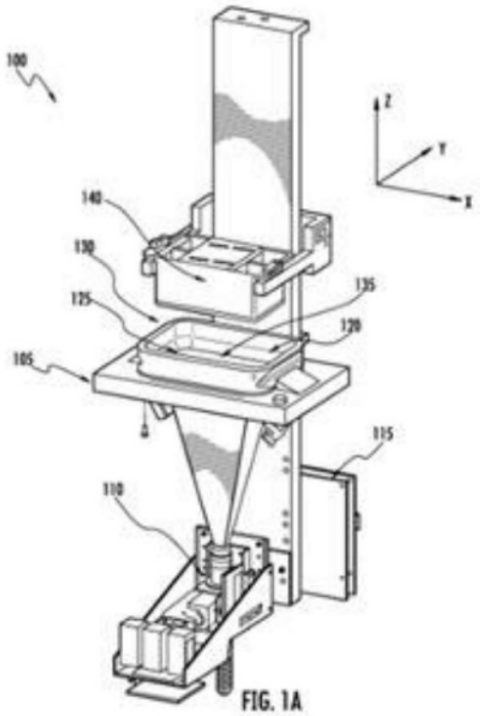


FIG. 1A

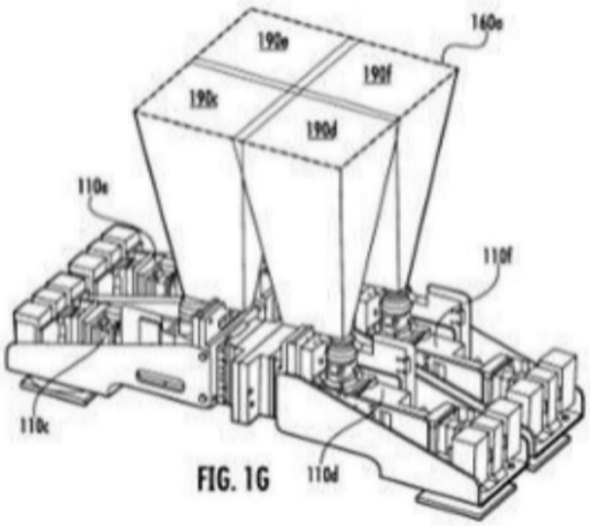


FIG. 1G

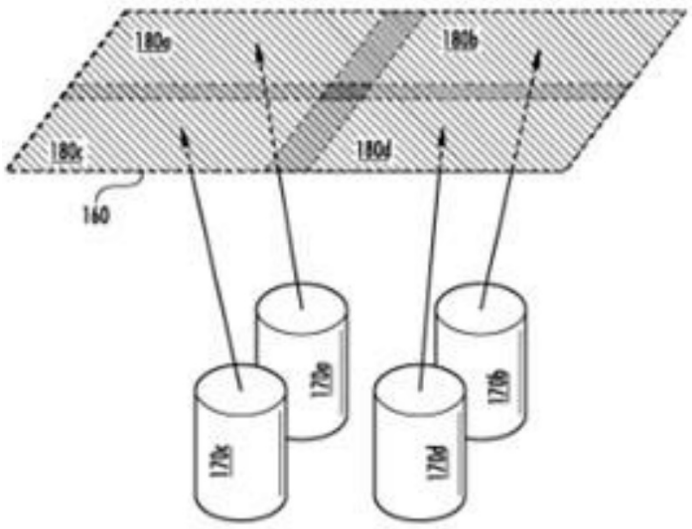


FIG. 1E

63. As depicted in FIGS. 1E and 1G, two or more "adjacent sub-images in the array also can overlap at two or more sub-image edges." *Id.*, 1:51-52. The use of multiple image projectors can create inaccuracies that the set of filters adjusts for to "improve the composite image quality," in addition to inaccuracies associated with the sub-images individually. *Id.*, 5:8-9; *see also id.*, 8:59–9:15. Such further inaccuracies are described as follows:

> Various issues can cause a composite image to be distorted compared to the ideal composite image. Some examples of issues that cause distortion of a composite image are mechanical assembly and mounting geometry (e.g., projectors with different angles relative to the build area that can lead to skewed projected sub-images), . . . and differences between projectors within the image projection system (e.g., variations in projected intensity between projectors).

Id. at 4:51-63. As the '511 Patent describes, these additional inaccuracies are also accounted for by **adjusting the digital filters** to allow for the "ideal composite image." *Id.* at 5:5-6 [6] To account for the various inaccuracies, and without limiting these concepts, the '511 Patent provides examples of what the four filters account for (i.e., their general purpose)—including:

(1) **an irradiance mask** that normalizes irradiance, for example, by accounting for "projector-based spatial energy non-uniformities." *Id*. at 11:24-33. This is achieved by "correct[ing] differences between sub-images." *Id*. at 11:33-36; *see also Id*. at 23:25-26 (the filter "create[s] a uniform irradiance across the whole image.").

(2) **a gamma adjustment mask** that considers the fact that different resins have different reactivity. This is achieved by, for example, grayscaling or "remapping" pixel intensity levels on a scale of 0 to 255 based on an "addressable range of reactivity for curing a resin" which "maximizes the number of gray-scale levels available . . . to minimize aliasing artifacts from curved or smooth surfaces being produced on an inherently square-pixel based projection system." *Id.* at 23:30-35; *id.* at 23:37-41 ("Gamma correction filters, such as the one described in this example,

[6] This can be "beneficial because it can be more cost effective to adjust the properties of the sub-images to improve the composite image quality . . ., compared to improving the mechanical alignment tolerances for the parts of the assembled PRPS to improve the composite image quality." *Id*. at 5:7-11.

can be used for each different resin to remove variations and improve part-to-part consistency.").

(3) **a warp correction filter** that corrects geometry, such as "warp or skew in projected images that are caused by [for example] variation in projector optics or alignment within the build area." *Id.* 8:39-41; *see also id*., 18:21-29 ("FIG. 10D shows a non-limiting example of a composite image made up of sub-images, where the light source is stationary, and a lens moves by rotation in the direction to project the sub-images. In different cases of moving optical systems, each projected image can be calibrated for position, warp and skew, and/or other corrections, as described further herein.").

(4) **an edge blending bar** that accounts for overlap in projection images by, for example, "fad[ing] out" "perimeters of adjacent sub-images" so that "the transition between the adjacent sub-images can be made less noticeable." *Id*. 8:59-9:3, *id.* 10:29-35.

C. Summary of the Prosecution History

1. Examiner Rejections, the Irradiance Mask Limitation, and Reasons for Allowance

64. I have read sections of the prosecution history (EX1002) of the '511 Patent. On May 24, 2021, the applicant filed a Request for Participation in the Patent Prosecution Highway Pilot Program ("PPH Request"). The PPH Request stated that "All claim limitations from patentable claims 15-27 in the PCT patent application

are included in the currently pending claims 1-13 of the corresponding US patent application." *See* (EX1002), PPH Request (dated May 24, 2021), p. 2. On July 9, 2021, I understand that the USPTO issued a decision that dismissed the PPH Request for failing to include the required information disclosure statement ("IDS") listing. *See* (EX1002), Decision on Request to Participate in the PPH Program and Petition to Make Special (dated July 9, 2021) ("PPH Request Decision"), p. 3. Applicant filed the IDS together with a subsequent PPH Request on July 14, 2021 ("Subsequent PPH Request"). The subsequent PPH Request was granted on July 16, 2021.

65. On September 2, 2021, I understand the examiner rejected several of the claims on various grounds. I understand the examiner rejected claims 1-8 based on nonstatutory double patenting grounds as being unpatentable over claims 14-21 of U.S. Patent No. 10,780,640. *See* (EX1002), Non-Final Office Action (dated September 2, 2021), p. 3. I understand the examiner further rejected independent claim 1, among others, based on obviousness. The examiner contended that the claims were unpatentable over Ueda (U.S. Patent Application Publication 2016/0368221) in view of Hull (U.S. Patent Application Publication 2008/0159586), Kobayashi (U.S. Patent Application Publication 2016/0121547), Saruhashi (U.S. Patent Application Publication 2015/02022805) and Ueno (U.S. Patent 7,318,718). *See* (EX1002), Non-Final Office Action (dated September 2, 2021), p. 4.

66. On December 16, 2021, the examiner interviewed the applicant's representative. The examiner's interview summary provides that "[r]egarding claim 1, applicant argues that Kobayashi et al. does not teach an irradiance mask that normalizes irradiance. No agreement was reach[ed]." *See* (EX1002), Applicant-Initiated Interview Summary (from December 6, 2021; dated December 21, 2021). The examiner's interview summary further provides that "[r]egarding claim 3, it was agreed that Kobayashi does not teach wherein the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors." *See id*.

67. On December 20, 2021, the applicant filed a response arguing that "the method of adjusting the energy in Kobayashi is fundamentally different from that recited in present claim 1," and specifically that "the excessive curing problem and solution described in Kobayashi is fundamentally different from the problem that is addressed by the solution of an irradiance mask recited in the present claim 1." (EX1002), Amendment After Non-Final Office Action (dated December 20, 2021), p. 6. The applicant further argued that "Kobayashi is related to reducing illumination based on counting the total number of times an area is illuminated throughout an entire print process," and that in contrast the applicant's claims "describe[] that 'an irradiance masking filter … applies a normalizing irradiance mask to an image (or each sub-image in a composite image) such that the image (or composite image) has

a uniform irradiance range (i.e., from zero exposure to a maximum exposure limit) across the area." *Id*. The applicant contended that Kobayashi does "exactly the opposite" of the applicant's claims. *See id*. The applicant continued by citing differences between Kobayashi's FIG. 8 and Example 1 in paragraphs [0114]-[0115] of the applicant's specification. *See id*. at p. 7. The applicant further argued that the term "normalize" is "well-known to a POSITA, and that the methods described in Kobayashi would not be interpreted as 'normalizing' by a POSITA," and stated that the claims in light of the specification support their assertion. *See id*. at p. 7-8. The applicant further argued, with respect to claim 3, that Kobayashi does not teach adjusting energy across the build area "to 'compensate for non-uniformities in optics of [a] plurality of image projectors," and instead "intentionally adjusts the illumination energy to be non-uniform to compensate for areas that are irradiated with light a large number of times throughout a printing process." *See id*. at p. 7.

68. In the response filed December 20, 2021, the applicant further included new dependent claims 14 and 15. The applicant specifically noted that these new claims "include further limitations on the irradiance mask." *Id*. at p. 8.

69. The applicant filed an electronic terminal disclaimed ("TD") on December 20, 2021, which accompanied the response and was approved the same day. The TD was filed with respect to U.S. Pat. No. 10,780,640.

70. On January 28, 2022, the examiner stated in the Notice of Allowance that "[r]egarding [independent] claim 1, the prior art does not teach an irradiance mask that normalizes irradiance in combination with the other features instantly claimed." *See* (EX1002), Notice of Allowance (dated January 28, 2022), p. 2.

71. On February 28, 2022, the applicant filed a so-called "Rule 312 Amendment" that amended the claims in various ways, such as adding the word "pool" to the gamma adjustment mask element in independent claim 1[7]. The Rule 312 Amendment also removed the phrase "the area of" from the composite image element in claim 14[8] and added "<u>each</u> sub-image" in place of "a sub-image" to claim 15[9]. *See* (EX1002), Rule 312 Amendment, p. 2, 4. The applicant stated that these amendments were "to make a minor correction in antecedent basis." *Id*. at p. 5. This amendment was entered on March 25, 2022. On March 8, 2022, the Applicant filed an additional information disclosure statement ("Additional IDS"). The '511 Patent issued on May 24, 2022.

[7] Independent claim 1 was amended to read "a gamma adjustment mask that adjusts sub-image energy based on a reactivity of <u>resin in</u> the resin <u>pool</u>."

[8] Dependent claim 14 was amended to read "… such that the composite image has a uniform irradiance range across ~~the area of~~ the composite image."

[9] Dependent claim 15 was amended to read "… applying the irradiance mask to [[a]] <u>each</u> sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity."

72. In summary, the "irradiance mask that normalizes irradiance" limitation allowed for the Issue Notification of the '511 Patent on May 4, 2022.

2. **Challenged Claims**

73. I understand that Petitioner is challenging claims 1–15 of the '511 Patent (the "Challenged Claims"). I have analyzed each of these claims and for the reasons I detail below, it is my opinion that each of these claims is unpatentable over the prior art discussed below.

Claim	Limitation
1[a]	A method comprising:
1[b]	a. providing an additive manufacturing system, comprising:
1[c]	an image projection system comprising a plurality of image projectors; and
1[d]	an image display subsystem;
1[e]	b. projecting a composite image onto a build area within a resin pool using the image projection system, wherein:
1[f]	the image projection system is controlled by the image display subsystem;
1[g]	the composite image comprises a plurality of sub-images arranged in an array;
1[h]	two or more adjacent sub-images in the array overlap at two or more sub-image edges; and
1[i]	each sub-image is projected onto a portion of the build area using one of the plurality of image projectors; and
1[j]	c. adjusting properties and aligning a position of each sub-image in the array using a set of filters comprising:
1[k]	an irradiance mask that normalizes irradiance;
1[l]	a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool;
1[m]	a warp correction filter that provides geometric correction; and
1[n]	an edge blending bar at one or more sub-image edges.

2	The method of claim 1, wherein the image display subsystem controls the image projection system and each of the image projectors using digital light processing.
3	The method of claim 1, wherein the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors.
4	The method of claim 1, wherein the gamma adjustment mask comprises a logarithmic relationship between a cure depth of the resin and energy per unit area in the build area.
5	The method of claim 1, wherein the resin is selected from the group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations thereof.
6	The method of claim 1, wherein the edge blending bar comprises a blending distance and a function selected from the group consisting of: linear, sigmoid and geometric.
7	The method of claim 1, wherein the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured.
8	The method of claim 1, further comprising a system controller that synchronizes exposure control of the plurality of image projectors with each other.
9	The method of claim 1, wherein the projecting the composite image further comprises moving the plurality of sub-images during an exposure of a layer of an object being manufactured.
10	The method of claim 1, wherein the movement of the sub-images is either a step-expose-step type movement or a continuous movement.
11[a]	The method of claim 9, wherein:
11[b]	the plurality of sub-images comprises a 1D array of sub-images oriented in a first direction; and
11[c]	the movement of the sub-images is in a second direction perpendicular to the first direction.
12[a]	The method of claim 9, wherein:
12[b]	the plurality of sub-images comprises a 2D array of sub-images with rows oriented along a first direction and columns oriented along a second direction; and
12[c]	the movement of the sub-images is in either one of the first or second directions, or both the first and second directions.
13[a]	The method of claim 9, wherein:

13[b]	the plurality of sub-images arranged in the array comprises one or more rows oriented along a first direction and one or more columns oriented along a second direction; and
13[c]	the movement of the sub-images is in a third direction that is different from both the first and second directions.
14	The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image.
15	The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity.

D. Claim Construction (Ordinary and Customary Meaning)

74. I understand that there are two types of claims: independent claims and dependent claims. I understand that an independent claim stands alone and includes only the limitations it recites. I understand that a dependent claim is a claim that depends on another claim. I understand that a dependent claim includes all of the limitations recited in the dependent claim as well as any limitations included in the corresponding independent claim.

75. I understand that there is a heavy presumption that claim terms are to be given their ordinary and customary meaning. The ordinary meaning of a claim term is not the meaning of the term in the abstract, but, rather, its meaning to the person of ordinary skill in the field after reading the entire patent. Ordinary meaning

is not determined in a vacuum. Rather, determining the limits of a patent claim requires understanding its terms in the context in which they were used by the inventor, considered by the examiner, and understood in the field of the invention.

76. I understand that in the absence of a special meaning/definition in the patent itself, claim terms should be given their ordinary and customary meaning, that is, the meaning that a skilled artisan would attribute to the terms in the "context of the entire patent." I understand that the POSITA should only interpret a claim term more narrowly than its ordinary meaning under two circumstances: (1) when a patentee sets out a definition and acts as its own lexicographer, or (2) when the patentee disavows the full scope of a claim term either in the specification or during prosecution history. The standards for finding lexicography and disavowal are exacting.

77. I understand that this person skilled in the art at the time of the invention is assumed to have read the claim terms in light of the entire patent record, including the other claims, the patent specification, and the patent prosecution history. I have interpreted the claim terms in the '511 Patent in light of this understanding.

78. I understand it is the person of ordinary skill in the field of the invention through whom the claims are understood. Such person is deemed to read the words used in the patent document with an understanding of their meaning in the field, and to have knowledge of any special meaning and usage in the field. Thus, the claims

of a patent are understood by reviewing the same resources as would be understood by the skilled artisan having read the context of the entire patent—i.e., the claims, specification and the prosecution history. For example, Claim 1 provides:

1[a] A method comprising:

1[b] a. providing an additive manufacturing system, comprising:

1[c] an image projection system comprising a plurality of image projectors; and

1[d] an image display subsystem;

1[e] b. projecting a composite image onto a build area within a resin pool using the image projection system, wherein:

1[f] the image projection system is controlled by the image display subsystem;

1[g] the composite image comprises a plurality of sub-images arranged in an array;

1[h] two or more adjacent sub-images in the array overlap at two or more sub-image edges; and

1[i] each sub-image is projected onto a portion of the build area using one of the plurality of image projectors; and

1[j] c. adjusting properties and aligning a position of each sub-image in the array using a set of filters comprising:

1[k] an irradiance mask that normalizes irradiance;

1[l] a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool;

1[m] a warp correction filter that provides geometric correction; and

1[n] an edge blending bar at one or more sub-image edges.

79. Of note, Claim 1 provides four filters – limitations 1[k]-1[n]. Further elucidation of these limitations is helpful in better understanding what the '511 Patent is directed to and its underlying purposes.

80. As a general observation, I note that these limitations (limitations 1[k]-1[n]) are phrased in broad terms and their substantive content are common to each and every claim in the '511 Patent—and that I have not identified any special definitions in the specification to narrow their ordinary and customary meaning. Nonetheless, I appreciate the context of the claims, specification, and prosecution history informs how a POSITA would understand these terms.

E. POSITA Understanding of the Ordinary and Customary Meaning of Core Claim Limitations in the Context of the Entire Patent.

1. POSITA's understanding of the ordinary and customary meaning of – "*an irradiance mask that normalizes irradiance*"

81. Based on the context of the entire patent, a POSITA's understanding of an irradiance mask is that it exists within at least one of the digital filters and is applied to **normalize irradiance non-uniformities** within the image projection system arising from projector-based spatial energy non-uniformities. *Id.*, 7:62-64; *see also id.*, 7:67-8:1 ("an irradiance mask filter 240"); *see also id*., 11:33-36 ("Irradiance masking filters can be applied to the image projection system as a whole (i.e., on the composite image), and/or to each of the sub-images individually to correct differences between sub-images."). More specifically, a POSITA would

understand that an irradiance masking filter "applies a normalizing irradiance mask to an image (or each sub-image in a composite image) such that the image (or composite image) has a **uniform irradiance range** (i.e., from zero exposure to a maximum exposure limit) across the area." *Id.*, 11:24-30.

82. This can be achieved by, for example, adjusting "**parameters** of the irradiance mask filter . . . based on lowest region of energy (i.e., that corresponds to the darkest region of pixels) in display plane." *Id.*, 11:37-39. In other embodiments of the invention, "the parameters of the irradiance mask filter are set based on highest region of energy (i.e., that corresponds to the brightest region of pixels) in display plane." *Id.*).

83. Having read the prosecution history, I further understand that the reason for issuance of the '511 Patent was based on the irradiance mask limitation.

84. The concept of irradiance mask—to normalize irradiance non-uniformities within the image projection system such that the image or composite image has a uniform irradiance range—as described in the '511 Patent is consistent with how the POSITA would understand the concept in the claims, specification, and prosecution history (i.e., in its ordinary and customary way). Nothing special is being attributed to the concept beyond what was known in the art and through conventional wisdom at the time of the filing of the '511 Patent. Tellingly, and unlike other defined terms in the specification, there is no definition of irradiance mask or

filter in the specification; nor can I appreciate in the specification/prosecution history a clear disavowal of the ordinary and customary meaning of the term irradiance mask or filter. Indeed, the following prior art references use the phrase or a similar phrase (as well as the underlying concept) in the same way, such as by teaching that ***light intensity is being standardized*** in U.S. Patent No. 8,666,142 ("Shkolnik") and how ***illuminance is being made uniform*** in International Patent Application Publication No. WO2017/154564 A1 ("Sekine") (translation). I understand that neither of these references were before the examiner before issuance of the '511 Patent.[10]

2. **POSITA's understanding of the ordinary and customary meaning of – "*a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool*"**

85. Based on the context of the entire patent, a POSITA's understanding of a gamma adjustment mask is that it exists within at least one of the digital filters—and is applied to account for the "different resin formulations" and the "different curing times" of different resins as energy is applied. '511 Patent (EX1001), 5:64-6:4.

86. Moreover, the specification provides that the purpose of the "gamma correction filter" is to "**enable[] correct smoothing (and/or antialiasing) of pixels**

[10] That the '511 Patent expressly defines the specific term—"Irradiance" as "Radiant power, per unit area, incident upon a surface, e.g., the Polymer Interface"—does not alter the POSITA's understanding of irradiance mask.

by mapping the pixel intensity range (e.g., 0-255) to the minimum and maximum reactivity characteristics of the pixel." *Id*. at 12:8-12.

87. The specification teaches that "gamma corrections" are "[m]ethods for adjusting the curing time for a specific resin." *Id*., 6:3-5 ("Methods for adjusting the **curing time for a specific resin (i.e., gamma corrections**) are discussed further herein"). The specification further teaches that such adjustments are needed because "**different** resin formulations . . . have **different** curing times." *Id*., 5:65-61. Further, the specification teaches:

> [B]ased on the curing behavior of a particular resin, the gamma correction filter for the composite image (or sub images within the composite image) is optimized to map the irradiance range to the particular resin reactivity range. This can enable **smoother and more accurate surfaces to be realized across different resins**. The reactivity of the resin can change based on the resin composition (e.g., pigments, photo-initiators, photo-initiator concentrations, etc.). Furthermore, resins tend to have nonlinear response curves with respect to energy. Gamma correction filter provides **resin reactivity leveling**, and enables correct smoothing (and/or antialiasing) of pixels by mapping the **pixel intensity range (e.g., 0-255)** to the minimum and maximum reactivity characteristics of the pixel.

Id., 11:65-12.

88. This same purpose is reflected in the claims themselves—for example: claim 1 provides "a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool."

89. The concept of gamma adjustment in the claims, specification, and prosecution history is being described in its ordinary and customary way. Nothing

special is being attributed to its meaning beyond what was known in the art and through conventional wisdom at the time of the filing of the '511 Patent. Tellingly, and unlike other defined terms in the specification, there is no more specific definition of gamma adjustment mask in the specification; nor can I appreciate a clear disavowal associated with the term gamma adjustment mask in the specification/prosecution history. Indeed, the following prior art references use the phrase (or its underlying concept of gamma adjustment) in the same way: U.S. Patent No. 8,666,142 ("Shkolnik") and U.S. Patent Application Publication No. 2017/0102679 ("Greene").

3. POSITA's understanding of the ordinary and customary meaning of – "*a warp correction filter that provides geometric correction*"

90. Based on the context of the entire patent, a POSITA's understanding of a warp correction filter is that it exists within at least one of the digital filters and is applied to correct for some type of geometric distortion. *Id.* at 7:61-63, 7:64-65 ("a stack of digital filters 200 containing a warp correction filter 210"). For "example, a warp correction filter can be used to correct warp or skew in projected images that are caused by variation in projector optics or alignment within the build area." *Id.* at 8:38-41; *see also* FIG. 3.

91. The purpose of warp correction is to "enable more accurate alignment and other corrections to be made on sub-images within a composite image . . . print

curved (or non-planar, or non-2D) layers (or slices), which is useful for some applications and part types." *Id.* at 8:45-48; *id.*, 18:27-29, *id.,* 18:16-29 (discussing use of "optical system" to calibrate "warp and skew").

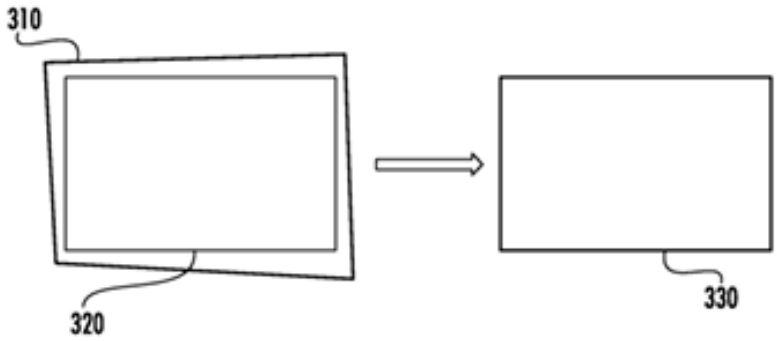


FIG. 3

92. The concept of warp correction in the claims, specification, and prosecution history is being described in its ordinary and customary way. Nothing special is being attributed to the meaning beyond what was known in the art and through conventional wisdom at the time of the filing of the '511 Patent. Tellingly, and unlike other defined terms in the specification, there is no definition of warp correction filter in the specification; nor can I appreciate a clear disavowal associated with the term warp correction filter in the specification/prosecution history. Indeed, the following prior art references use the phrase warp correction (or its underlying concept) in the same way as described in the '511 Patent: U.S. Patent No. 8,666,142 (Shkolnik) and International Patent Application Publication Number WO 2017/154564 A1 (Sekine) (translation). I understand that neither of these references were before the examiner before issuance of the '511 Patent.

4. POSITA's understanding of the ordinary and customary meaning of – "*an edge blending bar at one or more sub-image edges*"

93. Based on the context of the entire patent, a POSITA's understanding of an edge blending bar (filter) is that it is applied to one or more overlapping sub-image edges. This, for example, "enable[s] the data within the overlapping regions … to be **faded out** so that the transition between adjacent sub-images can be made less noticeable." *Id.* at 9:3-5 (depicted in FIG. 2B). Because edge blending fades out the shaded regions, it therefore "improve[es] the quality of the "printed object surface." *Id.* at 9:8-11. In some embodiments, "the number of edge blending bars, the edge blending distances, and the edge blending functions are chosen based on the distance of overlap between adjacent sub-images within a composite image." *Id.* at 9:38-41.

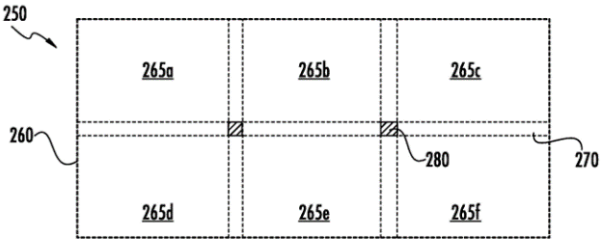


FIG. 2B

94. Moreover, the concept of edge blending (bar) in the claims, specification and prosecution history is being used in its ordinary and customary way. Nothing special is being attributed to the meaning beyond what was known in the art and through conventional wisdom at the time of the filing of the '511 Patent. Tellingly, and unlike other defined terms in the specification, there is no definition of edge blending bar in the specification; nor can I appreciate a clear disavowal

associated with the term edge blending bar in the specification/prosecution history. Indeed, the following prior art references use the phrase edge blending or a similar phrase (or its underlying concept) in the same way as described in the ’511 Patent: U.S. Patent No. 8,666,142 (Shkolnik); and International Patent Application Publication Number WO 2017/154564 A1 (Sekine) (translation). I understand that neither of these references was before the examiner before issuance of the ’511 Patent.

V. PRIOR ART CONSIDERED

A. U.S. Patent No. 8,666,142 (“Shkolnik”)

95. U.S. Patent No. 8,666,142 (“**Shkolnik**”) is entitled, “System and Method for Manufacturing,” and was published on March 4, 2014 with a filing date of November 18, 2008. This date precedes the earliest priority date of the ’511 Patent. Shkolnik is in the same field of endeavor as the ’511 Patent and is reasonably pertinent to the problems encountered in 3D printing (additive manufacturing) using light projection and photocurable resins and is relevant prior art under the legal standards addressed, above.

96. Shkolnik is a lengthy and detailed document with 50 schematics/drawings depicting embodiments of the invention. The patent is directed towards a system that is used for increasing accuracy in the making of 3D components using either (1) a single pattern generator or (2) multiple pattern

generators.[11] An example of a pattern generator may include the use of "DLP (Digital Light Processing technology) from Texas Instruments® . . . or any type of selective light modulation system." *Id.* at 1:25-31. In much the same way as the '511 Patent, Shkolnik discloses techniques to address inaccuracies in 3D printing—specifically in the context of "where a pattern generator provides an image to a reactive material for selective hardening." *Id*. at 4:40-43.

97. According to Shkolnik, such pattern generators "typically have linear and nonlinear distortions that cause inaccuracies in the resulting part . . . [and the] inaccuracies may be surface defects or more serious flaws that may cause the part to be structurally defective." *Id*. at 4:44-48

98. FIG. 15A of Shkolnik is an example of an "upward projecting multiple pattern generator system 1550 of FIG. 15, where dual pattern generators 102, 104 are being calibrated." *Id.* at 40:50-53. Such calibration is undertaken to compensate for inaccuracies in the system. Shkolnik addresses the same problems as the '511 Patent—and offers the very same solutions to provide "precise and consistent manufacturing processes . . . to compensate for the inaccuracies." *Id.* at 5:50. The concepts addressed within the specification are well-known in the industry as well as being concepts I have used in both academia and industry before 2008.

[11] A "pattern generator" in the context of Shkolnik is an image projector/light modulator as used in the '511 Patent (such as a DLP-based device).

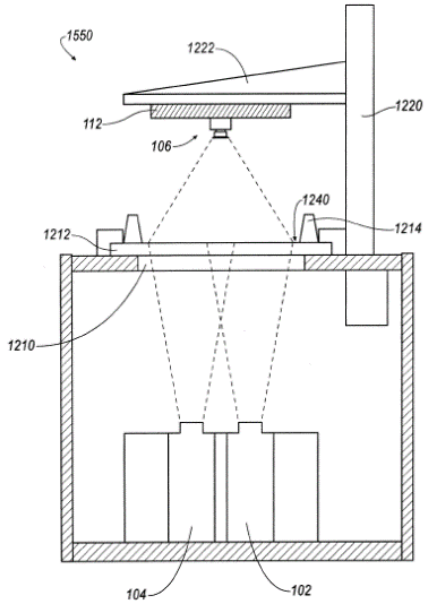


FIG. 15A

99. To a large extent, Shkolnik provides even more detail than the '511 Patent when describing *how* the inaccuracies of the system are compensated.

100. Shkolnik further accounts for the problems associated with the overlap caused by a multi-pattern generator system.

101. The specification of Shkolnik depicts how overlap in images can occur and how this overlap is then accounted for through what a POSITA would consider **edge blending techniques**—specifically, with reference to FIG. 7C: "the intensity of the pixels from pattern generators, that account for overlap pixel region 726, 736 may be reduced in intensity (e.g., 50% from each pattern generator) to reduce over-exposure of reactive material at overlap portions 728, 738." *Id.* at 34:4-14, *see also id*. at 34:57-64 ("Here, for example, portions of the separated images are at a full

intensity within region 724, 734 up to overlap pixel regions 726,736 and **fade to** no intensity toward overlap portions 728, 738.").

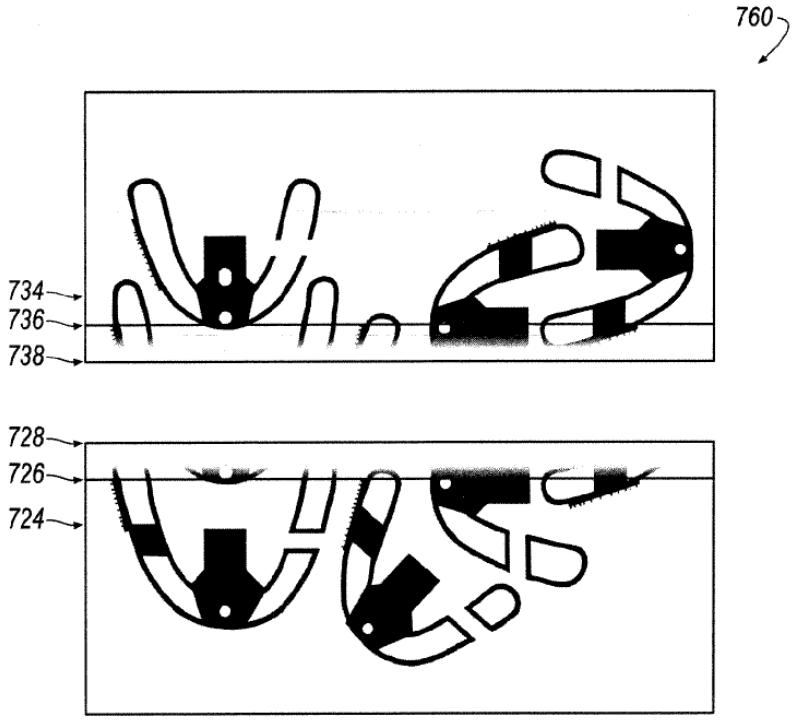


FIG. 7C

102. The **fading effect** (e.g., shown here between 736 and 738: and 726 and 728) use a linear interpolation algorithm to reduce intensity such that when overlapped, the combined intensity is the same as the original image 750."). FIG. 7A of Shkolnik also illustrates edge blending, as further discussed below.

103. Shkolnik further accounts for **warp correction** as depicted in FIGS. 5A-5C. As the specification provides: "In step 1320, the ideal patterns are modified by the pattern generator calibration/correction maps determined in method 1200." *Id*., 5-6. The controller then outputs corrected patterns to pattern generators, which

may include "simple translation" or "complete two-dimensional mapping of the image to compensate for geometric distortion of the pattern generator." *Id.* at 8-10.

104. Examples of geometric distortion are shown in FIGS.5A-5C and may include both "linear and non-linear distortion," where modification of the "ideal patterns removes such distortion when finally output by a pattern generator." *Id.* at 12-15.

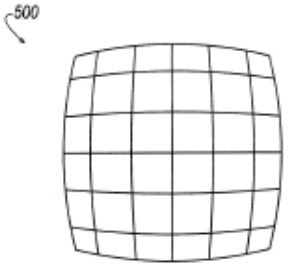


FIG. 5A

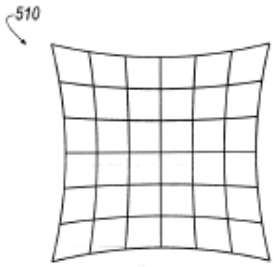


FIG. 5B

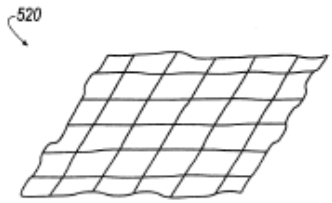


FIG. 5C

105. Shkolnik also teaches gamma adjustment techniques that are the same as those claimed in the '511 Patent.[12] The following passages are illustrative of the gamma adjustment techniques employed in Shkolnik:

> As discussed herein, the term "total exposure" may be considered the intensity of the electromagnetic radiation multiplied by the time that the electromagnetic radiation is allowed to interact with the reactive material. When performing voxelized construction, the total exposure determines the depth of cure for each voxel separately and independently of any other voxel. In an example, where the intensity is 250 and the time is 1 second, the exposure will be 250 times 1 second to effectuate a desired depth of cure for a specific voxel. **The time and intensity to achieve a particular depth of cure is material dependent**. Thus, the **time and intensity determined to provide a particular curing depth for a first reactive material may not be usable for a second reactive material**. Thus, the **depth of cure can be a function of at least the exposure time, the intensity of the electromagnetic radiation, and the properties of the reactive material**. The combination of intensity and exposure time can be expressed independently (e.g., in data file or data structure) or they may be combined and expressed for each voxel as a grayscale value where the exposure time is predetermined.
>
> Although the intensity may be used to determine the strength of the electromagnetic radiation (e.g., brightness or intensity when discussing visible or UV light, for example), the intensity may also be used to determine the length of time (e.g., exposure time) that the electromagnetic radiation is turned "on" for the pixel. Moreover, the intensity may also determine the intensity and "on" time for the pixel, where the intensity may remain constant over the "on" time, or the intensity may vary.

[12] There, the specification teaches that "gamma corrections" are "[m]ethods for adjusting the curing time for a **specific resin**." '511 Patent (EX1001), 6:3-5. The specification further teaches that such adjustments are needed because "**different resin formulations . . .have different curing times**." *Id*., 5:65-6:1; see also, *id*., 12:7-12 ("[R]esins tend to have **nonlinear** response curves with respect to energy. Gamma correction filter provides resin reactivity leveling, and enables correct smoothing (and/or antialiasing) of pixels by mapping the pixel intensity range (e.g., 0-255) to the minimum and maximum reactivity characteristics of the pixel.").

> While the **intensity is typically expressed as an integer number (e.g., 0... 255), the intensity value may be compensated or adjusted before being sent to the pattern generator, or may be compensated or adjusted at the pattern generator, or both**. For example, where reactive material 118 has a minimum intensity threshold for polymerization or partial-polymerization, **the "off" or zero (0) value intensity (e.g., brightness and/or "on" time) may be determined based on the reactive material threshold**. In a typical case, a low level of brightness may correspond to a zero (0) intensity (see FIG. 7D where the background field is illuminated but below the polymerization threshold of reactive material 118).
>
> Note, however, that the **percent intensity value assigned to a voxel is material dependent**, and that there may not be a linear relation between them (e.g., the intensity values for 50% depth of cure may be different for each reactive material). A **detailed example of voxelized correction including intensity modification** is shown below with respect to FIGS. 1MA-1MG. As discussed herein a voxel data may be expressed as a bitmap with intensities assigned for each pixel in the bitmap, **the intensity providing variable depth of cure for each voxel**.

Shkolnik (EX1004), 10:14-33; 9:38-58; 18:32-42.

106. In short, Shkolnik teaches the assignment of an "intensity value" or level to each pixel or voxel of a sub-image. *Id.* at 9:47-51. For example, Shkolnik teaches that for an 8-bit system "intensity ranges of 0 to 255 are convenient." *Id.* at 9:59-62.

107. Further, Shkolnik teaches that the intensity value takes into account the unique curing behavior of the relevant resin, including in a nonlinear manner, and that such adjustment is **helpful for improving printing accuracy**. *Id*. at 18:32-37.

108. For instance, regarding smoothing, Shkolnik teaches the following:

In an example using the original bitmap's pixel information, the boundary of the part may be reconstructed for later use in the geometric correction method. Moreover, using the bitmaps threshold value (in this example 40%), the boundary of the component may be reconstructed in a relatively accurate manner for later correction. For example, in FIG. 1MBB, **the boundary is determined to be a smooth surface, rather than follow the jagged edge that would otherwise be determined by pixels G21 and G23.** The component boundary may be estimated as being nearly through the center of each outer boundary pixel (e.g., G21 and G23) and may also be influenced by neighboring pixels to estimate a **smooth surface**. Here, the component boundary is estimated through nearly the middle of pixels G21, G23 because the "on" threshold **for each pixel is 40%**. Other methods may be applied, however, **using boundary estimation (rather than using the original jagged edge determined by the original bitmap pixels) may provide for improved results** using the geometric correction methods.

Id. at 26:15-33.

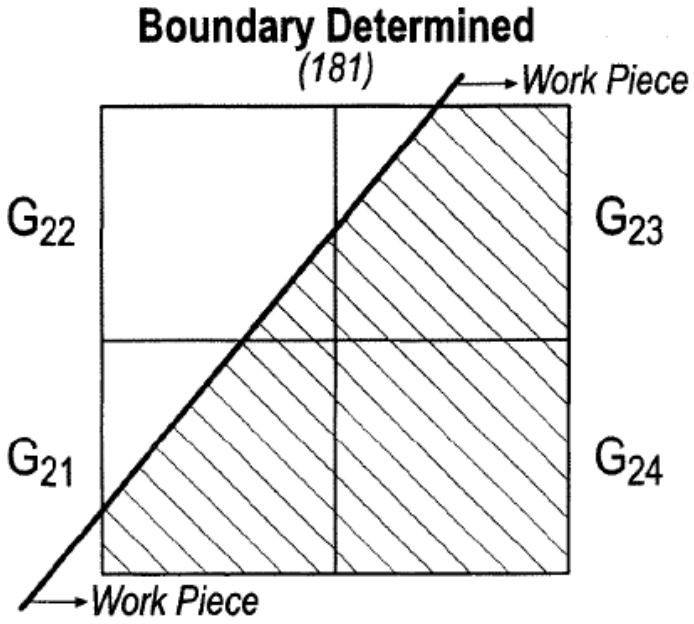


FIG. 1MB

109. Finally, Shkolnik addresses what the POSITA would consider **irradiance normalization**—and while not using that phrase specifically, I

understand Shkolnik to teach the same concept for the same reason as the '511 Patent. For example, I understand Shkolnik's phrases, "intensity compensation" and "so that the combined intensity is [made] standard" to equate with the same concept that is being attributed to "that normalizes irradiance." *Compare* Shkolnik (EX1004) at 5:49, *id.* at 34:21-22 *with* '511 Patent (EX1001) at Claim 1. Stated another way, to standardize the light generated from the pattern generators, the light is being reduced to provide uniform levels and ensure normalization across the relevant resin area.

110. In sum, the overarching purpose of Shkolnik is to ensure that linear and non-linear distortions in the pattern generators are compensated for not only with respect to intensity, but also in relation to overlapping edges and material dependent resins—along with "geometric [warp] distortion of the pattern generator." *Id.* at 8-10. Indeed, Shkolnik's methods and purpose can be summed up as follows:

> These methods generally include manipulating the pattern to compensate for the inaccuracy prior to generation of the pattern. A calibrated imager (e.g., a camera) may be used to view an uncompensated test pattern to determine the inaccuracies for a pattern generator. The uncompensated test pattern may then be compared with the **ideal (or expected) test pattern** to generate a pattern correction map.

Id. at 5:40-46.

111. Notably, these methods (and purpose) are also reflected in the '511 Patent—adopting the same techniques to achieve the same ideal test pattern. *See* '511 Patent (EX1001), 4:50-51 ("The intended image to be projected onto the build

area can be referred to as the ideal composite image."); *see also id.*, 9:44-48 ("In some such cases, . . . the total intensity of the pixels within the overlapping region substantially match the intensity of the ideal composite image within that region.").

B. WO2017/154564 A1 ("Sekine")

112. International Patent Application Publication No. WO2017/154564 A1 ("Sekine")—translated—is entitled "Three-Dimensional Shaping Device" and was published on September 14, 2017, with an international filing date of February 22, 2017 and an earliest priority date of March 9, 2016. These dates precede the earliest priority date of the '511 Patent. Sekine is in the same field of endeavor as the '511 Patent and is reasonably pertinent to the problems encountered in 3D printing using light projection and photocurable resins and is, therefore, relevant prior art under the relevant standards addressed, above.

113. Sekine is a PCT application originally filed and published in Japanese. The original Japanese-language application has been translated by a professional translating service, Sun IP. The translator's name is Eric Vance. Mr. Vance has over 9 years of professional translation experience, JLPT N1 Certification, OPI advanced high certification, and BS/BA degrees in Physiology and Japanese.

114. Sekine is directed towards a system that is used for increasing accuracy in the making of 3D components using a multiple projector system. *Id*. at [0005]-[0009]. More specifically, Sekine provides a "first image projection means for

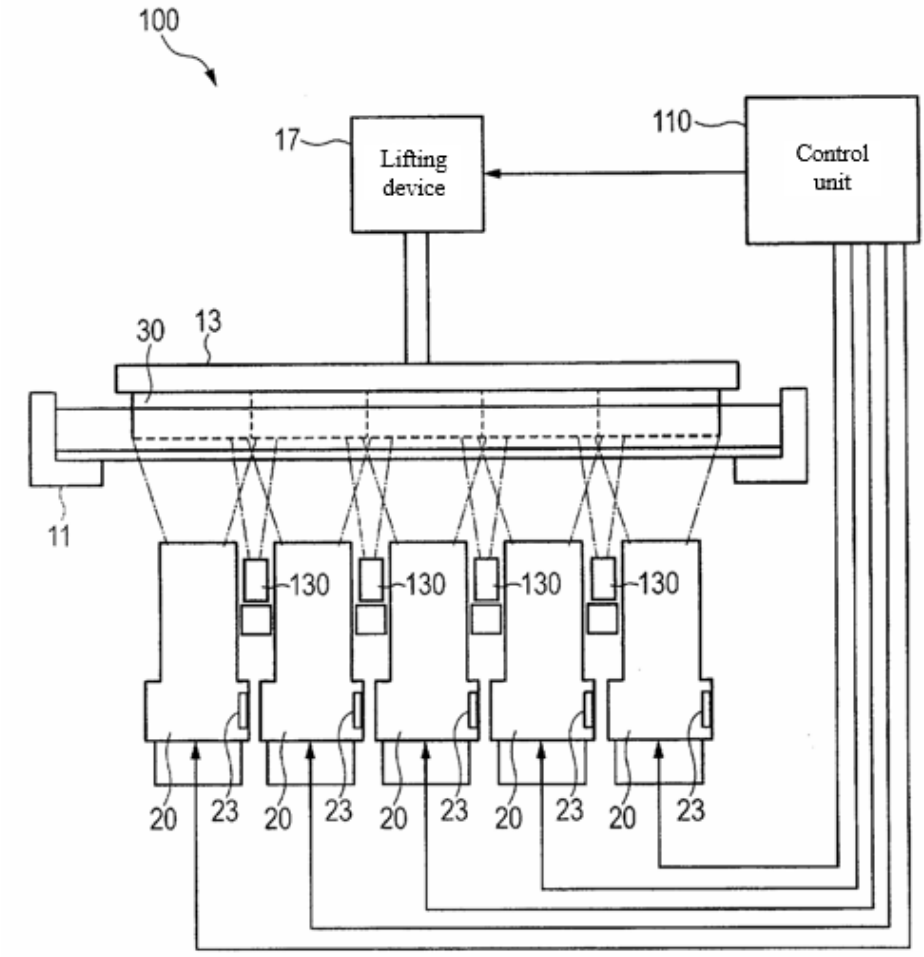
projecting a first exposure image into the resin material from the incident surface," and "a second image projection means for projecting a second exposure image continuous with the first exposure image into the resin material from the incident surface," as well as additional projectors in some cases, **to allow for improved printing accuracy**—e.g., a "three-dimensional shap[ed] device that does not readily form streak patterns or slits . . . on a surface of a shaped product." *Id*. at [0009]-[0010].

115. FIG. 1 depicts a diagram of the configuration of the three-dimensional projector system—which is "arranged in a 5×5 configuration to create a shaped product 30." *Id.* at [0014]. Projectors 20 project exposure images on the surface of an image forming element 23 into the resin material 10 in the container 11." *Id.* at [0017]. The image forming element 23 "forms the exposure image illuminated by a light source 21, which is one example of **illumination** means." *Id*. at [0018].

116. The light source 21 generates "ultraviolet light using an ultraviolet LED to illuminate the image forming element 23." *Id.* A projection optical system 25 "projects the exposure image formed by the image forming element 23 through the incident surface 12a into the resin material 10." *Id*.; *see also id*. at [0019] ("The image forming element 23 is formed by arranging minute movable mirrors corresponding to individual pixels in a grid pattern, and a reflected image of the illumination light is output from the light source 21."); *see also id.,* [0043].

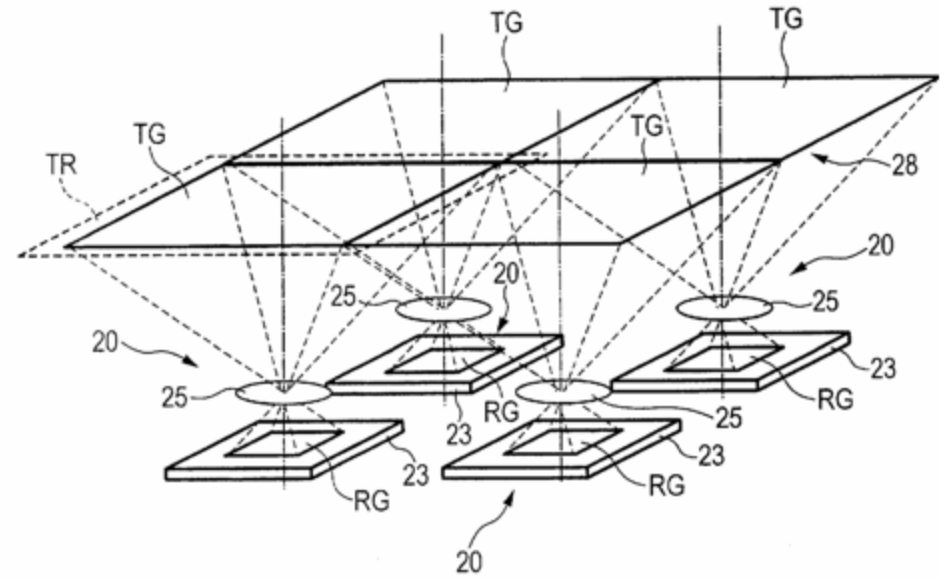
Moreover, a "boundary region of adjacent projection regions is captured by a camera 130, and overlap of the projection regions in the boundary region is mechanically adjusted based on the captured image." *Id*. at [0018].

[FIG. 1]



117. As further illustrated in FIG. 5, the "four projectors project the exposure image RG divided into four to form the projection image TG at the image formation position." *Id.* at [0043].

[FIG. 5]



118. Regarding image formation, and the illuminance involved in that process, the specification further provides that the "mirror of each pixel of the image forming element 23 may simply be turned ON/OFF in synchronization with switching of the exposure image RG." *Id*. at [0021]. It may also be set to a "brightness gradation (intensity modulation amount) for each pixel constituting the exposure image." *Id.* The image forming element 23 can turn the mirror of each pixel ON/OFF (change of reflection angle) 250 times per second within a duty ratio range of 0 to 100%." *Id.* And so "by individually setting an ON duty ratio for the mirror of each pixel, it is also possible to output intermediate tones (grayscale) of the pixels." *Id.*

119. The ability to make this illuminance intensity adjustment—which is also disclosed in Shkolnik[13] and the '511 Patent[14]—is important because one of the problems that confronts those working in the field are different illumination intensities across the boundary line (or across the entire image being projected)—i.e., "[w]hen the illumination of the product projection image differs across the boundary of adjacent projection images, streaks in the shaping direction are formed at the boundary position of the shaped product 30." *Id*. at [0070].

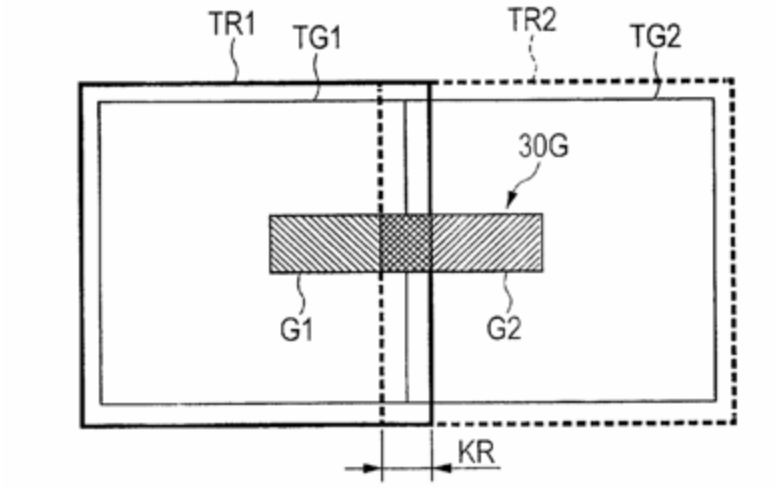
120. To solve this problem, the specification of Sekine states that "adjustments are made to eliminate the brightness difference between adjacent projection images." *Id.* More specifically, when differences occur, the system allows "the brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 [to be] controlled to make the illumination distribution uniform." *Id.* at [0071]. This is the same as the irradiance normalization technique in Shkolnik and the '511 Patent.

[13] There, the verbiage provides: "configured to normalize irradiance." Shkolnik (EX1004) at 5:49; *see also id.* at 34:21-22 ("If desired, both pattern generators 102, 104 could . . . could each reduce the intensity of output so that the combined intensity is standard.").

[14] There, the verbiage provides that "normalizes irradiance" infers, for example, "projector - based spatial energy non-uniformities." *Id.* at 11:22-25. This is achieved by "correct[ing] differences between sub-images." *Id.* at 11:25-34; *see also id*. at 23:22-23 (the filter "create[s] a uniform irradiance across the whole image.").

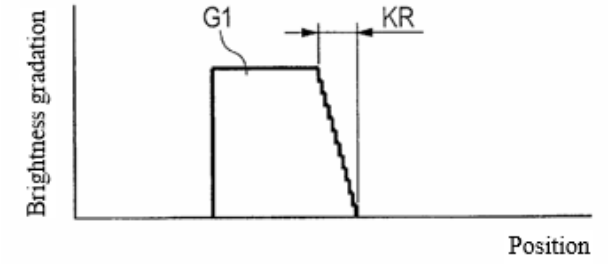
121. Sekine also teaches a mechanism for improving printing resolution by blending the ends of adjacent sub-images. As stated above in the discussion of brightness normalization, Sekine teaches that adjacent sub-images can overlap, and that adjustments to the sub-images can be made to ensure proper printing despite the overlap, such as by adjusting brightness. In addition, Sekine teaches the use of "grayscaling" or "stepping" of adjacent sub-images where their edges overlap, such that the two sub-images blend into one another gradually. This correction mechanism is described in detail with reference to Figure 17, for instance. Figure 17 is reproduced below for convenience. In Figure 17, an overall image 30G is desired. The overall image 30G is rectangle shaped and includes two parts, denoted as G1 (left half of the rectangle in Figure 17) and G2 (right half of the rectangle in Figure 17). The first part G1 is included in a first sub-image (TG1) produced by a first projector (the projector itself is not shown in Figure 17). The second part G2 is included in a second sub-image (TG2) produced by a second projector (not shown). The element "KR" in Figure 17 shows the boundary region where the sub-images TG1 and TG2 overlap. Sekine (EX1005), [0101]-[0105].

[FIG. 17A]

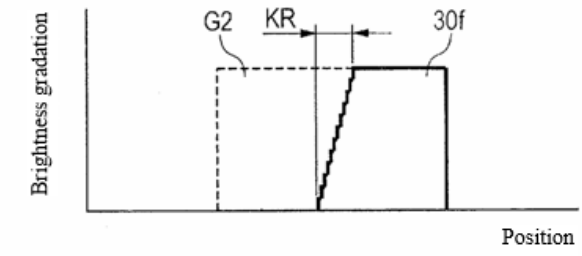


122. Notably, as shown in Figure 17B, the brightness or irradiation is G1 is graded or "grayscaled" within the overlap region KR —that is, G1 has a "stair step" brightness, with brightness decreasing as G1 gets closer to G2. Similarly, as shown in Figure 17C, the brightness of G2 is also graded or grayscaled, with brightness decreasing as G2 gets closer to G1. *Id.* at [0101]-[0105]. In this way, the edges of sub-images TG1 and TG2 are blended together. As taught by Sekine, this approach avoids both "gaps" (where there is not enough light, and thus the photocurable resin is under-exposed) and also "streaks" (where there is too much light, and thus the photocurable resin is over-exposed). *Id.* at [0070]-[0072], [0101]-[0105].

[FIG. 17B]



[FIG. 17C]

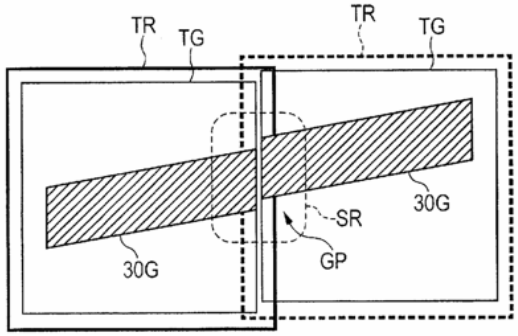


123. This teaching of Sekine is consistent with common knowledge in the industry and with the disclosures of both Shkolnik and the ’511 Patent. For example, the ’511 Patent teaches an “edge blending bar” that accounts for overlap in projection images by, for example, “fad[ing] out” “perimeters of adjacent sub-images” so that “the transition between the adjacent sub-images can be made less noticeable.” ’511 Patent (EX1001), 9:3-8; *id.* at 10:27-32. Similarly, Shkolnik teaches that multiple pattern generators (e.g., multiple DLP devices) “could each reduce the intensity of output so that the combined intensity is standard.” Shkolnik (EX1004), 34:19-22. More particularly, Shkolnik teaches that it may be desirable “to reduce intensity such that when [multiple sub-images are] overlapped, the combined intensity is the same as the original image.” Shkolnik (EX1004), 34:61-64.

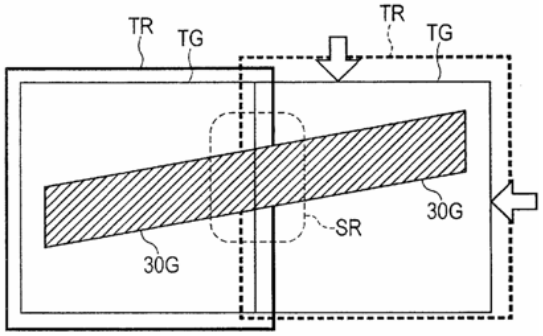
124. As noted above, Sekine teaches the correction of various errors or distortions associated with the use of multiple projectors in additive manufacturing. Geometric corrections are discussed in detail. For instance, Sekine states the following at paragraph [0062]: "when using multiple projectors 20 to project individual exposure images RG formed by dividing the overall exposure image…distortion of the image itself" can occur, such as indicated by a "displacement of the [overall] image pattern at the boundary of the adjacent [sub-images]." To address such geometric misalignment or distortion, Sekine teaches that the system of Sekine corrects the sub-images so that the overall image matches the designed position, rather than being distorted. Sekine (EX1005), [0063].

125. One example of such geometric correction is described in Figures 9, 10A, and 10B of Sekine. *Id.* at [0064]-[0068]. Figure 9 is a flowchart for "displacement correction control." Figures 10A and 10B (reproduced below for convenience) show "before" and "after" depictions of a geometrically displaced image (Figure 10A) and corrected image (Figure 10B).

[FIG. 10A]



[FIG. 10B]



126. As illustrated in Figure 10A, if a displacement error occurs between adjacent projection regions TR, a gap GP may form in the desired product image. The desired image is depicted as a hatched rectangle, denoted as element 30G in Figure 10. *Id.* at [0067]. Sekine teaches that one way to correct this distortion is by adjusting position and tilt. *Id.* Specifically, as illustrated in Figure 10B, the individual projection regions TR are not moved. Instead, the projection image TG is moved within the projection region TR as indicated by the arrows to eliminate the gap GP. With reference to Figure 2, this correction can be achieved by (1) moving the contour position of the product 30 displayed in the exposure image RG on the image forming element 23 by a "positional correction amount" and also (2) tilting

by a "tilt correction amount." *Id.* at [0067]. According to Sekine, these position and angle adjustments remove the distortion and correct the geometry of the printed article. These teachings of Sekine are consistent with common knowledge in the field. Practitioners within the digital display and projection community were well familiar with the concept of geometric correction (e.g., warp correction and other types of geometric correction), and had access to prior art (such as Sekine) that disclose geometric correction such as warp correction, both generally and also with respect to disclosing specific methods, techniques, and algorithms that would enable one to perform geometric correction (such as disclosed by Sekine).

127. In sum, Sekine—just like Shkolnik—is directed towards an additive manufacturing system that accounts for inaccuracies inherent in multi-projector photocuring. Sekine discloses three of the four "filters" that are disclosed in the '511 Patent. The only filter **not** explicitly disclosed is gamma adjustment.

C. U.S. Patent Application Publication No. 2017/0102679

128. U.S. Patent Application Publication No. 2017/0102679 ("Greene") is entitled "Sub-Pixel Grayscale Three-Dimensional Printing" and was published on April 14, 2017, with a filing date of October 6, 2016 and a priority date of October 7, 2015. These dates precede the earliest priority date of the '511 Patent.

129. Greene is in the same field of endeavor as the '511 Patent and is reasonably pertinent to the problems encountered in 3D printing (additive

manufacturing) using light projection and photocurable resins and is, therefore, relevant prior art under the relevant standards addressed, above.

130. Greene is directed towards the use of grayscaling in 3D printing, as applied (or accounting for) the different resins used in the 3D printing process. The purpose of the technology includes "to smooth out edges in three-dimensional printing" (Greene (EX1006), [0008]), while accommodating for the fact that the resins used in the process are different and require varying exposure time. *Id.*, [0037].

131. Greene teaches at paragraphs [0037]-[0040] a process that assigns grayscale intensity levels to various voxels or pixels[15] of the digital model. The entirety of paragraph [0040] of Greene is reproduced below.

> At 435, the process assigns one or more grayscale intensity levels to one or more grayscale voxels based respectively on the one or more containment degrees. If the digital model, for example, covers 60% of the volume of a voxel (e.g., 60% containment degree), then the process can assign an intensity level that is 60% of the white intensity level. In another example, if the digital model covers 80% of the volume of a voxel, then the process can assign an intensity level that is 80% of the white intensity level. The one or more grayscale intensity levels are greater than a black intensity level, but less than the white intensity level assigned at 420. The one or more grayscale intensity levels are not sufficient to completely cure the photoactive resin during the predetermined curing time. **In some implementations, the process can adjust the one or more grayscale intensity levels based on** a nonlinear characteristic of a light source within the 3D printer, **a nonlinear characteristic of the photoactive resin**, or both. **For example, a photoactive resin may have a nonlinear relationship**

[15] A voxel is the three-dimensional equivalent of a two-dimensional pixel.

> **between intensity levels and a curing degree.** In cases where the nonlinearity is substantially a power function (e.g., $y=x^{\gamma}$), an adjustment can be performed by applying the inverse power ($1/\gamma$) to the grayscale intensity levels, **e.g., by performing gamma correction**. Alternatively, a lookup table can be applied to correct for arbitrary nonlinearities. In some implementations, the intensity levels are R-bit values, where R is a predetermined number of bits associated with a graphic file format that range from 0 (black) to 255 (white). For example, the intensity levels can be represented as 8-bit values that range from 0 (black) to 255 (white). Other values for R are possible.

132. For instance, a specific voxel or pixel can be assigned an intensity level that is 60% of a "white" (or fully cured) intensity level, *id*., [0040],[16] where a "white" intensity level is "sufficient to cure photoactive resin during a predetermined curing time," as compared to a "black" intensity level that corresponds to zero light or zero curing. Greene (EX1006), [0037] ("The white intensity level is sufficient to **cure photoactive resin** during a predetermined curing time for a layer. In some implementations, the white intensity level is a percentage (e.g., 90% or 95%) of a maximum intensity level generated by a 3D printer; in this case, the maximum intensity level exceeds an intensity level sufficient to cure photoactive resin. Note that **different photoactive resins can require different curing intensities**."); *see also id.* at [0038], [0040].

[16] Greene (EX1006), [0040] ("If the digital model, for example, covers 60% of the volume of a voxel (e.g., 60% containment degree), then the process can assign an intensity level that is 60% of the white intensity level.").

133. In short, a pixel having a "grayscale" intensity level can be considered to experience more curing than a "black" pixel or voxel (where no curing occurs), but less than a "white" pixel or voxel (where "maximum" or close to maximum curing occurs). Thus, per Greene, the intensity values can be treated as "R-bit values," where R is a predetermined number of bits associated with a graphic file format, such as 8 bits. For example, Greene teaches at paragraph [0040] that "the intensity levels can be represented as 8-bit values that range from 0 (black) to 255 (white)."

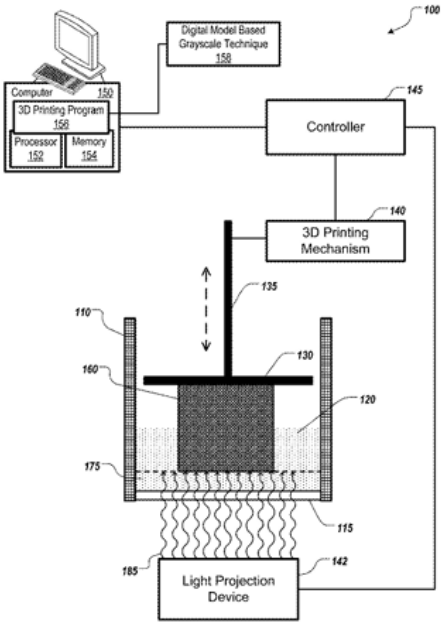
134. Further, at paragraph [0047], Greene addresses gamma adjustment with respect to additional embodiments.

> At 720, the process generates containment degrees for the finalized pixels based on the respective groups of K*K*K super-pixels. At 725, the process assigns intensity levels based on the containment degrees. **In some implementations, the intensity levels are gamma corrected based on nonlinearities associated with** the printer's projection system, **resin**, or both.

135. Notably, as seen above, the pixel (grayscale) intensity level of Greene (e.g., on a scale of 0 to 255) can be **adjusted "based on** a nonlinear characteristic of a light source within the 3D printer**, a nonlinear characteristic of the photoactive resin, or both**." Greene (EX1006), [0040], [0047] ("The intensity levels are gamma corrected based on nonlinearities associated with the . . . resin"). That is, gamma correction in Greene permits an intensity value between 0 and 255 to be assigned to

pixels based on the unique nonlinear characteristics of whatever resin is used in a given print job. *Id.*

136. In addition to the detailed discussion of gamma correction, Greene discloses a general additive manufacturing system that photocures a liquid resin:



> A 3D printer system can include a vat capable of holding a liquid including a photoactive resin, wherein the vat includes a window; a build plate configured and arranged to move within the vat during three-dimensional printing of a structure on the build plate; a light projection device to project light through the window; and a controller to control the printing of the structure, movement of the build plate, and light modulation of the light projection device. The controller can be configured to perform operations that include mapping a digital model onto a three-dimensional grid of voxels.

Id. at [0007]; *see also id*. at [0023] ("The system 100 includes a vat 110 to hold a liquid 120, which includes one or more photoactive resins. The vat 110 includes a window 115 in its bottom through which light is transmitted to cure resin to form a 3D printed structure 160 in a layer-by-layer build process.").

137. The purposes of the system of Greene include to more "accurately represent the digital model, e.g., a smoother edge is formed as shown in image l00lb rather than a jagged, stair-stepped edge as shown in image l00la." *Id*. at [0053]; *see*

also id. at [0008] (the "technology can be used to smooth out edges in three dimensional printing.").

D. EP 3,053,729 A1 ("Jørgensen")

138. European Patent Application Publication No. EP 3,053,729 A1 ("Jørgensen") (EX1028) is entitled "Method for exposing a photo polymerizable material for solidification of material layer by layer to build a 3D object" and was published on August 10, 2016, with a filing date of February 4, 2015. These dates precede the earliest priority date of the '511 Patent. Jørgensen is in the same field of endeavor as the '511 Patent and is reasonably pertinent to the problems encountered in 3D printing using light projection and photocurable resins and is, therefore, relevant prior art using the relevant standards, addressed above.

139. Jørgensen is directed towards DLP-based additive manufacturing, including for purposes of meeting "the demand for larger building areas" while "obtaining…high resolution." *See* Jørgensen (EX1028), [0001]-[0004]. More specifically, Jørgensen teaches DLP systems and methods that are "capable of increasing the resolution of the solidification material compared to the static image of projected light … by using **image scrolling** while the light projector is in motion relative to the exposed [photopolymerizable] material." *Id.* at [0002], [0006]. Additionally, Jørgensen teaches that to print a "large exposed pattern image," the image may be divided into sub-images and exposed sequentially using a **"step and**

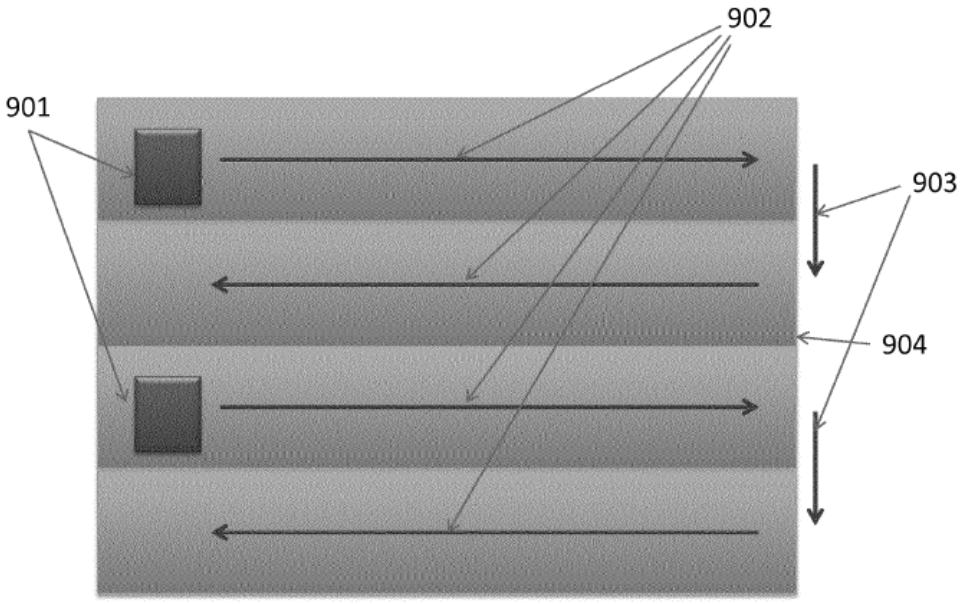
flash" procedure. *Id.* at [0013]. Alternatively, Jørgensen teaches that a composite image may be printed **"in a continuous way,"** in which the "light projector is moving relative to the exposed [photopolymerizable] material" continuously, pixel-by-pixel. *Id.* at [0015]. Jørgensen further teaches that multiple images may be "**stitched together** forming a continu[ous] image strip." *Id*. at [0008], FIG. 3.

140. In addition, Jørgensen describes multiple ways the light projector can move relative to the photopolymerizable material. For example, Jørgensen teaches that the light projector can "be moved relative to the material" back and forth along an axis, which Jørgensen denotes as the "x axis." *Id*. at [0009], [0015], FIG. 3. It is also possible, according to Jørgensen, for the light projector to be moved along another axis as well, such as an axis Jørgensen denotes as the "y-axis," which allows the building area to be increased even further, for example to a size that "can in theory be infinite." *See id.* at [0009]-[0010].

141. Moreover, Jørgensen teaches that "multiple light projectors" can be used in parallel "to speed up the building process even further." *Id*. at [0010]. As one example, Jørgensen teaches two-dimensional movement of an array of light projectors in a serpentine manner across the build area. *See id*. at [0021], FIG. 9 (reproduced below). In FIG. 9, the light projectors are denoted as "901" and the "light sensitive media" (e.g., photopolymerizable material) is denoted as "904." *Id*. The "scrolling" projectors 901 move relative to the photopolymerizable material as

indicated by the arrows in FIG. 9. *Id*. Specifically, as taught by Jørgensen, the projectors 901 first move to the right along the x axis (which is denoted as "902" in FIG. 9). *Id*. Next, the projectors 901 "shift" downward along the y axis (denoted as "903") before then moving back to the left along the x axis. *Id*. Using such "scrolling," Jørgensen teaches that it is possible to "both increase the build area and decrease the building time." *Id*. at [0021].

FIGURE#9



E. Yi *et al.*, "Delta DLP 3-D Printing of Large Models," *IEEE Transactions on Automation Science and Engineering* (DOI: 10.1109/TASE.2017.2751664) ("Yi")

142. Yi (EX1029) is a non-patent literature paper by Ran Yi *et al.* and titled "Delta DLP 3-D Printing of Large Models," published on October 2, 2017 by the Institute of Electrical and Electronic Engineers (IEEE) and republished on July 2, 2018 as part of Volume 15, Number 3, of *IEEE Transactions on Automation Science*

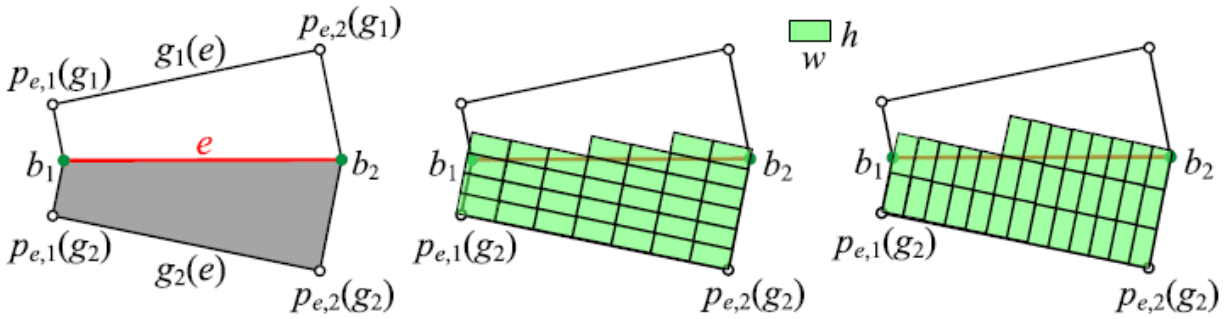
and Engineering (DOI: 10.1109/TASE.2017.2751664). Both of these publication dates precede the earliest priority date of the ’511 Patent. Yi is in the same field of endeavor as the ’511 Patent and is reasonably pertinent to the problems encountered in 3D printing using light projection and photocurable resins and is, therefore, relevant prior art using the relevant standards addressed, above.

143. Yi is directed towards DLP-based additive manufacturing, including “**DLP-based 3-D printing with a large size**.” *See* Yi (EX1029), p.1194. Yi discloses a system with a moveable platform and a light projector. *See id.* at p.1194, FIG. 1. More specifically, Yi discloses “a new DLP system that allows the platform to move not only vertically (in *z*-axis) but also horizontally (in *x*-*y* plane).” *Id.* at p.1194. In the Yi system, “[i]n addition to moving vertically (along *z*-axis), the working platform holding cured models can move **and rotate horizontally** (i.e., in the *x*-*y* plane).” *Id.* This functionality allows the platform to be “moved to **any position** in a cylindrical working envelope.” *See id.* at p.1195.

144. In the figures, Yi represents individual projected images as rectangles, where each such rectangle corresponds to “the maximal area that can be projected by a light source, which is a rectangular region in our delta DLP 3-D printer.” *See id*. at p.1196, FIG. 4. Yi refers to each such rectangle as an “elementary rectangle.” *Id*. Yi further discloses “sets” or arrays of rectangles having multiple columns and rows. *See*, *e.g.*, *id*. at p.1198, FIG. 7, FIG. 8 (green rectangles). Additionally, Yi

teaches that "bigger models are made by multiprojections for each layer." *Id*. at p.1202, FIGS. 13, 14.

145. Notably, the system of Yi is movable and rotatable in the x-y plane such that "the rectangles are allowed to be in **any orientation**," when projected onto the curable material surface, and are not limited to having their "sides parallel to two orthogonal directions." *See id.*, p.1194. Yi depicts one example of such an off-axis orientation in FIG. 7 (reproduced below). *See id.* at p.1198, FIG. 7.



F. Basis of Grounds - § 311(b)

146. The basis for each ground is summarized below:

Ground	Claims	Basis for Rejection
§ 102 – Ground 1	1-8, 14, 15	Anticipation by Shkolnik
§ 103 – Ground 2	1-8, 14, 15	Obviousness over Sekine + Greene
§ 103 – Ground 3	1-8, 14, 15	Obviousness over Shkolnik + Sekine
§ 103 – Ground 4	9-12	Obviousness over Sekine + Greene + Jørgensen
§ 103 – Ground 5	13	Obviousness over Sekine + Green + Jørgensen + Yi

147. Notably, the combination of Sekine and Shkolnik is dependent on circumstances where the Panel both (a) adopts a much narrower construction of the irradiance mask filter limitation is adopted, and (b) further concludes that Shkolnik may not disclose the limitation as narrowly construed.

VI. GROUND 1: CLAIMS 1-8, 14, AND 15 ARE UNPATENTABLE AS ANTICIPATED IN LIGHT OF PRIOR ART SHKLONIK

A. Claim Construction

148. Unless specifically noted otherwise below, I have accorded claim terms their ordinary and customary meaning as understood by a POSITA and in light of the patent specification and prosecution history.

149. I have been informed by counsel and understand that claim terms need not be construed when there is no dispute as to the meaning of a term that could affect the outcome of the proceeding. It is my opinion that none of the claims of the '511 Patent require construction to determine their validity in view of the prior art I have analyzed in this Declaration. Thus, for purposes of this proceeding, it is my opinion that no formal claim construction is necessary. That is, I have applied the ordinary and customary meaning to my analysis.

B. Prior Art to the Claims

150. Based upon my review of the prior art, particularly the references detailed in this declaration, it is my opinion that the subject matter of each of the

Challenged Claims would have been anticipated to one of ordinary skill in the art in view of the known prior art references.

C. Shkolnik Discloses All Claimed Limitations

1. Claim 1

(a) Element 1[a]: A method comprising:

151. Shkolnik is directed to systems and methods for additive manufacturing. Shkolnik (EX1004), 4:22-23. Therefore, it is my opinion that Shkolnik discloses the preamble of claim 1 of the ’511 Patent.

(b) a. providing an additive manufacturing system, comprising:

152. Shkolnik teaches providing an additive manufacturing system. As discussed above with respect to the preamble of claim 1, Shkolnik is directed to systems and methods for additive manufacturing. Shkolnik (EX1004), 4:22-23.

153. Therefore, it is my opinion that Shkolnik discloses this element of claim 1 of the ’511 Patent.

(c) an image projection system comprising a plurality of image projectors; and

154. Shkolnik teaches an additive manufacturing system comprising an image projection system comprising a plurality of image projectors. In general, Shkolnik teaches a system having an image projection system that includes one or

more image projectors, such as one or more digital light processing or "DLP" devices. Shkolnik (EX1004), 4:40-44. Such image projectors are sometimes referred to as "pattern generators" in Shkolnik. *See, e.g.*, Shkolnik (EX1004), 4:41-42; 7:56-57. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(d) an image display subsystem;

155. Shkolnik teaches an additive manufacturing system comprising an image display subsystem. As described in the '511 Patent, an image display subsystem can control the image projection system. *See, e.g.*, '511 Patent (EX1001), claim 1. Shkolnik teaches that its system can include various components and subsystems for controlling the image projection system and each of the image projectors of Shkolnik to adjust properties and alignment of a position of each sub-image in the array of sub-images described by Shkolnik. For example, Shkolnik teaches a controller that interfaces with multiple pattern generators and an imager "for self-calibration at any time before, during, or after manufacture" such as "image correction mapping…to modify an image or bitmap for positional inaccuracies." *See*, *e.g.*, Shkolnik (EX1004), 7:10-22; 8:6-32. Such a "controller" is denoted as element 120 in Figure 1A, and such an "imager" is denoted as element 106 in Figure 1A (see reproduction of Figure 1A below). Additionally, Shkolnik teaches that the

imager 106 "may be used for initial alignment and adjustment of pattern generators 102, 104 or for real-time, or near real-time, adjustment." *Id.* at 11:23-35.

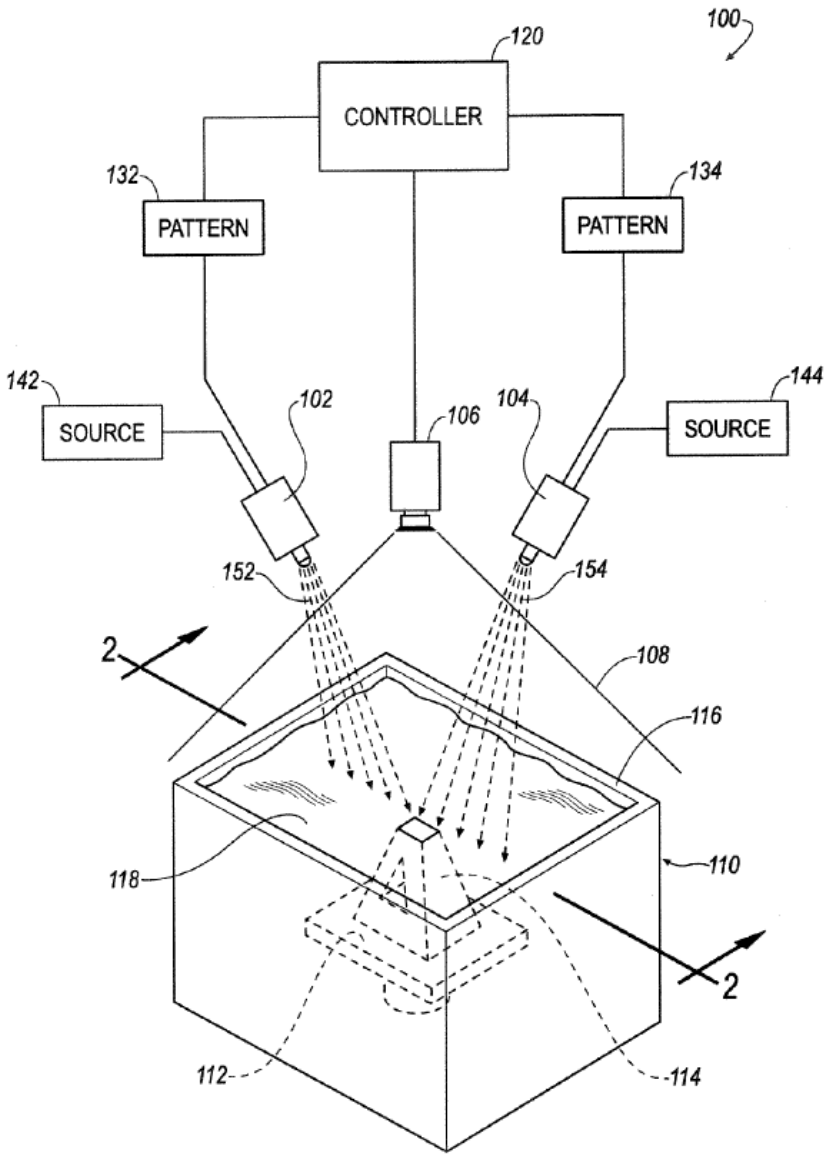


FIG. 1A

156. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(e) b. projecting a composite image onto a build area within a resin pool using the image projection system, wherein:

157. Shkolnik teaches projecting a composite image onto a build area within a resin pool using the image projection system. The image projectors of Shkolnik each project an image onto a reactive material, such as a container of photopolymerizable resin. Shkolnik (EX1004), 5:9-14. For example, Figure 1A of Shkolnik illustrates a system in which multiple image projectors or "pattern generators" (denoted as 102 and 104 in Figure 1A) each project an image or "pattern" (denoted as 152 and 154 in Figure 1A) onto a portion of a reactive material (denoted as 118 in Figure 1A) disposed within a container (denoted as 110 in Figure 1A), thereby forming a composite image (e.g., the complete image of the rabbit in Figure 7). Shkolnik also refers to such individual "patterns" as "sub-images." *See*, *e.g.*, *id.* at 33:59-63.

158. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(f) the image projection system is controlled by the image display subsystem;

159. Shkolnik teaches that the image projection system is controlled by the image display subsystem. Shkolnik teaches that its system can include various components and subsystems for controlling the image projection system and each of the image projectors of Shkolnik to adjust properties and alignment of a position of

each sub-image in the array of sub-images described by Shkolnik. Shkolnik specifically teaches a controller that interfaces with multiple pattern generators and an imager "for self-calibration at any time before, during, or after manufacture" such as "image correction mapping…to modify an image or bitmap for positional inaccuracies." *See*, *e.g.*, Shkolnik (EX1004), 7:10-22; *id.* at 8:6-32; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators."). Such a "controller" is denoted as element 120 in Figure 1A, and such an "imager" is denoted as element 106 in Figure 1A (see reproduction of Figure 1A above). Additionally, Shkolnik teaches that the imager 106 "may be used for initial alignment and adjustment of pattern generators 102, 104 or for real-time, or near real-time, adjustment." *Id.* at 11:23-35.

160. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(g) the composite image comprises a plurality of sub-images arranged in an array;

161. Shkolnik teaches the composite image comprises a plurality of sub-images arranged in an array. Shkolnik teaches a system having an image projection system that can include an array of image projectors that each project an image onto

a reactive material. Shkolnik (EX1004), 4:40-44; 5:9-14. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual patterns or "sub-images" provided by the individual image projectors or pattern generators (denoted as 712' and 712" in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). This figure is reproduced below for convenience.

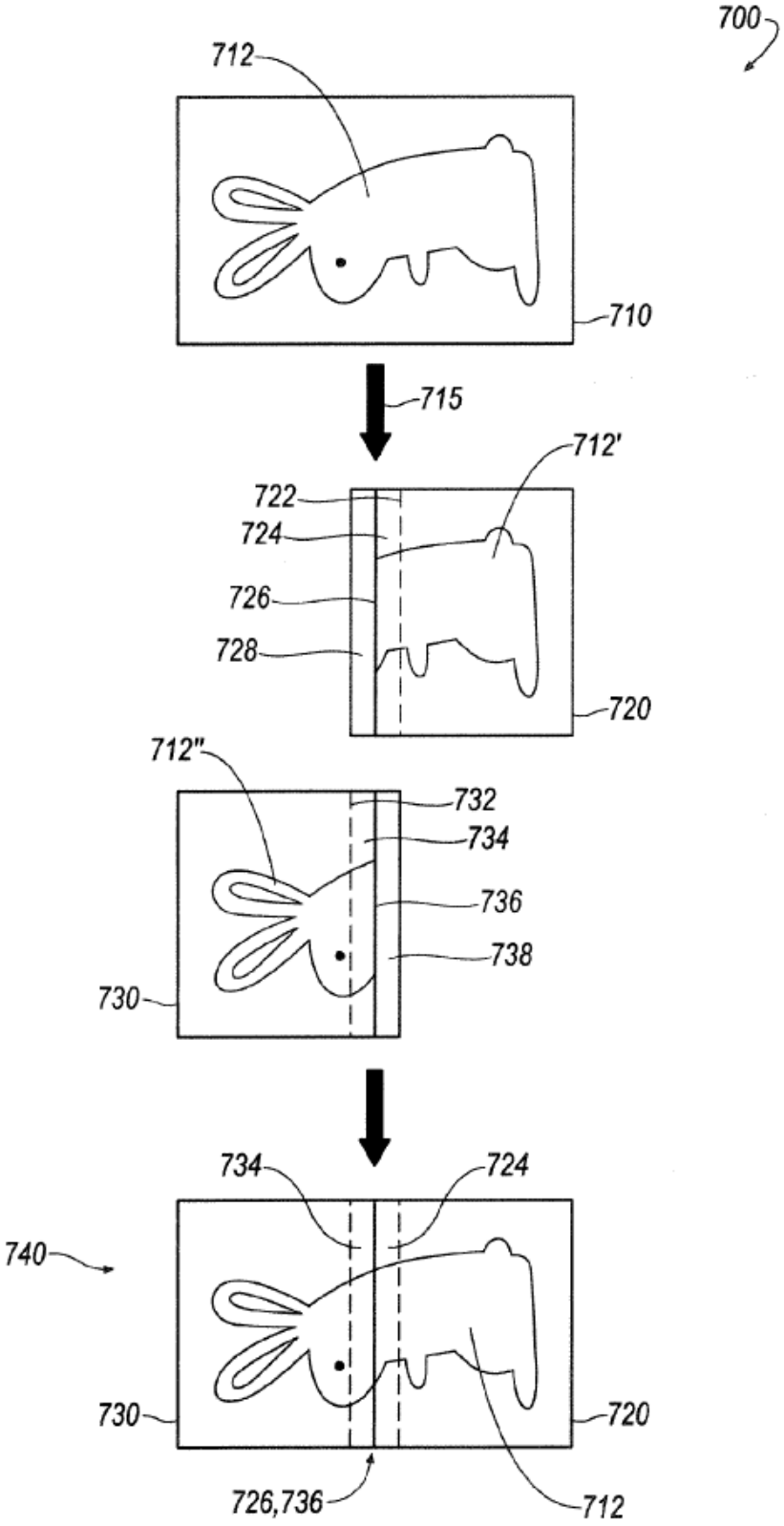

700
712
710
715
712'
722
724
726
728
720
712"
732
734
736
738
730
734
724
740
730
720
726,736
712

FIG. 7A

162. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the ’511 Patent.

(h) two or more adjacent sub-images in the array overlap at two or more sub-image edges; and

163. Shkolnik teaches that two or more adjacent sub-images in the array overlap at two or more sub-image edges. Shkolnik teaches that the images or patterns of an array of image projectors or pattern generators can overlap, including at their edges. Shkolnik (EX1004), 33:45-34:14. Such an overlap is illustrated, for example in Figure 4C and Figure 7A of Shkolnik. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual patterns “sub-images” provided by the individual image projectors or pattern generators (denoted as 712’ and 712” in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). The adjacent sub-images 712’ and 712” in Figure 7A overlap at two edges of the sub-images (e.g., at edges 722/726 and 732/736 in Figure 7A, forming overlap portions 728 and 738). These figures are reproduced below for convenience.

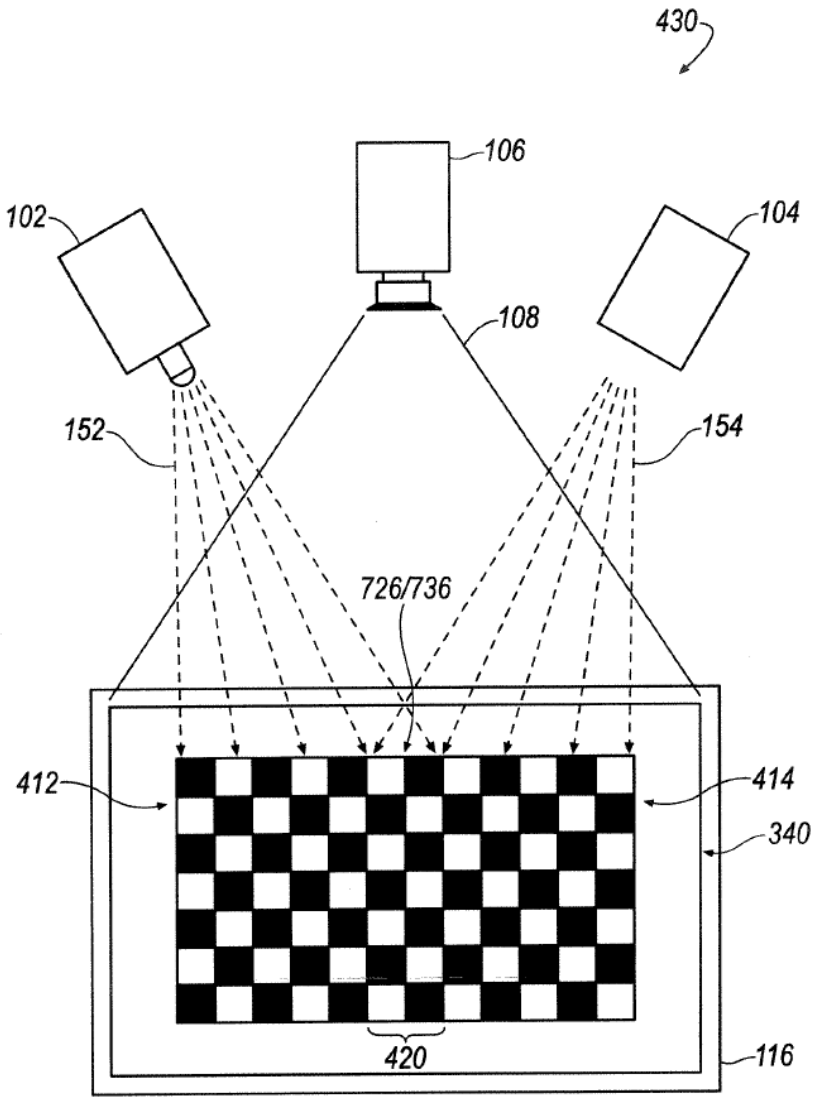


FIG. 4C

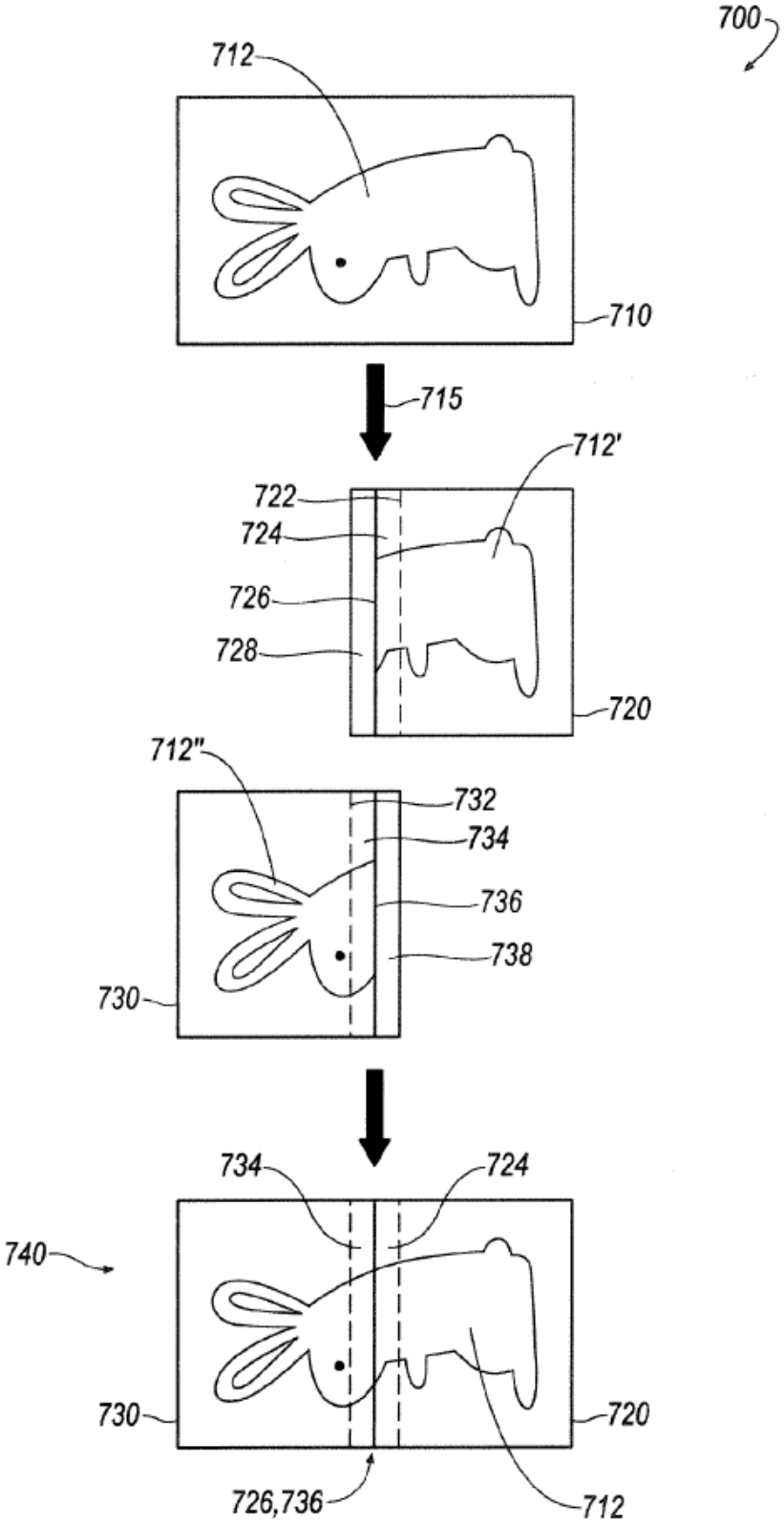

700
712
710
715
712'
722
724
726
728
720
712"
732
734
736
738
730
734
724
740
730
720
726,736
712

FIG. 7A

164. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the ’511 Patent.

(i) each sub-image is projected onto a portion of the build area using one of the plurality of image projectors; and

165. Shkolnik teaches that each sub-image is projected onto a portion of the build area using one of the plurality of image projectors. The image projectors of Shkolnik each project an image onto a reactive material, such as a container of photopolymerizable resin. Shkolnik (EX1004), 5:9-14. For example, Figure 1A of Shkolnik illustrates teaches a system in which multiple image projectors or “pattern generators” (denoted as 102 and 104 in Figure 1A) each project an image or “pattern” (denoted as 152 and 154 in Figure 1A) onto a portion of a reactive material (denoted as 118 in Figure 1A) disposed within a container (denoted as 110 in Figure 1A). This figure is reproduced above for convenience.

166. Therefore, it is my opinion that Shkolnik discloses this element of claim 1 of the ’511 Patent.

(j) c. adjusting properties and aligning a position of each sub-image in the array using a set of filters comprising:

167. Shkolnik teaches adjusting properties and aligning a position of each sub-image in the array using a set of filters. Shkolnik teaches that pattern generators such as DLP devices produce “patterns” (e.g., denoted as 132 and 134 throughout

Shkolnik), and that such "patterns" can be "bitmaps (digital information), physical masks (physical patterns), electronic masks (e.g., LCD or transmissive active masks), or other types of information, media, or device(s) that define a pattern." See Shkolnik (EX1004), 10:44-46; 11:4-8. Moreover, Shkolnik teaches that the patterns or sub-images produced by an array of pattern generators (such as DLP devices) can be corrected or "fixed" in various ways, such as to provide positional compensation and intensity compensation. *See*, *e.g.*, *id.*, 14:51-53; 17:24-27. Moreover, Shkolnik teaches that such adjustment can occur within each pattern generator or applied to the pattern generators externally. *See*, *e.g.*, *id.*, 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators."). Thus, the properties of each sub-image are being adjusted.

168. As another example, Shkolnik teaches that adjustments can be made to correct for both linear and non-linear distortions. The corrections or adjustments may also be iterative, undertaken in sequence, or carried out simultaneously. Shkolnik describes such adjustments of sub-images using a combination or "set" of filters, masks, or "maps" in many, many places throughout the 83-page disclosure of Shkolnik. *See*, *e.g.*, *id.*, 2:9-11 ("FIG. 1K [below] is an example of a generalized correction map generation system for use with the systems and methods described

herein."); 2:22-26; 2:36-38; 5:38-53; 10:7-13; 14:26-31; 14:51-56; 15:36-57; 17:18-31; 19:38-50; 20:2-11; 28:36-48; 32:40-63; Figures 1K, 1ME, 1MG, 1MFB, 1MGB, 1O, 1Q, 4A, 4B, 4C, and 6. Figure 1K is reproduced below for convenience.

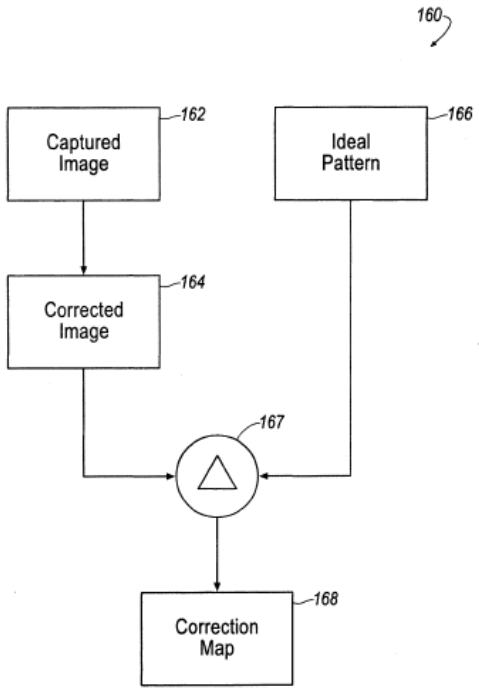


FIG. 1K

169. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(k) an irradiance mask that normalizes irradiance;

170. Shkolnik teaches a set of filters comprising an irradiance mask that normalizes irradiance. Among the many types of adjustments of sub-images taught

by Shkolnik, Shkolnik specifically teaches adjusting irradiance to match an 'ideal,' 'standard,' 'compensation,' or 'normalized' irradiance. For instance, Shkolnik teaches that "the pattern generator uses methods to compensate for the inaccuracies" of the pattern generator in order to "provide precise and consistent manufacturing processes," and these methods include "intensity compensation." Shkolnik (EX1004), 5:38-49. By "intensity," I understand Shkolnik to mean the "brightness" of light striking a given pixel or voxel (which is the same as irradiance), either alone or in combination with the exposure time of the pixel or voxel. *Id.*, 9:35-46.

171. Shkolnik further teaches that "[t]ypical sources of error in the…pattern generator may include mechanical misalignment of the components or supporting structure, misaligned lenses or mirrors, and malformed lenses or mirrors," as well as heating and/or cooling during operation, which "may cause components to move or expand, changing their position" or "[i]n the case of optical components, the position, shape, and size may change with heating and/or cooling." *Id*., 7:23-30. For example, Shkolnik teaches that in the case of DLP pattern generators, "micro-mirrors may change shape or position to cause **both linear and nonlinear distortions**, which may be compensated for." *Id*. at 7:33-37. What Shkolnik is teaching here is that a micromirror 'may change shape' and create 'distortions'—and a POSITA would understand that this is caused by degradation or temporary thermal cycling of the micromirror itself. Whether a micromirror has physically

changed its position, shape, or size will have a direct impact on intensity—and in the scenario where such a change has occurred, Shkolnik is teaching that there is a need for compensation (*i.e.*, to normalize).

172. Shkolnik further teaches that the brightness (or irradiance) and exposure time "may be parameters for the bitmap, together or separately." *Id.*, 10:7-8. Critically, Shkolnik assigns an "intensity value" to each pixel or voxel, such as an integer between 0 and 255—and states that "the intensity value may be compensated or adjusted before being sent to the pattern generator, or may be compensated or adjusted at the pattern generator, or both." *Id.*, 9:47-51. A POSITA would read this to mean that the adjustment to the intensity level is occurring at least at the sub-image level because the adjustment can occur at each pattern generator in the system 102, 104, and the pattern generators create the sub-images upon the resin work piece, 114. *Id.*, 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

173. If desired, the intensity value can provide grayscaling of pixels or voxels, per Shkolnik. *See*, *e.g.*, *id.* at 10:14-33. Adjustment of intensity occurs in many instances in Shkolnik. For example, in the context of a discussion of bitmap correction for a pattern generator (e.g., DLP device), Shkolnik states that "the

intensity (e.g., a grayscale value) may be adjusted to correct for linear and nonlinear distortions." *Id.* at 18:1-4. Similarly, in the context of edge blending (discussed further below), Shkolnik teaches that multiple pattern generations (e.g., multiple DLP devices) "could each reduce the intensity of output so that the combined intensity is standard." *Id.* at 34:19-22. Likewise in the same context, Shkolnik once again explicitly teaches that it may be desirable "to reduce intensity such that when [multiple sub-images are] overlapped, the **combined intensity is the same** as the original image." *Id.* at 34:61-64. Such edge blending in Shkolnik is intended to provide visual 'seamlessness' where sub-images overlap, and Shkolnik expressly teaches that such seamlessness can be achieved by precise control of irradiance in regions of the projected pattern that are addressed by two or more projectors. A significant theme of the entirety of Shkolnik is the accurate reproduction of an "original" or "ideal" image. Shkolnik particularly teaches that "corrected" or "adjusted" or "fixed" bitmaps or data sets are "adjusted for linear and nonlinear distortion of the pattern generator so that when projected, the ideal pattern [from the pattern generator] is generated on the build surface." *See*, *e.g.*, *id.* at 28:43-48; 30:22-25; 30:65-31:1. In other words, Shkolnik teaches that pattern generators (such as DLP devices) must be adjusted for distortion, such as distortion caused by defects in micro-mirrors or other optical elements, and that one of the ways to correct for

distortion is to ensure that "intensity" (*i.e.*, irradiance) matches a "standard" (*i.e.*, normalized) value.

174. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent. [17]

(l) a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool;

175. Shkolnik teaches a set of filters comprising a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool. As discussed above, Shkolnik teaches the assignment of an "intensity value" or level to each pixel or voxel of a sub-image. Shkolnik (EX1004), 9:47-51. For example, Shkolnik teaches that for an 8-bit system "intensity ranges of 0 to 255 are convenient." *Id.*, 9:59-62. Moreover, Shkolnik teaches that "the time and intensity

[17] Additionally, I observe that the teachings of Shkolnik are consistent with common knowledge in the industry at the time of filing of the '511 Patent. In visual image projection systems, irradiance directly affects the perceived brightness of the projected image, on a pixel-by-pixel basis. Methods to control irradiance are necessary to produce images with good quality. Extensive irradiance control methods for multi-projector visual imaging systems have been developed and employed for years. For visible images, irradiance correction and irradiance uniformity correction may be referred to as photometric control or photometric correction. These same visible-image irradiance control techniques are applicable to spatial irradiance control of light-based multi-projector systems used in additive manufacturing applications. It has long been known that one way of controlling irradiance is through the use of an "irradiance mask," which can be two-dimensional data array of irradiance control (*e.g.*, adjustment) values. For example, array elements in an irradiance mask might have a 1:1 correspondence with pixels in the image from one projector.

to achieve a particular depth of cure is material dependent," with the result (explicitly taught by Shkolnik) that a given intensity value that provides a particular curing depth for a specific resin "may not be usable" for a different resin. *Id.* at 10:22-26; *see also id.* at 18:32-37 ("Note, however, that the percent intensity value assigned to a voxel is material dependent, and that there may not be a linear relation between them (e.g., the intensity values for 50% depth of **cure** may be **different** for each **reactive material**).").

176. In addition, Shkolnik teaches that when a resin (such as "reactive material 118" in Shkolnik) "has a minimum intensity threshold for polymerization or partial-polymerization, the 'off' or zero (0) value intensity (e.g., brightness and/or 'on' time) may be determined **based on the reactive material threshold**." *Id.* at 9:51-55. For example, Shkolnik teaches that "correction" of a pattern for forming an object can be achieved by **mapping the intensity values to the resin reactivity**, resulting in **more accurate additive manufacturing**: "A detailed example of voxelized correction including intensity modification is shown below with respect to FIGS. 1MA-1MG. As discussed herein a voxel data may be expressed as a bitmap with intensities assigned for each pixel in the bitmap, the intensity providing **variable depth of cure for each voxel**." *Id.* at 18:37-42. As noted above on multiple occasions, this correction of a pattern for forming an object can occur at each pattern generator, which means the correction is occurring at least at the sub-image level.

Id. at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

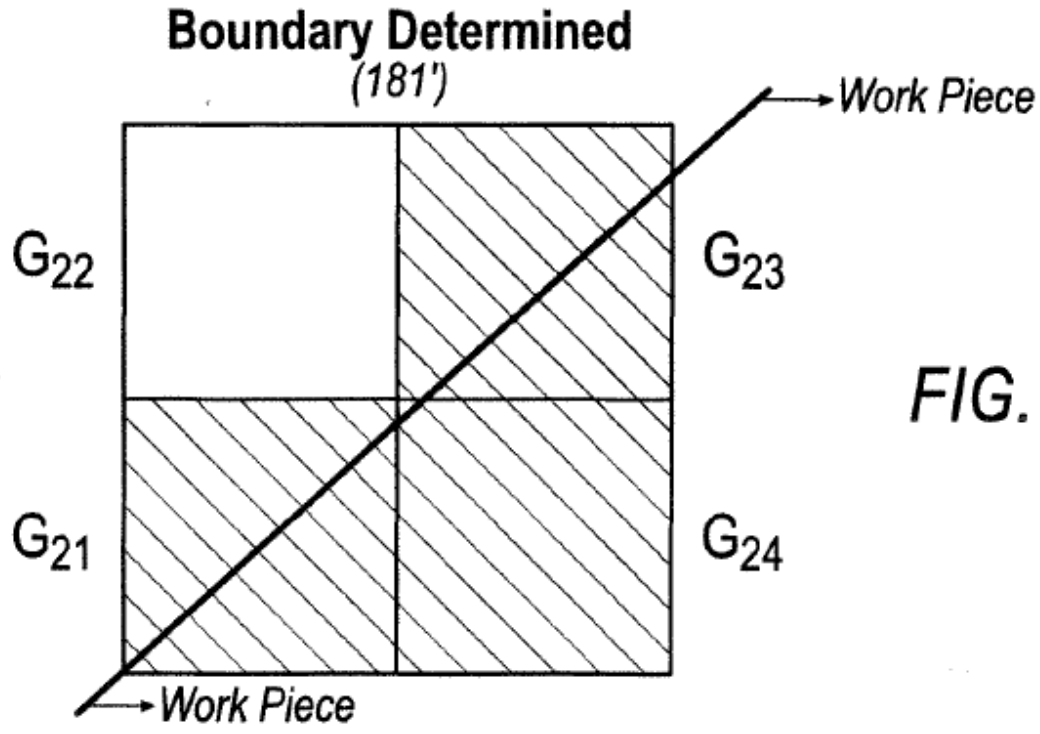


FIG. 1MBB

177. In sum, this discussion of gamma adjustment in Shkolnik is consistent with the POSITA's understanding of the ordinary and customary meaning of the term gamma adjustment in the '511 Patent as set out above. *See*, Section IV. E.2. ("[T]he specification provides that the purpose of the 'gamma correction filter' is to 'enable[] correct smoothing (and/or antialiasing) of pixels by mapping the pixel

intensity range (e.g., 0-255) to the minimum and maximum reactivity characteristics of the pixel.'") (quoting '511 Patent (EX1001), at 12:9-12); *see also id.* ("The specification teaches that 'gamma corrections' are '[m]ethods for adjusting the curing time for a specific resin.' *Id*. at 6:3-5. The specification further teaches that such adjustments are need because 'different resin formulations . . .have different curing times.'") (quoting '511 Patent (EX1001), 5:66-5:67).

178. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(m) a warp correction filter that provides geometric correction; and

179. Shkolnik teaches a set of filters comprising a warp correction filter that provides geometric correction. As stated above, Shkolnik teaches that pattern generators (such as DLP devices) must be adjusted for distortion, such as distortion caused by defects in micro-mirrors or other optical elements. *See*, *e.g.*, Shkolnik (EX1004), 7:23-37. Shkolnik specifically teaches that mechanical misalignment, misaligned or malformed lenses or mirrors, or changes in hardware caused by heating/cooling "may impart geometric distortion (e.g., where an expected straight line may be curved)." *Id*. at 7:23-31. Shkolnik specifically lists "distortion of a rectangular grid," "barrel distortion," and "pincushion (pillow) distortion" as possible types of geometric distortion, "which may be compensated for" by the

system of Shkolnik. *Id*. at 7:32-37. Figure 5A of Shkolnik particularly illustrates an example of a "barrel distortion." *Id.* at 32:64-66. Similarly, Figure 5B illustrates a "pincushion distortion," and Figure 5C illustrates an example of "a nonlinear and skewed distortion." *Id.* at 32:67-33:10. Please refer to the figures reproduced below for convenience.

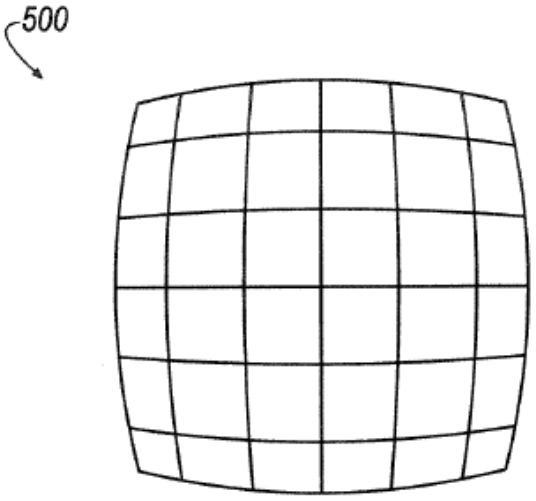


FIG. 5A

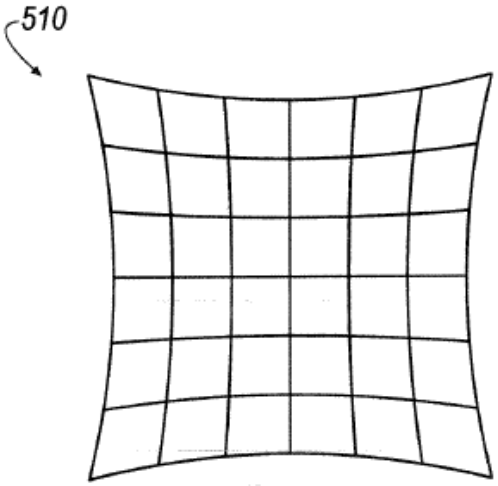


FIG. 5B

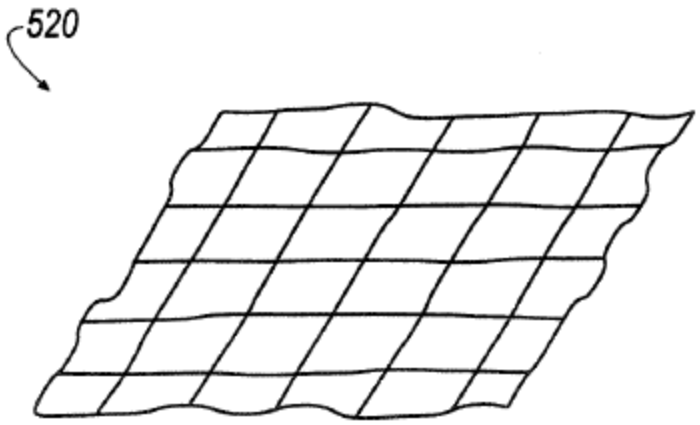


FIG. 5C

180. Shkolnik further teaches that each of these geometric distortion types is "commonly associated with optical systems" that include multiple pattern generators (e.g., DLP devices), such as pattern generators 102 and 104 described above. *Id.* at 32:64-33:10. Additionally, Shkolnik teaches that "[t]he above methods [of image adjustment/correction disclosed by Shkolnik] may be used to correct such distortion." *Id.* at 32:64-33:10. Shkolnik then provides a more detailed description and illustration of how to correct a pincushion distortion: namely, how "to transform the pincushioned output of pattern generators 102, 104 to a more usable output" by using "pattern correction methods 620" and "calibration patterns 612, 614." *Id.* at 33:18-45 and Figure 6. Figure 6 of Shkolnik shows calibration patterns 612, 614 being generated (e.g., from pattern generators 102, 104) as uncompensated patterns. Shkolnik teaches that using the methods of Shkolnik for pattern correction (denoted generically as element 620 in Figure 6), an "adjusted combined image 630 is provided that removes distortion from the system." *Id.* at 33:11-16. As noted above,

this ‘pattern correction’ can occur at each pattern generator, which means that the correction is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 (“Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.”).

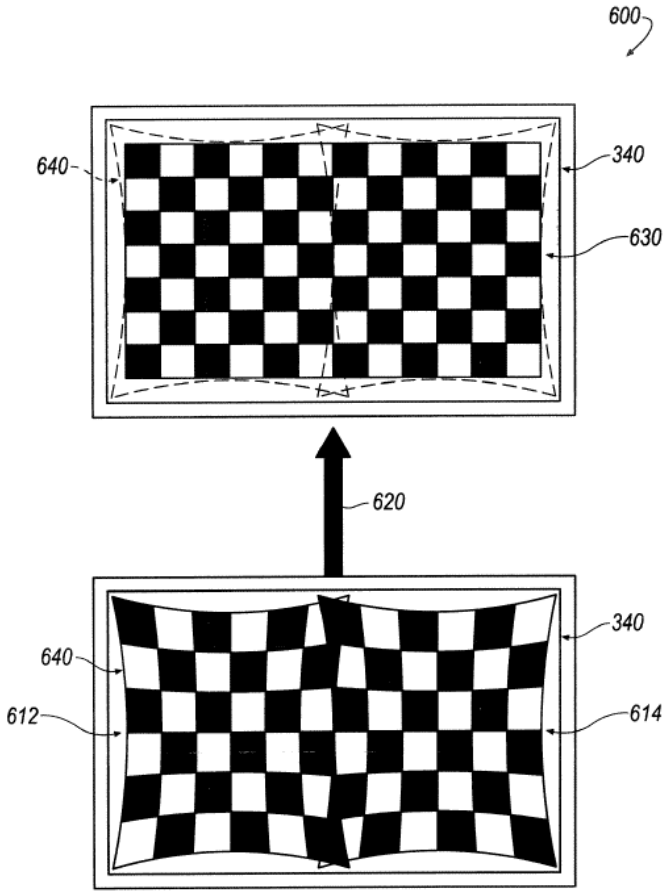


FIG. 6

181. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the ’511 Patent.

(n) an edge blending bar at one or more sub-image edges.

182. Shkolnik teaches a set of filters comprising an edge blending bar at one or more sub-image edges. As described above, an “edge blending bar” is just a name for using one or more edge blending techniques in an area of overlap in two or more sub-images. “Edge blending,” in the context of a multi-projector system, describes

the process or technique of managing areas of the composite projected image that are addressed by more than one projected image. These are the "overlap" areas. Additionally, it is my understanding that there is nothing technologically significant about the phrase "edge blending bars." Other terms such as "edge blending," "pixel blending," "image blending," or "stitching"—or no specific technical term at all—can be used to refer to the same thing—a zone of overlap in which one or more various edge-blending functions are performed.

183. As stated above, Shkolnik teaches a system having an image projection system that includes one or more image projectors or "pattern generators," such as one or more DLP devices. Shkolnik (EX1004), 4:40-44. The plurality of image projectors of Shkolnik each project an image onto a reactive material. *Id.*, 5:9-14. Moreover, Shkolnik teaches that the images or patterns can overlap, including at their edges. *Id.*, 33:45-34:14. Such overlap is illustrated, for example in Figure 4C and Figure 7A of Shkolnik. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual sub-images provided by the individual image projectors (denoted as 712' and 712" in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). The adjacent sub-images 712' and 712" in Figure 7A overlap at two edges of the sub-images (e.g., at edges 722/726 and 732/736 in Figure 7A, forming overlap portions 728 and 738). These figures are

reproduced below for convenience. With reference to Figure 7A, Shkolnik teaches that the complete image (e.g., the complete rabbit in Figure 7A) is divided in such a manner that the two sub-images 712' and 712" have overlap portions 728 and 738 between the two sub-images 712' and 712". *Id*. at 33:50-67. Per Shkolnik, the overlap regions "are used to provide a seamless region between the two [sub-images]." *Id.* at 34:2-4. However, Shkolnik expressly warns the reader that there is a "potential for over-exposure of reactive material" due to the overlap of the sub-images. *Id*. at 34:2-14.

184. To solve this problem, Shkolnik teaches an adjustment to the pixels at the edges of the sub-images can be made. Specifically, Shkolnik teaches that "the intensity of pixels from pattern generators 102, 104 that account for overlap pixel region 726, 736 may be reduced in intensity (e.g., 50% from each pattern generator 102, 104) to reduce over-exposure of reactive material 118 at overlap portions 728, 738." *Id.* at 34:10-14. Moreover, Shkolnik teaches that such adjustment can be performed in a dynamic manner: "Potential overlap regions 728, 738 allow for on-the-fly adjustment to image patterns 712', 712" during use that may be desirable to adjust for heat and other changes to the system that may introduce distortion." *Id.* at 34:35-38.

185. Shkolnik further teaches that if one or both of the pattern generators changes alignment during use, "the areas of potential overlap regions 728, 738 may

be used to further adjust the projected image to maintain alignment," with the result that "overlap pixel regions 726, 736 may be moved within potential overlap regions 728, 723 and 724, 734 during operation." *Id*. at 34:38-43. As noted above, this adjustment can occur at each pattern generator, which means that the adjustment is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

186. As noted above, this teaching of Shkolnik is the same as that of the '511 Patent, which teaches, for instance, an "edge blending bar" that accounts for overlap in projection images by, for example, "fad[ing] out" "perimeters of adjacent sub-images" so that "the transition between [the] adjacent sub-images can be made less noticeable." '511 Patent (EX1001), 9:6-8; *id.* at 10:30-35.

187. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

188. The following dependent claims are also anticipated.

2. **Claim 2 – The method of claim 1, wherein the image display subsystem controls the image projection system and each of the image projectors using digital light processing.**

189. Shkolnik teaches that the image display subsystem controls the image projection system and each of the image projectors using digital light processing. As

discussed above with respect to element 1[f] of claim 1, Shkolnik teaches that the image display subsystem controls the image projection system. Specifically, Shkolnik teaches that pattern generators, such as DLP devices, produce "patterns" (e.g., denoted as 132 and 134 throughout Shkolnik). As additionally discussed above, Shkolnik teaches that its system can include various components and subsystems for controlling the image projection system and each of the image projectors of Shkolnik to adjust properties and alignment of a position of each sub-image in the array of sub-images described by Shkolnik. For example, Shkolnik teaches a controller that interfaces with multiple pattern generators and an imager "for self-calibration at any time before, during, or after manufacture" such as "image correction mapping…to modify an image or bitmap for positional inaccuracies." *See*, *e.g.*, Shkolnik (EX1004), 7:10-22; 8:6-32. Such a "controller" is denoted as element 120 in Figure 1A, and such an "imager" is denoted as element 106 in Figure 1A (see reproduction of Figure 1A above). Additionally, Shkolnik teaches that the imager 106 "may be used for initial alignment and adjustment of pattern generators 102, 104 or for real-time, or near real-time, adjustment." *Id.* at 11:23-35.

190. With respect to "digital light processing" ("DLP"), Shkolnik specifically teaches that the pattern generators may be DLP devices. *See id.* at 7:56-67 ("Examples of pattern generators may ***include Digital Light Processing technology (DLP) from Texas Instruments®*** or …"); *see also id.* at 8: 63-65 ("In

this example, pattern generators 102, 104 may be configured as ***Digital Light Projector (DLP) devices*** that include micro-mirrors to create patterns 132, 134."); and *id*. at 6:43-47 ("In an example where a grayscale value is assigned to a pixel **and a DLP® type pattern generator** is used, the DLP® micro-mirror may be moved so as to expose the pixel at the build surface in an alternating manner to provide an overall grayscale value.").

191. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 2 of the '511 Patent.

3. Claim 3 – The method of claim 1, wherein the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors.

192. Shkolnik teaches that the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors. For example, Shkolnik discusses that "[t]ypical sources of error in the…pattern generator may include mechanical misalignment of the components or supporting structure, misaligned lenses or mirrors, and malformed lenses or mirrors," as well as heating and/or cooling during operation, which "may cause components to move or expand, changing their position" or "[i]n the case of optical components, the position, shape, and size may change with heating and/or cooling." Shkolnik (EX1004), 7:23-30. Shkolnik further teaches that

in the case of DLP pattern generators, "micro-mirrors may change shape or position to cause **both linear and nonlinear distortions**, which may be compensated for." *Id.* at 7:33-37. What Shkolnik is teaching here is that a micromirror 'may change shape' and create 'distortions'—and a POSITA would understand that this is caused by degradation or temporary thermal cycling of the micromirror itself. Whether a micromirror has physically changed its position, shape, or size will have a direct impact on intensity—and in the scenario where such a change has occurred, Shkolnik is teaching that there is a need for compensation (*i.e.*, to normalize).

193. As discussed above, Shkolnik further teaches that the brightness (or irradiance) and exposure time "may be parameters for the bitmap, together or separately." *Id.* at 10:7-8. Notably, Shkolnik assigns an "intensity value" to each pixel or voxel, such as an integer between 0 and 255—and states that "the intensity value may be compensated or adjusted before being sent to the pattern generator, or may be compensated or adjusted at the pattern generator, or both." *Id.* at 9:47-51. A POSITA would read this to mean that the adjustment to the intensity level is occurring at least at the sub-image level because the adjustment can occur at each pattern generator in the system (*e.g.*, 102, 104), and the pattern generators create the sub-images upon the resin work piece (*e.g.*, 114). *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described

herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

194. In other words, Shkolnik teaches that pattern generators (such as DLP devices, which each produce a sub-image) must be adjusted for distortion, such as distortion caused by defects in micro-mirrors or other optical elements, and that one of the ways to correct for distortion is using an irradiance mask.

195. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 3 of the '511 Patent.[18]

4. Claim 4 – The method of claim 1, wherein the gamma adjustment mask comprises a logarithmic relationship between a cure depth of the resin and energy per unit area in the build area.

[18] Additionally, I observe that the teachings of Shkolnik are consistent with common knowledge in the industry at the time of filing of the '511 Patent. In visual image projection systems, irradiance directly affects the perceived brightness of the projected image, on a pixel-by-pixel basis. Methods to control irradiance are necessary to produce images with good and consistent quality. Extensive irradiance control methods for multi-projector visual imaging systems have been developed and employed for years. For visible images, irradiance correction and irradiance uniformity correction may be referred to as photometric control or photometric correction. These same visible-image irradiance control techniques are applicable to spatial irradiance control of light-based multi-projector systems used in additive manufacturing applications. It has long been known that one way of controlling irradiance is through the use of an "irradiance mask," which can be two-dimensional data array of irradiance control (*e.g.*, adjustment) values. For example, array elements in an irradiance mask might have a 1:1 correspondence with pixels in the image from one projector.

196. As stated above, Shkolnik teaches a gamma adjustment mask. As also stated above, **any** gamma adjustment necessarily includes accounting for the unique chemistry and physics of a specific photocurable resin (e.g., with reference to that resin's working curve). See Shkolnik (EX1004), 10:22-26 ("the time and intensity to achieve a particular depth of cure is material dependent"). Moreover, for **any** photocurable resin, the relationship between a cure depth of the resin and energy per unit area is **always** logarithmic.

197. Indeed, the logarithmic relationship between cure depth and energy per unit area is literally a textbook principle that has been well known in the field for decades, as evidenced by Jacobs (EX1007), e.g. at page 204, inherent to all photocurable resins of the type described by Shkolnik.

198. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 4 of the '511 Patent.

5. Claim 5 – The method of claim 1, wherein the resin is selected from the group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations thereof.

199. Shkolnik teaches that the resin is selected from a group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations thereof. Specifically, Shkolnik teaches the use of "a material comprising a resin containing at least one ethylenically unsaturated compound (including but not

limited to (meth)acrylate monomers and polymers) and/or at least one epoxy group." Shkolnik (EX1004), 5:17-24. Additionally, Shkolnik teaches that "a curable silicone composition" may be used as a reactive material. *Id.* at 4:65-5:8.

200. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 5 of the '511 Patent.

6. Claim 6 – The method of claim 1, wherein the edge blending bar comprises a blending distance and a function selected from the group consisting of: linear, sigmoid and geometric.

201. Shkolnik teaches that the edge blending bar comprises a blending distance and a function selected from a group consisting of linear, sigmoid and geometric. As described above, Shkolnik teaches that sub-images or patterns can overlap, including at their edges. Shkolnik (EX1004), 33:45-34:14. Additionally, Shkolnik teaches that the "overlap regions" or "overlap portions" (e.g., denoted as 726 and 736, or 728 and 738 in Shkolnik)—which are the "blending distance"—can have any desired width, such as "from one pixel to any number of pixels to generate any width of overlap portions." *Id.* at 34:4-7. Edge blending or "fading" of overlap regions is described in significant detail by Shkolnik, such as with reference to Figures 4 and 7 (see discussion above regarding claim 1). Moreover, with reference once again to Figure 7, Shkolnik teaches that the "fading effect" created by the edge blending of Shkolnik can "use a linear interpolation algorithm to reduce intensity

such that when overlapped, the combined intensity is the same as the original image." *Id.* at 34:53-64.

202. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 6 of the '511 Patent.

7. Claim 7 – The method of claim 1, wherein the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured.

203. Shkolnik teaches that the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured. As an initial matter, a POSITA would understand that locations adjusted by the edge blending bar are "within an object being manufactured." As discussed above with respect to the "edge blending bar" in claim 1, the term—or no specific technical term at all—can be used to refer to a zone of overlap in which one or more various edge-blending functions are performed. The zones are necessarily within the object being manufactured, as other areas (*i.e.*, where an object is not being manufactured), do not need to be blended in any manner and generally correspond to a zero irradiance (*i.e.*, no solidification of resin should occur at such a location). In this regard, it is clear from the context of Shkolnik that the locations are "within an object being manufactured," since the whole process is "for

manufacturing" and for "manufacture of large components." *See* Shkolnik (EX1004), 4:22-4:34.

204. Additionally, as further discussed above, Shkolnik teaches the following regarding boundaries:

> In an example using the original bitmap's pixel information, the boundary of the part may be reconstructed for later use in the geometric correction method. Moreover, using the bitmaps threshold value (in this example 40%), the **boundary of the component** may be reconstructed in a relatively accurate manner for later correction. For example, in FIG. 1MBB, t**he boundary is determined to be a smooth surface, rather than follow the jagged edge that would otherwise be determined by pixels G21 and G23.** The component boundary may be estimated as being nearly through the center of each outer boundary pixel (e.g., G21 and G23) and may also be influenced by neighboring pixels to estimate a **smooth surface**. Here, the component boundary is estimated through nearly the middle of pixels G21, G23 because the "on" threshold **for each pixel is 40%**. Other methods may be applied, however, **using boundary estimation (rather than using the original jagged edge determined by the original bitmap pixels) may provide for improved results** using the geometric correction methods.

Id. at 26:15-33.

205. As stated above, Shkolnik teaches that the images or patterns generated by the pattern generators can overlap, including at their edges. *Id.* at 33:45-34:14. Such overlap is illustrated, for example in Figure 4C and Figure 7A of Shkolnik. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual sub-images provided by the individual image projectors (denoted as 712' and 712" in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete

image of the rabbit). The adjacent sub-images 712' and 712" in Figure 7A overlap at two edges of the sub-images (e.g., at edges 722/726 and 732/736 in Figure 7A, forming overlap portions 728 and 738). These figures are reproduced above with respect to claim 1 for convenience. With reference to Figure 7, Shkolnik teaches that the complete image (e.g., the complete rabbit in Figure 7) is divided in such a manner that the two sub-images 712' and 712" have overlap portions 728 and 738 between the two sub-images 712' and 712". *Id*. at 33:50-67. Per Shkolnik, the overlap regions "are used to provide a seamless region between the two [sub-images]," specifically at edges. *Id.* at 34:2-4.

206. To solve the problem of intensity overlap at such boundary locations, Shkolnik teaches an adjustment to the pixels at the sub-images edges can be made. Specifically, Shkolnik teaches that "the intensity of pixels from pattern generators 102, 104 that account for overlap pixel region 726, 736 may be reduced in intensity (e.g., 50% from each pattern generator 102, 104) to reduce over-exposure of reactive material 118 at overlap portions 728, 738." *Id.* at 34:10-14. Moreover, Shkolnik teaches that such adjustment can be performed in a dynamic manner: "Potential overlap regions 728, 738 allow for on-the-fly adjustment to image patterns 712', 712" during use that may be desirable to adjust for heat and other changes to the system that may introduce distortion." *Id.* at 34:35-38. Shkolnik thus adjusts the one or more sub-image edges based on at least one layer boundary location, which are

within an object being manufactured. Further, as noted above, this adjustment can occur at each pattern generator, which means that the adjustment is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

207. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 7 of the '511 Patent.

8. Claim 8 – The method of claim 1, further comprising a system controller that synchronizes exposure control of the plurality of image projectors with each other.

208. Shkolnik teaches a system controller that synchronizes exposure control of the plurality of image projectors with each other. As discussed above, Shkolnik discusses use of the pattern generators to simultaneously project multiple sub-images. For example, Shkolnik discusses that "In general, an application of the system and method described herein may ***use a pattern generator*** to build a three-dimensional object by exposing a reactive material (discussed below as e.g., a polymerizable material) to electromagnetic radiation." Shkolnik (EX1004), 4:48-52. Shkolnik discusses a "controller 120" that "receives and sends patterns 132, 134 to pattern generators 102, 104 that selectively produce patterns 132, 134 to produce a work piece 114," where components work "**with controller 120** and **pattern**

generators 102, 104 to produce a solid uninterrupted component." *Id.* at 8:10-17. It would be clear to a POSITA reading Shkolnik that the multiple pattern generators discussed in Shkolnik may be synchronized "as work piece 114 is built layer by layer using pattern generators 102, 104." *See* Shkolnik (EX1004), 35:33-35.

209. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 8 of the '511 Patent.

9. **Claim 14 – The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image.**

210. Shkolnik teaches that the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image. Shkolnik teaches that intensity compensation (or "correction") is performed. *See* Shkolnik (EX1004), 5:47-49 ("This pattern correction map may include positional compensation (e.g., to adjust linear and nonlinear distortions) and **may also provide for intensity compensation**."). Shkolnik teaches that use of a grayscale value may be utilized to "control a pattern generator's output," for example "to **provide full *intensity*, no output, or variations in between**." *See id.* at 6:23-31. Shkolnik further teaches that for each pattern generator "the pattern

generator may reduce the ***amount of electromagnetic radiation*** **that the reactive material is exposed to for each pixel according to the exposure time**." *Id.* As discussed above, Shkolnik discusses that an intensity ("irradiance") correction may be performed to correct distortions in the image from component abnormalities. *See id.* at 18:1-5 ("In an example where a voxelized construction process is used, both the position **and the intensity (e.g., a grayscale value) may be adjusted to correct for linear and nonlinear distortions**."). Shkolnik teaches that the calibration (*i.e.*, "adjusting") may be performed simultaneously for "multiple pattern generators." *See id.* at 32:55-57. A POSITA would appreciate that by simultaneously "calibrating multiple pattern generators," specifically to have "an intensity range scaled from zero (the minimum) to 255 (maximum)," the sub-images would be "scaled" to the same range (*i.e.*, representing "a uniform irradiance range"). As discussed above, the "sub-images" of Shkolnik generated by different pattern generators are patterns that can together form an overall composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). The complete image (*i.e.*, the "composite image") is configured based on the scaled intensity range of the sub-images forming the image, specifically to have each pixel be irradiated at a value that results in the desired curing, and thereby a POSITA would appreciate that the composite image similarly includes the scaled ("uniform") intensity range across the composite image.

211. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 14 of the ’511 Patent.

10. Claim 15 – The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity.

212. Shkolnik teaches that the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity. By “projector-based spatial energy non-uniformity,” a POSITA would understand the ’511 Patent to mean non-uniformities of irradiance energy caused by a projector, for example, “non-uniformities in the projector optics and/or optical path.” *See* ’511 Patent (EX1001), 11:50-52.

213. These non-uniformities are exactly the same as those accounted for in Shkolnik. Shkolnik teaches that “[t]ypical sources of error in the … pattern generator may include mechanical misalignment of the components or supporting structure, misaligned lenses or mirrors, and malformed lenses or mirrors,” as well as heating and/or cooling during operation, which “may cause components to move or expand, changing their position” or “[i]n the case of optical components, the position, shape,

and size may change with heating and/or cooling." Shkolnik (EX1004), 7:23-30. For example, Shkolnik teaches that in the case of DLP pattern generators, "micro-mirrors may change **shape or position** to cause **both linear and nonlinear distortions**, which may be compensated for." *Id.* at 7:33-37. What Shkolnik is teaching here is that a micromirror "may change shape" and create "distortions"—and a POSITA would understand that this is caused by degradation or temporary thermal cycling of the micromirror itself. Whether a micromirror has physically changed its position, shape, or size will have a direct impact on intensity—and in the scenario where such a change has occurred, Shkolnik is teaching that there is a need for compensation (*i.e.*, to "normalize") arising from the sources of error (*i.e.*, a "projector-based spatial energy non-uniformity").

214. As discussed above, among the many types of adjustments of sub-images taught by Shkolnik, Shkolnik specifically teaches adjusting irradiance to match an 'ideal,' 'standard,' 'compensation,' or 'normalized' irradiance—all of which the POSITA would treat as meaning the same thing. For instance, Shkolnik teaches that "the pattern generator uses methods to compensate **for the inaccuracies**" of the pattern generator in order to "provide **precise and consistent** manufacturing processes," and these methods include "**intensity** compensation." *Id.* at 5:38-49. By "intensity," a POSITA would understand Shkolnik to mean the "brightness" of light striking a given pixel or voxel (which is the same as irradiance),

either alone or in combination with the exposure time of the pixel or voxel. *Id.* at 9:35-46.

215. Shkolnik further teaches that the brightness (or irradiance) and exposure time "may be parameters for the bitmap, together or separately." *Id.* at 10:7-8. Notably, Shkolnik assigns an "intensity value" to each pixel or voxel, such as an integer between 0 and 255—and states that "the intensity value may be compensated or adjusted before being sent to the pattern generator, or may be compensated or adjusted **at the pattern generator**, or **both**." Shkolnik (EX1004), 9:47-51. A POSITA would read this to mean that the adjustment to the intensity level is occurring at least at the sub-image level because the adjustment can occur at each pattern generator in the system (*e.g.*, 102, 104), and the pattern generators create the sub-images upon the resin work piece (*e.g.*, 114). *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators."). A POSITA would also understand the individual projector-based standardizing to be normalizing irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity, for example, the projector-based spatial energy non-uniformity arising being any non-uniformity of a specific pattern generator that produces a particular sub-image.

216. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 15 of the ’511 Patent.

VII. GROUND 2: CLAIMS 1-8, 14, 15 ARE UNPATENTABLE AS OBVIOUS OVER SEKINE AND GREENE

A. Sekine and Greene Disclose All Claim Limitations

217. The method described and claimed in the ’511 Patent merely addresses well-known problems in the industry and “solves” those well-known problems using well-known techniques. As described above, Shkolnik teaches each and every limitation of claims 1-8, 14, and 15 of the ’511 Patent. Additionally, as described below, Sekine explicitly teaches all but one of the limitations of claims 1-8, 14, and 15 of the ’511 Patent. The remaining limitation is explicitly taught by Greene. For the reasons further described below, it was obvious to combine the teachings of Sekine and Greene, thereby arriving at claims 1-8, 14, and 15 of the ’511 Patent.

218. I have been informed by counsel and understand that claim terms need not be construed when there is no dispute as to the meaning of a term that could affect the outcome of the proceeding. It is my opinion that none of the claims of the ’511 Patent require construction to determine their validity in view of the prior art I have analyzed in this Declaration. Thus, for purposes of this proceeding, it is my opinion that no formal claim construction is necessary. That is, I have applied the ordinary and customary meaning to my analysis.

B. Claim-by-Claim Analysis

1. Claim 1

(a) Element 1[a]: A method comprising:

219. Sekine is directed to both systems and methods for additive manufacturing. *See*, *e.g.*, Sekine (EX1005), [0001], [0005], [0013], and [0014]. Therefore, it is my opinion that Sekine discloses the preamble of claim 1 of the '511 Patent.

(b) a. providing an additive manufacturing system, comprising:

220. Sekine teaches providing an additive manufacturing system. Sekine is directed to systems and methods for additive manufacturing. *See*, *e.g.*, Sekine (EX1005), [0001], [0005], [0013], and [0014]. It should be noted that Sekine (as translated from the original Japanese) sometimes uses the term "three-dimensional shaping device" to refer to an additive manufacturing apparatus or system. Therefore, it is my opinion that Sekine discloses this element of claim 1 of the '511 Patent.

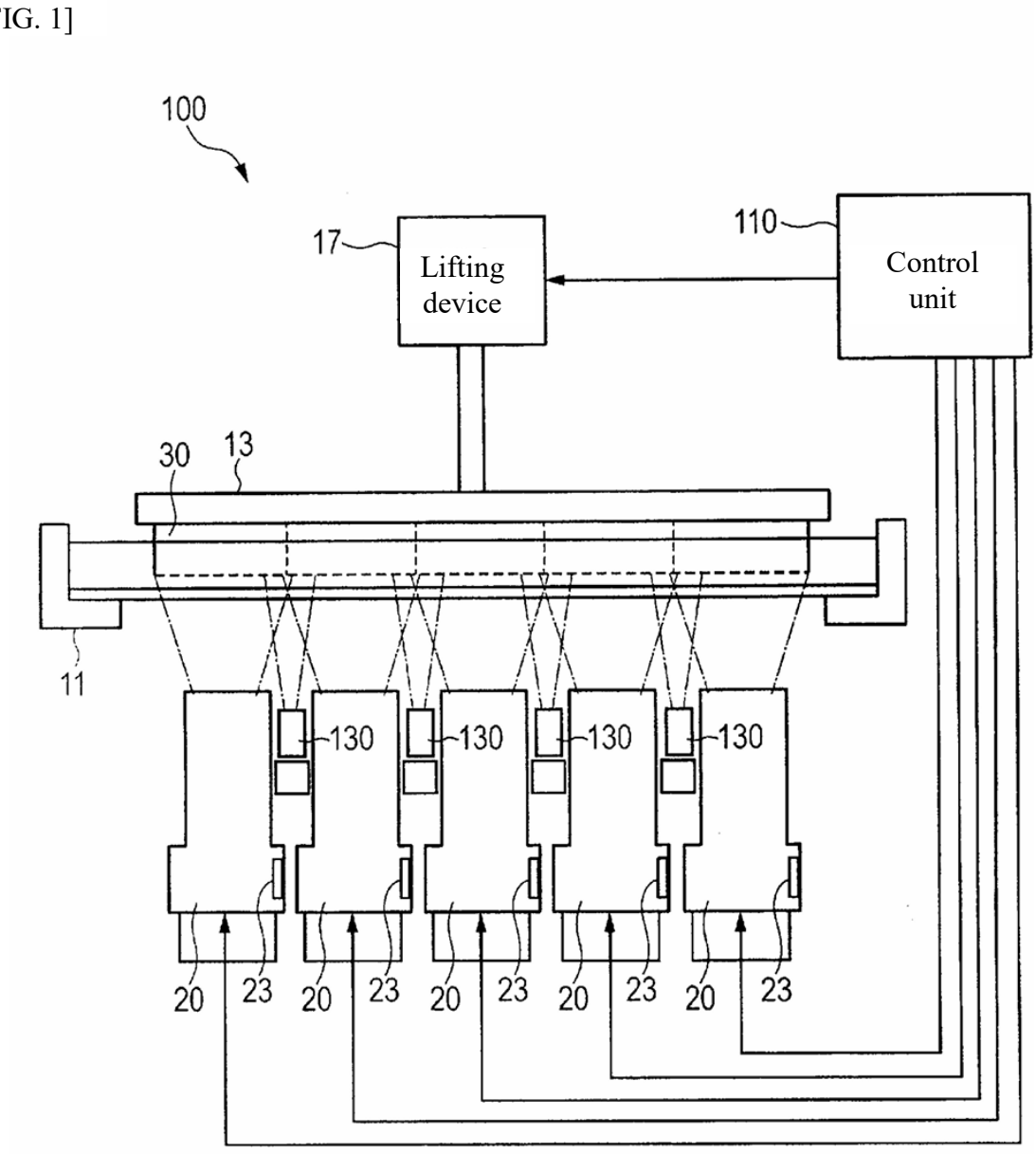
(c) an image projection system comprising a plurality of image projectors; and

221. Sekine teaches an image projection system comprising a plurality of image projectors. Sekine discloses this limitation of the '511 Patent in numerous places. For example, Figure 1 of Sekine illustrates an additive manufacturing system,

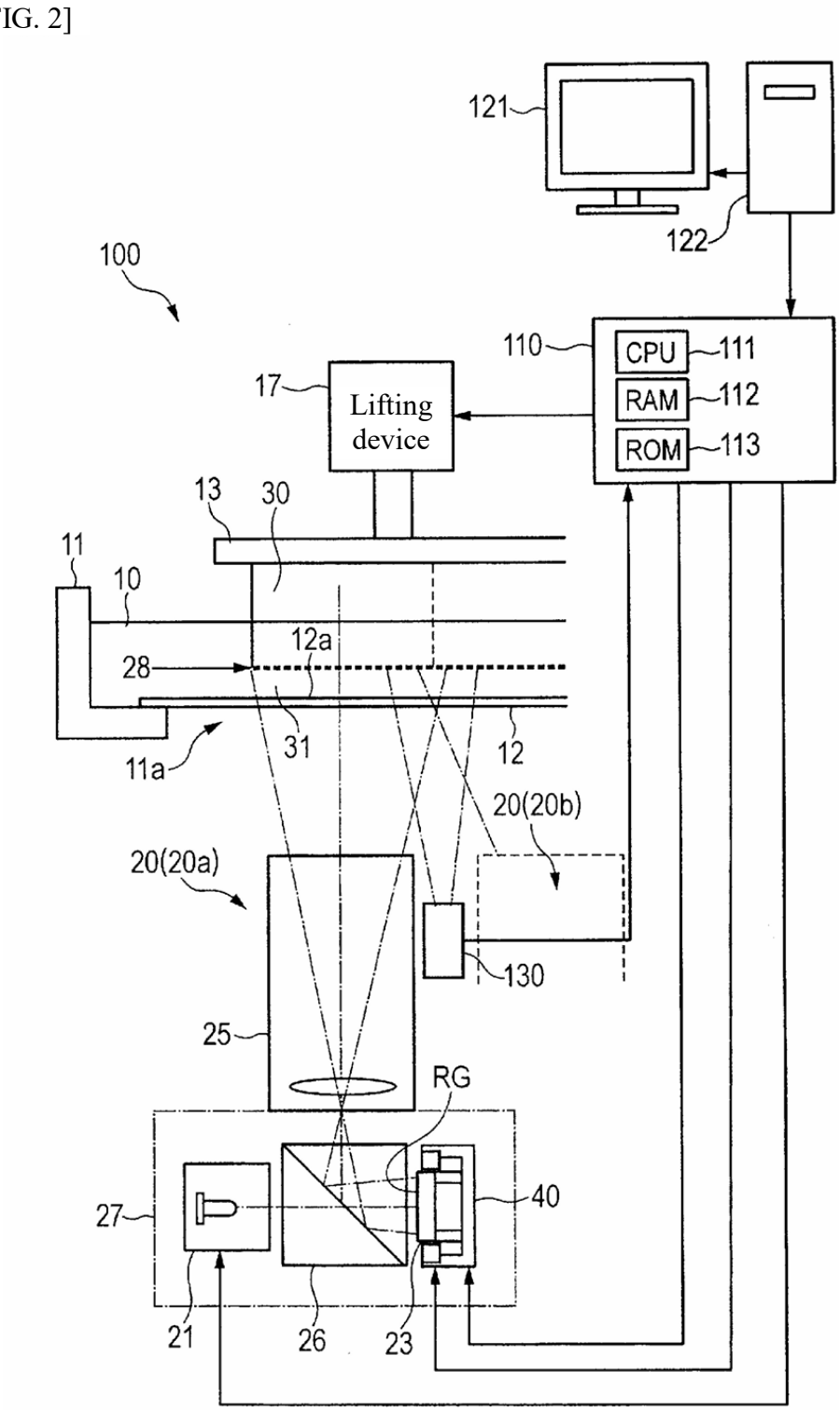
and Figure 2 of Sekine more specifically illustrates the configuration of the additive manufacturing system's image projection system. Sekine (EX1005), [0011], [0013], [0014]. With reference to Figures 1 and 2 (reproduced below for convenience), Sekine teaches that the additive manufacturing system 100 projects an image into a liquid resin material 10 in a container 11 using projectors 20 arranged in a 5 x 5 grid of 25 projectors total. *Id.* at [0013]-[0019], [0033]. The projectors 20 can be DLP devices or digital micromirror devices ("DMDs"). *Id.* at [0019].

222. As illustrated in the "side view" of Figure 1 of Sekine, five projectors 20 are visible within the 5 x 5 grid or array. Figure 5 of Sekine provides a perspective view of the system. This angle permits a 2 x 2 portion of the projector array to be seen, with four projectors 20 clearly arranged in a row-column array. This figure is also reproduced below for convenience. Each of these implementations includes multiple projectors.

[FIG. 1]


100
17
Lifting device
110
Control unit
30
13
11
130
130
130
130
20
23
20
23
20
23
20
23
20
23

[FIG. 2]

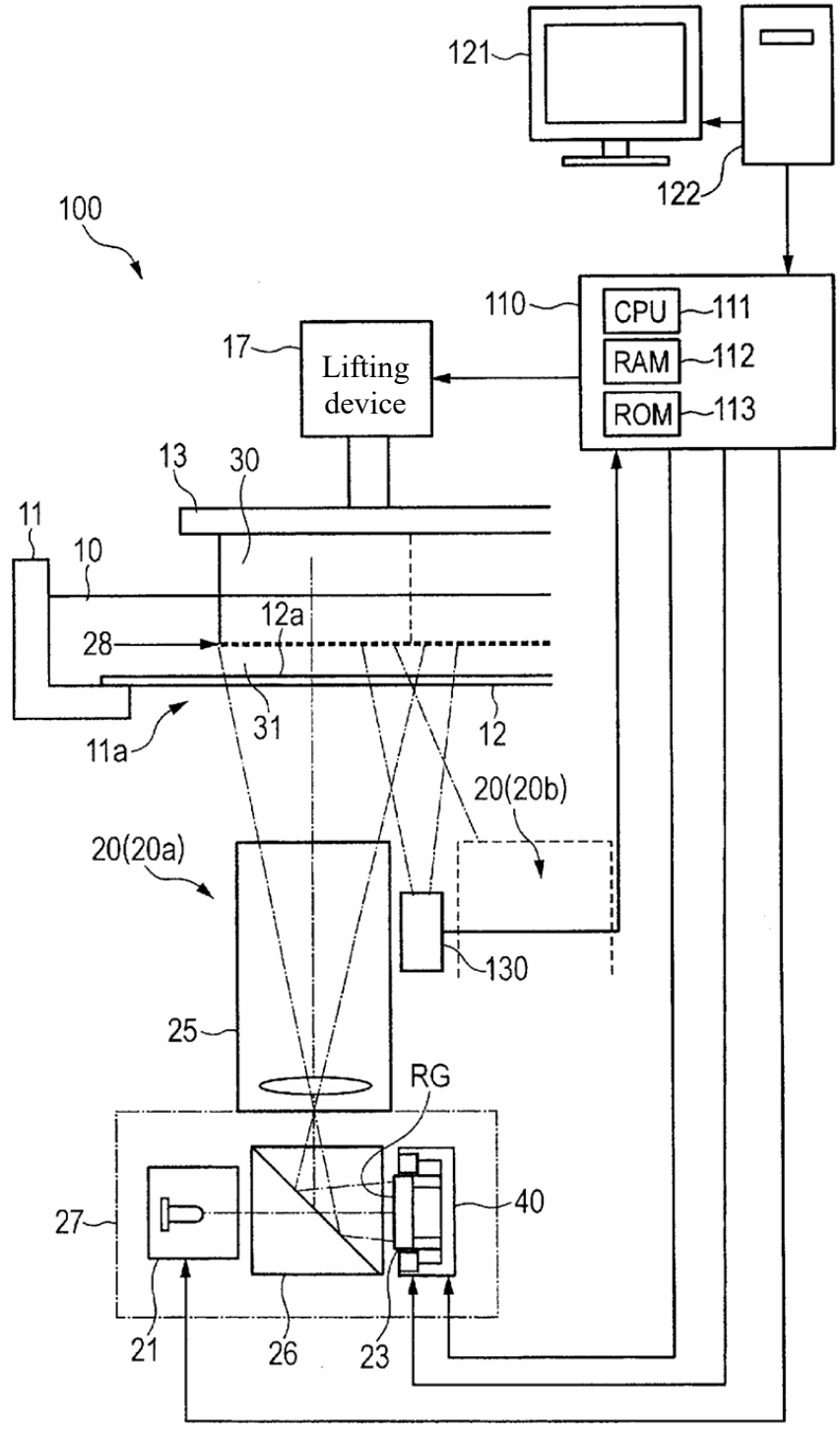


223. Therefore, it is my opinion that Sekine discloses this element of claim 1 of the ’511 Patent.

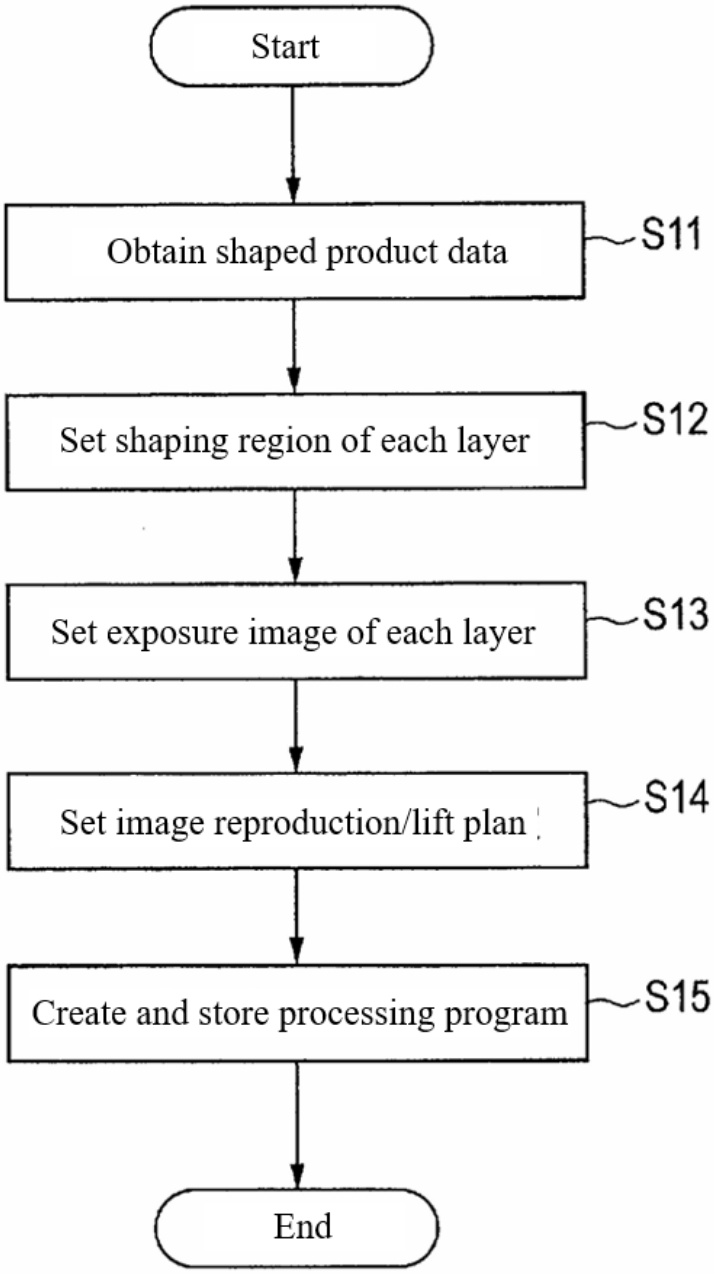
(d) an image display subsystem;

224. Sekine teaches an image display subsystem. As described in the '511 Patent, an image display subsystem can control the image projection system. *See*, *e.g.*, '511 Patent (EX1001), claim 1. Sekine teaches a subsystem that controls the image projection system and each of the image projectors to adjust properties and alignment of the positions of the sub-images produced by the projector array of Sekine. For example, with reference to the system of Figure 2 and the flowchart of Figure 3, Sekine teaches that an external computer 121 inputs design data of the desired product 30 into a control unit 110 and further inputs commands to the control unit 110, such as to start or interrupt the print job. Sekine (EX1005), [0027]. Sekine further teaches that a CPU (denoted as 111) acquires the design data (e.g., CAD data) of the product 30 from the external computer 121 (denoted as step S11 in Figure 3). *Id.* at [0028]. The CPU 111 or the external computer 121 then divides the product 30 into **sub-regions and assigns the sub-regions to the various projectors 20 for actual printing, based on parameters provided by the subsystem**. *Id.* at [0028]-[0030]. These figures are reproduced below for convenience.

[FIG. 2]


121
122
100
110
CPU
111
RAM
112
ROM
113
17
Lifting device
13
30
11
10
12a
28
31
12
11a
20(20b)
20(20a)
130
25
RG
27
40
21
26
23

[FIG. 3]



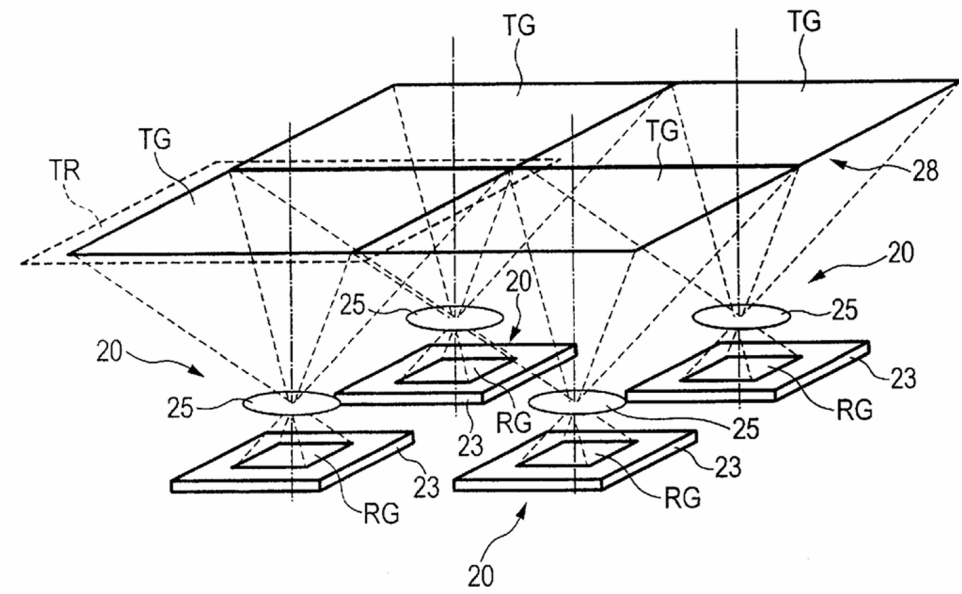
225. This division is further described at Sekine paragraph [0042], which teaches a "display subsystem, wherein the display subsystem controls the image

projection system and each of the image projectors to adjust properties and alignment of a position of each sub-image in the array":

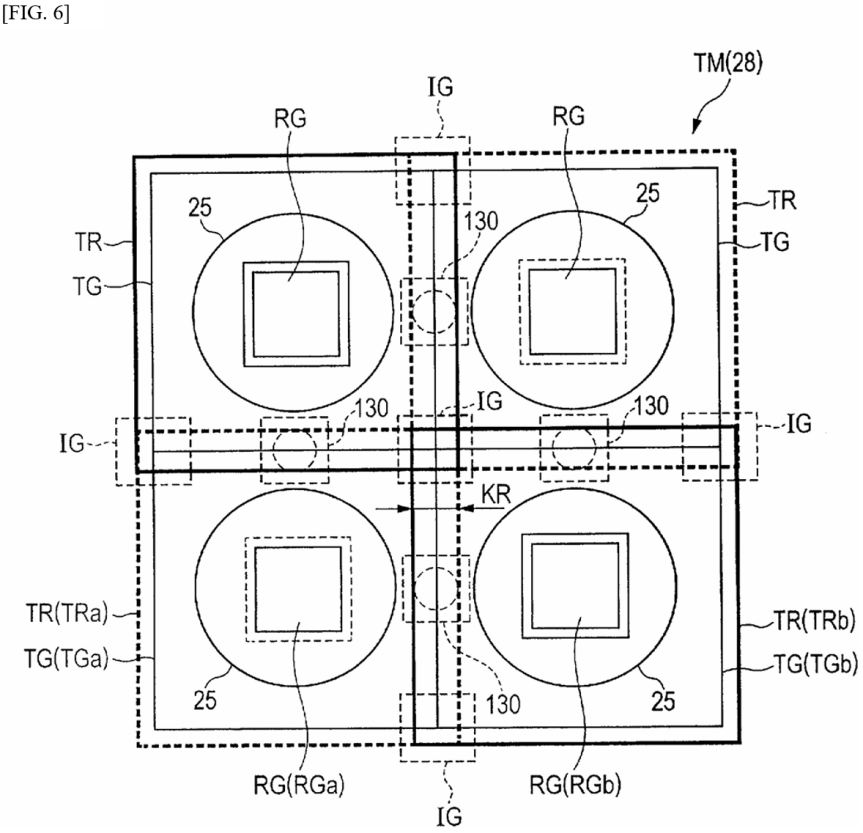
> (**Alignment Control**) FIG. 5 is a schematic diagram of the projection region of the projector. FIG. 6 is a descriptive diagram of the boundary region of the projection image. As illustrated in FIG. 2, the camera 130, which is one example of imaging means, captures the boundary region KR from the outer side of the container 11. The control unit 110 adjusts the boundary region (KR: FIG. 6) between the first projection image (TGa: FIG. 6) projected by the projector 20a with the first exposure image (RG_a: FIG. 6) and the second projection image (TGb: FIG. 6) projected by the projector 20b with the second exposure image.

Id. at [0042]; *see also id.* at FIGS. 2-3, 5, 6 (with Figures 5 and 6 reproduced below for convenience).

[FIG. 5]



[FIG. 6]



226. Additionally, Sekine teaches that the control unit 110 can adjust positions of adjacent sub-images by providing appropriate instructions to various actuators, as described in detail in paragraphs [0038]-[0041] of Sekine (EX1005). It is these actuators that undertake the equivalent work in the '511 Patent, *i.e.*, they control the image display subsystem to adjust properties and alignment of a position of each sub-image in the array.

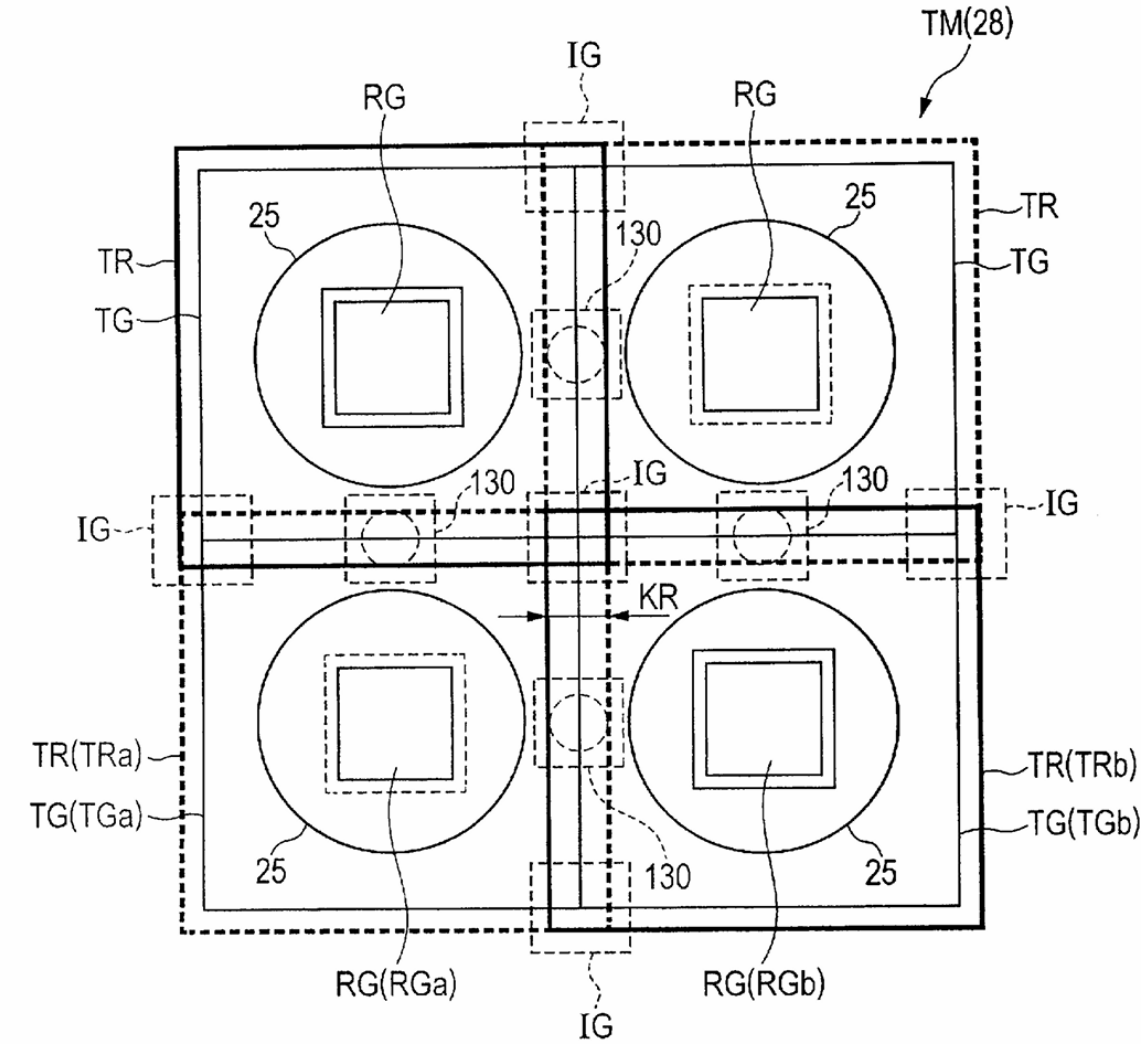
227. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 the '511 Patent.

(e) b. projecting a composite image onto a build area within a resin pool using the image projection system, wherein:

228. Sekine teaches projecting a composite image onto a build area within a resin pool using the image projection system. As discussed above, the "side view" of Figure 1 of Sekine illustrates five projectors 20 that are visible within the 5 x 5 grid or array. Figure 5 of Sekine provides a perspective view of the system. This angle permits a 2 x 2 portion of the projector array to be seen, with four projectors 20 clearly arranged in a row-column array. Figures 1 and 5 are reproduced above for convenience. Each projector 20 projects an image onto the surface of the liquid resin material 10. Sekine (EX1005), [0017]. Additionally, Sekine teaches that to form a large, single product (denoted as element 30 in Sekine) with high resolution, it is possible to divide the overall or composite image 30 into smaller pieces or sub-images, where each sub-image is provided by a separate projector in the array. *Id.* at [0035]. In this case, these sub-images are "stitched" together, such as shown in Figures 5 and 6 (reproduced above), where the individual sub-images are denoted as "TG." *Id.* at [0035]. As illustrated in Figure 6 of Sekine, the edges of "stitched" sub-images TG overlap in the boundary region denoted as "KR." *Id.* at [0044]. Moreover, Sekine teaches that the "seams" between sub-images can be eliminated by correcting "position displacement between adjacent projection images and to make the light distribution uniform." *Id.* at [0035]. For instance, it is possible to use the approach of "Embodiment 3" of Sekine, which is further discussed below with respect to the

"edge blending bar" of claim 1 of the '511 Patent. Figure 6 of Sekine is reproduced below for convenience.

[FIG. 6]



229. Therefore, it is my opinion that Sekine discloses this element of claim 1 of the '511 Patent.

(f) the image projection system is controlled by the image display subsystem;

230. Sekine teaches that the image projection system is controlled by the image display subsystem. Sekine discusses a subsystem that controls the image projection system and each of the image projectors to adjust properties and alignment of the positions of the sub-images produced by the projector array of Sekine. For example, as discussed above with reference to the system of Figure 2 and the flowchart of Figure 3 (reproduced above), Sekine teaches that an external computer 121 inputs design data of the desired product 30 into a control unit 110 and further inputs commands to the control unit 110, such as to start or interrupt the print job. Sekine (EX1005), [0027]. Sekine further teaches that a CPU (denoted as 111) acquires the design data (*e.g.*, CAD data) of the product 30 from the external computer 121 (denoted as step S11 in Figure 3). *Id.* at [0028]. The CPU 111 or the external computer 121 then divides the product 30 into **sub-regions and assigns the sub-regions to the various projectors 20 for actual printing, based on parameters provided by the subsystem**. *Id.* at [0028]-[0030].

231. This division is further described at paragraph [0042], which teaches a "display subsystem, wherein the display subsystem controls the image projection system and each of the image projectors to adjust properties and alignment of a position of each sub-image in the array":

> (**Alignment Control**) FIG. 5 is a schematic diagram of the projection region of the projector. FIG. 6 is a descriptive diagram of the boundary region of the projection image. As illustrated in FIG. 2, the camera 130, which is one

> example of imaging means, captures the boundary region KR from the outer side of the container 11. The control unit 110 adjusts the boundary region (KR: FIG. 6) between the first projection image (TGa: FIG. 6) projected by the projector 20a with the first exposure image (RG_a: FIG. 6) and the second projection image (TGb: FIG. 6) projected by the projector 20b with the second exposure image.

Id. at [0042]; *see also id.* at FIGS. 2-3, 5 (reproduced above for convenience).

232. Additionally, Sekine teaches that the control unit 110 can adjust positions of adjacent sub-images by providing appropriate instructions to various actuators, as described in detail in paragraphs [0038]-[0041] of Sekine (EX1005). It is these actuators that undertake the equivalent work in the ’511 Patent, *i.e.*, they control the image projection system to adjust properties and alignment of a position of each sub-image in the array. To the extent that analysis in element 1(d) above bears on the phrase—“the image display subsystem”—that analysis is incorporated here, given the repetitive language for this element tin the claim.

233. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 the ’511 Patent.

(g) the composite image comprises a plurality of sub-images arranged in an array;

234. Sekine teaches that the composite image comprises a plurality of sub-images arranged in an array. With reference to Figures 1 and 2 (reproduced above for convenience), Sekine teaches that the additive manufacturing system 100 projects an image into a liquid resin material 10 in a container 11 using projectors

20 arranged in a 5 x 5 grid of 25 projectors total. Sekine (EX1005), [0013]-[0019], [0033]. The projectors 20 can be DLP devices or digital micromirror devices ("DMDs"). *Id.* at [0019].

235. As illustrated in the "side view" of Figure 1 of Sekine, five projectors 20 are visible within the 5 x 5 grid or array. Figure 5 of Sekine provides a perspective view of the system. This angle permits a 2 x 2 portion of the projector array to be seen, with four projectors 20 clearly arranged in a row-column array. Each of these projectors projects a sub-image arranged consistent with the same orientation. Please refer to the figures reproduced above for convenience.

236. Therefore, it is my opinion that Sekine discloses this element of claim 1 of the '511 Patent.

(h) two or more adjacent sub-images in the array overlap at two or more sub-image edges; and

237. Sekine teaches that two or more adjacent sub-images in the array overlap at two or more sub-image edges. Sekine teaches use of multiple projectors, where each projector 20 projects an image onto the surface of the liquid resin material 10. Sekine (EX1005), [0017]. Sekine teaches that to form a large, single product (denoted as element 30 in Sekine) with high resolution, it is possible to divide the overall or composite image 30 into smaller pieces or sub-images, where each sub-image is provided by a separate projector in the array. *Id.* at [0035]. In this

case, these sub-images are "stitched" together, such as shown in Figures 5 and 6 (reproduced above), where the individual sub-images are denoted as "TG." *Id.* at [0035]. As illustrated in Figure 6 of Sekine, the edges of "stitched" sub-images TG overlap in the boundary region denoted as "KR." *Id.* at [0044]. Moreover, Sekine teaches that the "seams" between sub-images can be eliminated by correcting "position displacement between adjacent projection images and to make the light distribution uniform." *Id.* at [0035]. For instance, it is possible to use the approach of "Embodiment 3" of Sekine, which is further discussed below with respect to the "edge blending bar" of claim 1 of the '511 Patent.

238. Therefore, it is my opinion that Sekine discloses this element of claim 1 of the '511 Patent.

(i) each sub-image is projected onto a portion of the build area using one of the plurality of image projectors; and

239. Sekine teaches that each sub-image is projected onto a portion of the build area using one of the plurality of image projectors. Notably, these elements are depicted in Figures 1, 5, and 6 of Sekine (reproduced above). As noted above, Sekine teaches that to form a large, single product (denoted as element 30 in Sekine) with high resolution, it is possible to divide the overall or composite image 30 into smaller pieces or sub-images, where each sub-image is provided by a separate projector in the array. Sekine (EX1005), [0035]. In this case, these sub-images are "stitched"

together, such as shown in Figures 5 and 6 (reproduced above), where the individual sub-images are denoted as "TG." *Id.* at [0035].

240. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 of the '511 Patent.

(j) c. adjusting properties and aligning a position of each sub-image in the array using a set of filters comprising:

241. Sekine teaches adjusting properties and aligning a position of each sub-image in the array using a set of filters. Sekine teaches a subsystem that controls the image projection system and each of the image projectors to adjust properties and alignment of the positions of the sub-images produced by the projector array of Sekine. Additionally, similar to Shkolnik and as well known in the field, Sekine discloses multiple types of adjustments of sub-images, where multiple adjustment types can be used in the same print job to correct multiple types of errors. The '511 Patent refers to these correction mechanisms as "filters" or "masks." The translation of Sekine from the original Japanese describes these mechanisms using different terms, such as "illuminance correction control" or "alignment control." *See*, *e.g.*, Sekine (EX1005), [0042], [0073]. However, the concept is exactly the same.

242. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 of the '511 Patent. Details of the "set" of correction mechanisms (or "filters") of Sekine are described in further detail below.

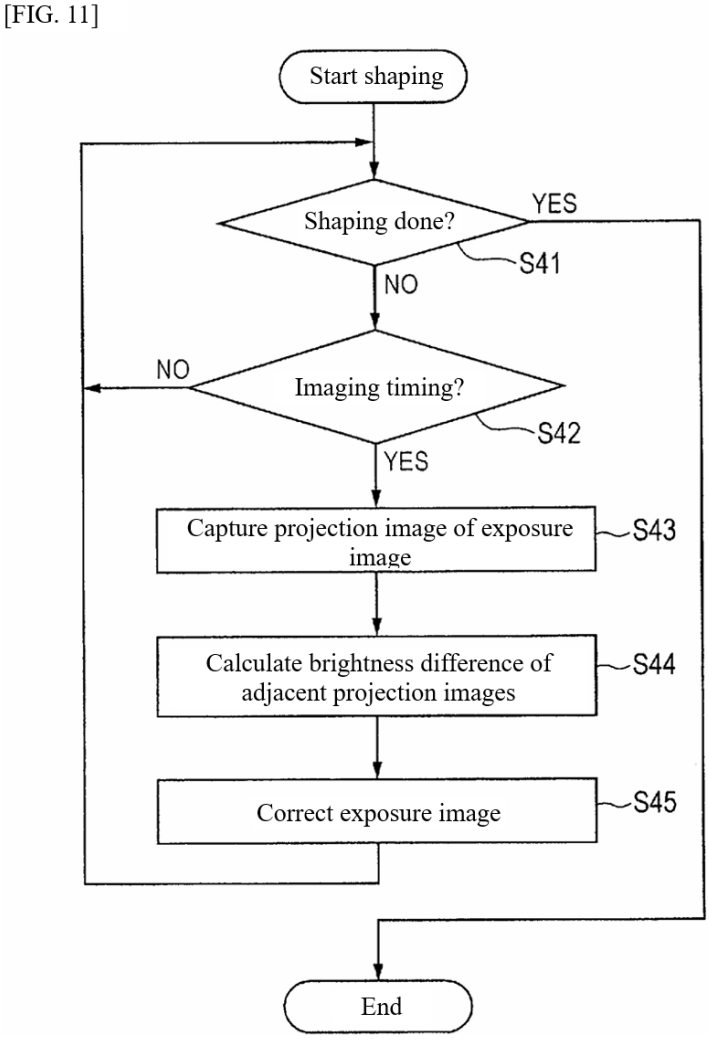
(k) an irradiance mask that normalizes irradiance;

243. Sekine teaches an irradiance mask that normalizes irradiance**.** One of the correction or adjustment mechanisms taught by Sekine is related to normalizing irradiance. Specifically, Sekine teaches that the "illumination" or "brightness" of an overall or composite image can be non-uniform, and that such lack of uniformity is undesirable. For instance, Sekine teaches that when multiple sub-images are stitched together to form a composite image, "gaps" or "streaks" may occur due to "brightness differences between adjacent projection images" or misalignment. Sekine (EX1005), [0070], [0099]. Moreover, Sekine teaches that brightness differences may be due to "performance differences" within the projection system (e.g., as related to the optics or light sources of the system). *Id.* at [0071].

244. Therefore, to address these variations, Sekine teaches a step of normalizing irradiance "to **eliminate** the brightness **difference between** adjacent projection images" and "make the illumination distribution **uniform**." *Id.* at [0070]-[0071]. Sekine further explains one way of doing so: "to ensure that the illuminance difference between adjacent projection images TG across the boundary is eliminated, the brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 is controlled to be the same." *Id.* at [0071]. Sekine also provides a flowchart in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of

adjustment means" for achieving uniform irradiance, whereby each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042] ("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Figure 5 is reproduced above, and Figure 11 is reproduced below for convenience.

[FIG. 11]



245. Additionally, these teachings of Sekine are consistent with common knowledge in the field at the time of the filing of the '511 Patent. Practitioners within the digital display and projection community were well-familiar with the concept of

irradiance uniformity, and had access to prior art references (such as Sekine) that disclose irradiance uniformity, both generally as well as providing specific methods, techniques, and algorithms that would enable one to perform irradiance uniformity adjustment.

246. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 of the ’511 Patent.

(l) a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool;

247. Sekine does not describe gamma adjustment as explicitly as the other filters or masks of claim 1 of the ’511 Patent. However, gamma adjustment or correction was well-known in the field at the time of Sekine, as well as at the time of the filing of the ’511 Patent. For instance, Greene—which is also directed to additive manufacturing using photocurable resins—teaches a “gamma correction” process that adjusts “grayscale intensity levels” of pixels based on “a nonlinear characteristic of the photoactive resin,” for the purpose of achieving improved printing accuracy (*e.g.*, to “smooth out edges”). *See*, *e.g.*, Greene (EX1006), [0008] [0037]-[0040], [0031], [0047]. I, too, have routinely applied gamma adjustment/correction in my laboratories since before the earliest possible priority date of ’511 Patent.

248. Just like Sekine and the ’511 Patent, Greene discloses an additive manufacturing system that includes a vat or pool holding a photoactive or curable resin. *Id.* at [0007]. Greene’s system further includes a light projection device and a controller to control the printing operation, just like Sekine and the ’511 Patent do. *See id.* Additionally, Greene teaches “mapping a digital model onto a three-dimensional grid” (*id.*) of voxels or pixels at certain “intensity levels”. *See* Greene (EX1006), [0037]-[0040]. Greene further teaches that a grayscale technique can be used with this digital model “to provide sub-pixel resolution and smoothing capabilities,” including to “smooth out edges” between different layers of a printed structure and “edges within a layer” of the printed structure. *Id.* at [0008], [0031].

249. Further, Greene teaches (at paragraphs [0037]-[0040]) a process that assigns grayscale intensity levels to various voxels or pixels[19] of the digital model.

250. The entirety of paragraph [0040] of Greene is reproduced below.

> At 435, the process assigns one or more grayscale intensity levels to one or more grayscale voxels based respectively on the one or more containment degrees. If the digital model, for example, covers 60% of the volume of a voxel (e.g., 60% containment degree), then the process can assign an intensity level that is 60% of the white intensity level. In another example, if the digital model covers 80% of the volume of a voxel, then the process can assign an intensity level that is 80% of the white intensity level. The one or more grayscale intensity levels are greater than a black intensity level, but less than the white intensity level assigned at 420. The one or more grayscale intensity levels are not sufficient to completely cure the photoactive resin during the predetermined curing time. **In some implementations, the process**

[19] A voxel is the three-dimensional equivalent of a two-dimensional pixel.

> **can adjust the one or more grayscale intensity levels based on** a nonlinear characteristic of a light source within the 3D printer, **a nonlinear characteristic of the photoactive resin**, or both. **For example, a photoactive resin may have a nonlinear relationship between intensity levels and a curing degree.** In cases where the nonlinearity is substantially a power function (e.g., $y=x^{\gamma}$), an adjustment can be performed by applying the inverse power ($1/\gamma$) to the grayscale intensity levels, **e.g., by performing gamma correction**. Alternatively, a lookup table can be applied to correct for arbitrary nonlinearities. In some implementations, the intensity levels are R-bit values, where R is a predetermined number of bits associated with a graphic file format that range from 0 (black) to 255 (white). For example, the intensity levels can be represented as 8-bit values that range from 0 (black) to 255 (white). Other values for R are possible.

251. For instance, a specific voxel or pixel can be assigned an intensity level that is 60% of a "white" (or fully cured) intensity level (*id.*, [0040]),[20] where a "white" intensity level is "sufficient to cure photoactive resin during a predetermined curing time," as compared to a "black" intensity level that corresponds to zero light or zero curing. *Id.* at [0037] ("The white intensity level is sufficient to **cure photoactive resin** during a predetermined curing time for a layer. In some implementations, the white intensity level is a percentage (e.g., 90% or 95%) of a maximum intensity level generated by a 3D printer; in this case, the maximum intensity level exceeds an intensity level sufficient to cure photoactive resin. Note

[20] Greene, [0040] ("If the digital model, for example, covers 60% of the volume of a voxel (e.g., 60% containment degree), then the process can assign an intensity level that is 60% of the white intensity level.").

that **different photoactive resins can require different curing intensities**."); *see also id.* at [0038], [0040].

252. In short, a pixel having a "grayscale" intensity level can be considered to experience more curing than a "black" pixel or voxel (where no curing occurs), but less than a "white" pixel or voxel (where "maximum" or close to maximum curing occurs). Thus, per Greene, the intensity values can be treated as "R-bit values," where R is a predetermined number of bits associated with a graphic file format, such as 8 bits. For example, Greene teaches at paragraph [0040] that "the intensity levels can be represented as 8-bit values that range from 0 (black) to 255 (white)."

253. Further, at paragraph [0047], gamma adjustment is addressed with respect to additional embodiments:

> At 720, the process generates containment degrees for the finalized pixels based on the respective groups of K*K*K super-pixels. At 725, the process assigns intensity levels based on the containment degrees. **In some implementations, the intensity levels are gamma corrected based on nonlinearities associated with** the printer's projection system, **resin**, or both.

254. Notably, as seen above, the grayscale intensity level of Greene (e.g., on a scale of 0 to 255) can be **adjusted "based on** a nonlinear characteristic of a light source within the 3D printer, **a nonlinear characteristic of the photoactive resin, or both.**" *Id.* at [0040], [0047] ("The intensity levels are gamma corrected based on nonlinearities associated with the . . . resin"). That is, gamma correction in Greene

permits an intensity value between 0 and 255 to be assigned to pixels based on the unique nonlinear characteristics of whatever resin is used in a given print job.

255. Further, and as gleaned from the teachings of the specification, the purpose of Greene—applying varying intensity levels to the resin in the manner disclosed above—is to more "accurately represent the digital model, e.g., a smoother edge is formed as shown in image l00lb rather than a jagged, stair-stepped edge as shown in image l00la." *Id*. at [0053]; *see also id.* at [0008] (the "technology can be used to smooth out edges in three dimensional printing.").

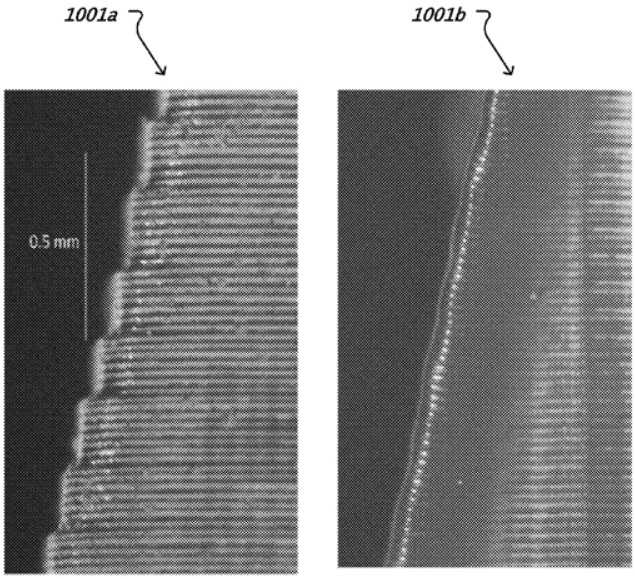


FIG. 10A FIG. 10B

256. In sum, this "gamma correction" of Greene is precisely what the '511 Patent claims based on the ordinary and customary meaning of the limitation. Greene's discussion thus aligns with the same meaning of gamma adjustment as the skilled artisan would understand that claim limitation in light of the context of the specification. *See*, Section IV. E.2. For example, the '511 Patent describes adjusting an image based on the unique curing characteristics of a specific resin as "gamma corrections." *See* '511 Patent (EX1001), 6:3-5; *see also id.* at 11:61-63.

257. Likewise, the ’511 Patent (just like Greene) teaches that “resins tend to have **nonlinear** response curves with respect to energy,” so that a “[g]amma correction filter provides resin reactivity leveling, and enables correct **smoothing**…of pixels by mapping the pixel intensity range (e.g., 0-255) to the minimum and maximum reactivity characteristics of the pixel.” See ’511 Patent (EX1001), 12:6-8; *see also id.* at Claim 1. In my opinion, the gamma adjustment limitation is taught by Greene’s disclosures.

258. Therefore, it is my opinion that it would have been obvious to combine the gamma adjustment mask of Greene with the filters to Sekine, thereby arriving at this limitation of claim 1 of the ’511 Patent. *See* Motivation to Combine. Section, VII.C.

(m) a warp correction filter that provides geometric correction; and

259. Sekine teaches a warp correction filter that provides geometric correction. Sekine teaches the correction of various errors or distortions associated with the use of multiple projectors in additive manufacturing. Geometric corrections are discussed in detail. For instance, Sekine states the following at paragraph [0062]: “when using multiple projectors 20 to project individual exposure images RG formed by dividing the overall exposure image…distortion of the image itself” can occur, such as indicated by a “displacement of the [overall] image pattern at the

boundary of the adjacent [sub-images].” To address such geometric misalignment or distortion, Sekine teaches that the system of Sekine corrects the sub-images so that the overall image matches the designed position, rather than being distorted. *Id.* at [0063]. Moreover, each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment of the ‘distorted image’ is occurring at the sub-image level. *Id.* at [0042]. (“(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector.”). Figure 5 is reproduced above for convenience.

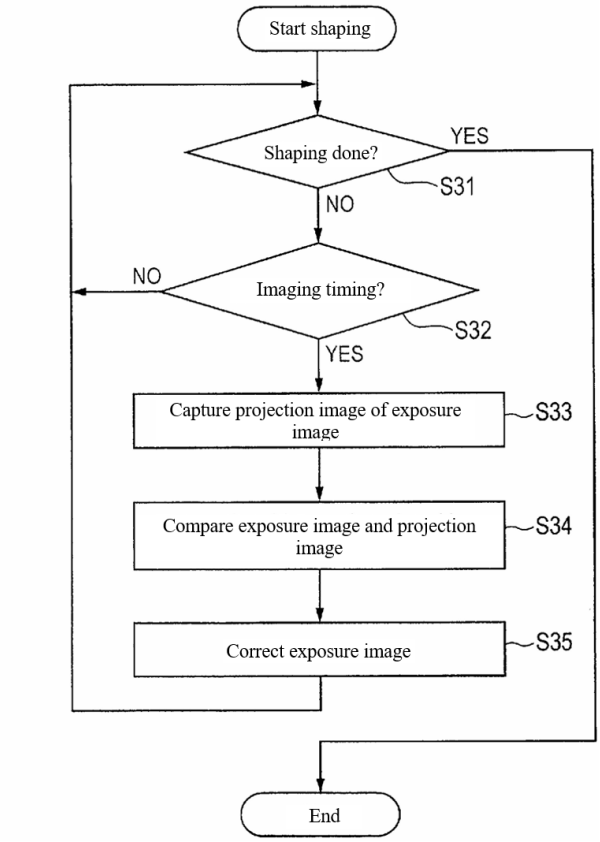
260. One example of such geometric correction is described in Figures 9, 10A, and 10B of Sekine. *Id.* at [0064]-[0068]. Figure 9 is a flowchart for “displacement correction control.” Figures 10A and 10B (reproduced above with respect to claim 1 for convenience) show “before” and “after” depictions of a geometrically displaced image (Figure 10A) and corrected image (Figure 10B). Figures 9, 10A, and 10B are reproduced below for convenience.

261. As illustrated in Figure 10A, if a displacement error occurs between adjacent projection regions TR, a gap GP may form in the desired product image. The desired image is depicted as a hatched rectangle, denoted as element 30G in Figure 10. *Id.* at [0067]. Sekine teaches that one way to correct this distortion is by adjusting position and tilt. Id. Specifically, as illustrated in Figure 10B, the individual projection regions TR are not moved. Instead, the projection image TG is

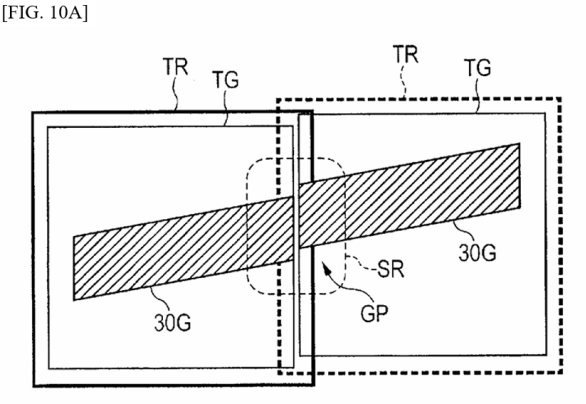
moved within the projection region TR as indicated by the arrows to eliminate the gap GP. With reference to Figure 2, this correction can be achieved by (1) moving the contour position of the product 30 displayed in the exposure image RG on the image forming element 23 by a "positional correction amount" and also (2) tilting by a "tilt correction amount." *Id.* at [0067]. Figure 2 is reproduced above for convenience.

262. According to Sekine, these position and angle adjustments remove the distortion and correct the geometry of the printed article. These teachings of Sekine are consistent with common knowledge in the field. Practitioners within the digital display and projection community were well familiar with the concept of geometric correction (e.g., warp correction and other types of geometric correction), and had access to prior art (such as Sekine) that disclose geometric correction such as warp correction, both generally and also with respect to disclosing specific methods, techniques, and algorithms that would enable one to perform geometric correction (such as disclosed by Sekine).

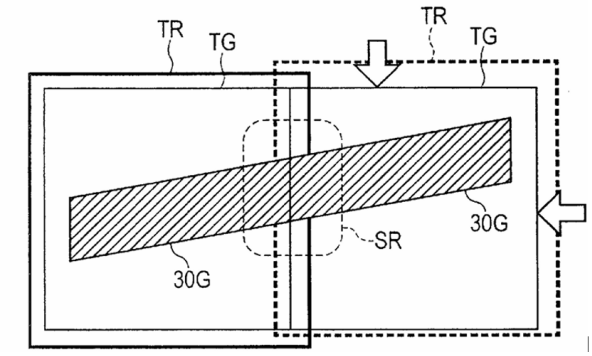
[FIG. 9]


Start shaping
Shaping done?
YES
S31
NO
Imaging timing?
NO
S32
YES
Capture projection image of exposure image
S33
Compare exposure image and projection image
S34
Correct exposure image
S35
End

[FIG. 10A]



[FIG. 10B]



263. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 of the ‘511 Patent.

(n) an edge blending bar at one or more sub-image edges.

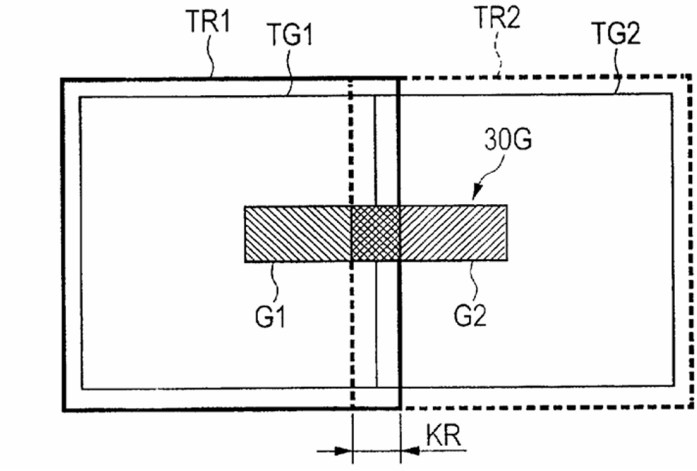
264. Sekine teaches an edge blending bar at one or more sub-image edges. Sekine also teaches a mechanism for improving printing resolution by blending the ends of adjacent sub-images. As additionally stated above in the discussion of brightness normalization, Sekine teaches that adjacent sub-images can overlap, and that adjustments to the sub-images can be made to ensure proper printing despite the overlap, such as by adjusting brightness.

265. In addition, Sekine teaches the use of "grayscaling" or "stepping" of adjacent sub-images where their edges overlap, such that the two sub-images blend into one another gradually. This correction mechanism is described in detail with reference to Figure 17A, for instance. Figure 17A is reproduced below for convenience. In Figure 17A, an overall image 30G is desired. The overall image 30G is rectangle shaped and includes two parts, denoted as G1 (left half of the rectangle in Figure 17A) and G2 (right half of the rectangle in Figure 17A). The first part G1 is included in a first sub-image (TG1) produced by a first projector (the projector itself is not shown in Figure 17A). The second part G2 is included in a second sub-image (TG2) produced by a second projector (not shown). The element "KR" in Figure 17A shows the boundary region where the sub-images TG1 and TG2 overlap. Sekine (EX1005), [0101]-[0105]. Moreover, because each projector is projecting the sub-image within the boundary allotted to that projector, the 'correction mechanism' in Figure 17A is occurring at the sub-image level. *Id.* at [0042]. ("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector.").

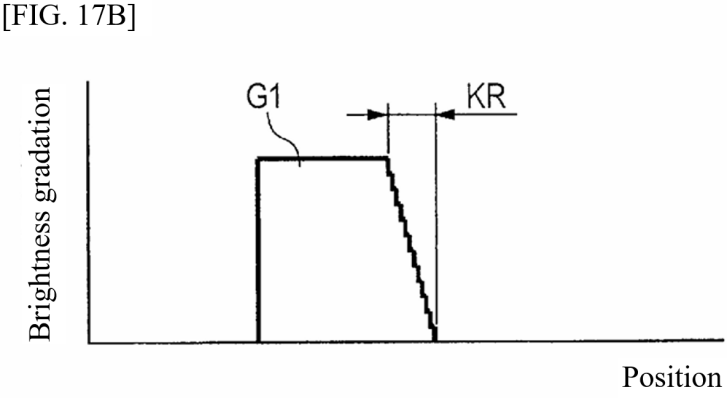
266. Notably, as shown in Figure 17B, the brightness or irradiation is G1 is graded or "grayscaled" within the overlap region KR —that is, G1 has a "stair step" brightness, with brightness decreasing as G1 gets closer to G2. Similarly, as shown in Figure 17C, the brightness of G2 is also graded or grayscaled, with brightness decreasing as G2 gets closer to G1. *Id.* at [0101]-[0105]. In this way, the edges of

sub-images TG1 and TG2 are blended together. As taught by Sekine, this approach avoids both “gaps” (where there is not enough light, and thus the photocurable resin is under-exposed) and also “streaks” (where there is too much light, and thus the photocurable resin is over-exposed). *Id.* at [0070]-[0072], [0101]-[0105]. This teaching of Sekine is consistent with common knowledge in the industry. Practitioners within the digital display and projection community have been well familiar with the concept of edge-blending and have had access to prior art (such as but not limited to Sekine) that disclose edge-blending generally, as well as providing specific methods, techniques, and algorithms (such as Sekine’s) that would enable one to perform edge-blending. Figures 17A, 17B, and 17C are reproduced below for convenience.

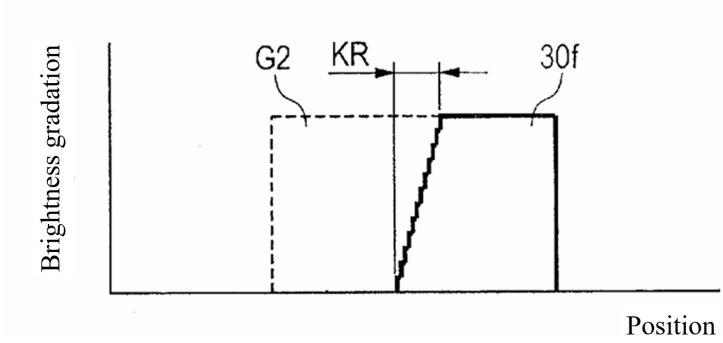
[FIG. 17A]



[FIG. 17B]



[FIG. 17C]



267. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 of the ’511 Patent.

268. The following dependent claims are also rendered obvious.

2. Claim 2 – The method of claim 1, wherein the image display subsystem controls the image projection system and each of the image projectors using digital light processing.

269. Sekine teaches that the image display subsystem controls the image projection system and each of the image projectors using digital light processing. As discussed above with respect to element 1[f] of claim 1, Sekine teaches that the image display subsystem controls the image projection system. Specifically, Sekine teaches a subsystem that controls the image projection system and each of the image

projectors to adjust properties and alignment of the positions of the sub-images produced by the projector array of Sekine. For example, with reference to the system of Figure 2 and the flowchart of Figure 3, Sekine teaches that an external computer 121 inputs design data of the desired product 30 into a control unit 110 and further inputs commands to the control unit 110, such as to start or interrupt the print job. Sekine (EX1005), [0027]. Sekine further teaches that a CPU (denoted as 111) acquires the design data (e.g., CAD data) of the product 30 from the external computer 121 (denoted as step S11 in Figure 3). *Id.* at [0028]. The CPU 111 or the external computer 121 then divides the product 30 into **sub-regions and assigns the sub-regions to the various projectors 20 for actual printing, based on parameters provided by the subsystem**. *Id.* at [0028]-[0030]. Figures 2 and 3 are reproduced above for convenience.

270. This division is further described at paragraph [0042], which teaches a "display subsystem, wherein the display subsystem controls the image projection system and each of the image projectors to adjust properties and alignment of a position of each sub-image in the array":

> (**Alignment Control**) FIG. 5 is a schematic diagram of the projection region of the projector. FIG. 6 is a descriptive diagram of the boundary region of the projection image. As illustrated in FIG. 2, the camera 130, which is one example of imaging means, captures the boundary region KR from the outer side of the container 11. The control unit 110 adjusts the boundary region (KR: FIG. 6) between the first projection image (TGa: FIG. 6) projected by the projector 20a with the first exposure image (RG_a: FIG. 6) and the second

projection image (TGb: FIG. 6) projected by the projector 20b with the second exposure image.

Id. at [0042]; *see also id.* at FIGS. 2-3, 5, 6 (reproduced above).

271. Additionally, Sekine teaches that the control unit 110 can adjust positions of adjacent sub-images by providing appropriate instructions to various actuators, as described in detail in paragraphs [0038]-[0041] of Sekine (EX1005). It is these actuators that undertake the equivalent work in the '511 Patent, *i.e.*, they control the image projection system to adjust properties and alignment of a position of each sub-image in the array.

272. With respect to "digital light processing" ("DLP"), Sekine specifically teaches that DLP devices may be utilized. For instance, Sekine teaches that an image forming element "employs a DMD element DLP9000 from Texas Instruments." *See* Sekine (EX1005), [0019]. DLP devices have been well-known and utilized before the filing of the '511 Patent. For example, Greene too discusses use of DLP projectors in a similar manner. *See* Greene (EX1006), [0026] ("In some implementations, the light projection device 142 includes a liquid crystal display (LCD) device, discrete light emitting diode (LED) array device, laser, ***or a digital light processing (DLP) projector***.").

273. Therefore, it is my opinion that Sekine discloses this limitation of claim 2 of the '511 Patent.

3. Claim 3 – The method of claim 1, wherein the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors.

274. Sekine teaches that the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors**.** Sekine discloses multiple types of adjustments of sub-images, including, *e.g.*, "illuminance correction control" or "alignment control." *See*, *e.g.*, Sekine (EX1005), [0042], [0073]. It is of course well understood that non-uniformities in the optics of projectors can cause illuminance and/or alignment errors, and the correction of such errors is discussed at great length in Sekine, including in paragraphs [0108]-[0111].

275. As another example, Sekine teaches that various actuators of the system of Sekine (*e.g.*, actuators denoted as 41-48 and 51-53) can be used to adjust optical elements of individual projectors to correct for displacement and angle errors, for instance. *See* Sekine (EX1005), Figure 2 and [0038]-[0041] (reproduced below for convenience).

> [0038]
> (Alignment Mechanism)
> FIGS. 4A to 4C are descriptive diagrams of the alignment mechanism of the image forming element 23. FIG. 4A is a side view, FIG. 4B is a plan view, and FIG. 4C is a front view. As illustrated in FIGS. 4A to 4C, an image display unit 40 holds the image forming element 23 on an inner side of a box-shaped housing 40f so as to be movable by actuators 41 to 48 and 51 to 53 using piezoelectric

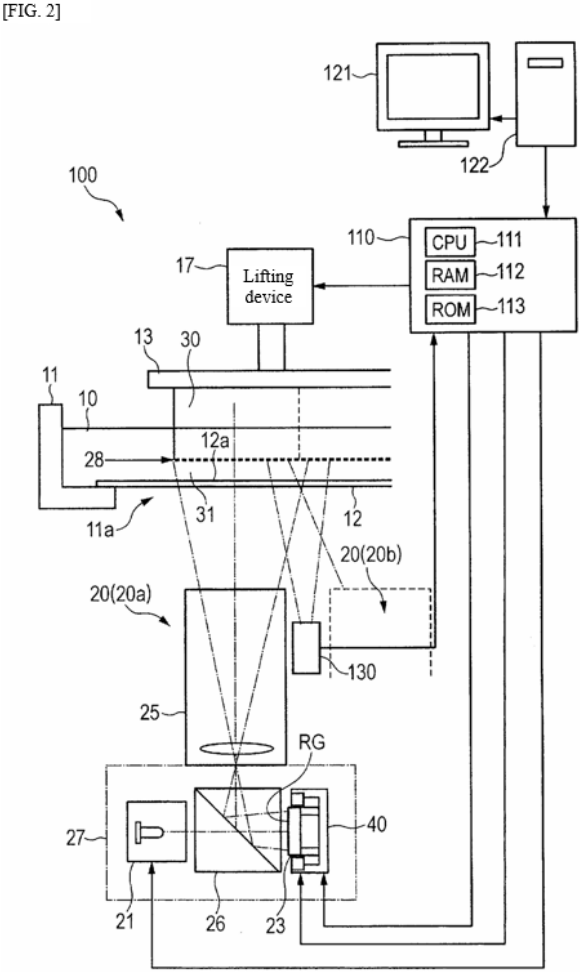
elements. The actuators 41 to 48 and 51 to 53 expand and contract according to an applied direct current voltage.

[0039] The actuators 41 to 48, which are one example of adjustment means, can adjust the position of the image forming element 23 in a plane that intersects the projection optical axis of the exposure image. The control unit 110 can adjust the relative position at the boundary region KR of the two adjacent projection images TG by controlling the actuators 41 to 48. The actuators 41, 42, 43, and 44 can move the image forming element 23 in a Y direction by combining their respective expansions and contractions. The actuators 45, 46, 47, and 48 can move the image forming element 23 in an X direction by combining their respective expansions and contractions. The actuators 41, 42, 43, 44, 45, 46, 47, and 48 can rotate the image forming element 23 in a XY plane to adjust the angle, by combining their respective expansions and contractions.

[0040] The actuators 51, 52, and 53 can move the image forming element 23 in a Z direction by expanding and contracting together. The actuators 51, 52, and 53 can adjust an angle of the image forming element 23 in an XZ plane and a YZ plane by combining their respective expansions and contractions.

[0041] The control unit (110: FIG. 2-below), which is one example of control means, processes the captured image taken by the camera 130 to calculate the amount of pixel displacement in two adjacent projection images and operates the actuators 41 to 48 to offset the displacement amount.

[FIG. 2]



276. Therefore, it is my opinion that Sekine discloses this limitation of claim 3 of the ’511 Patent.

4. Claim 4 – The method of claim 1, wherein the gamma adjustment mask comprises a logarithmic relationship between a cure depth of the resin and energy per unit area in the build area.

277. Greene teaches that the gamma adjustment mask comprises a logarithmic relationship between a cure depth of the resin and energy per unit area in the build area. As stated above, Greene teaches a gamma adjustment mask. As

also stated above, **any** gamma adjustment necessarily includes accounting for the unique chemistry and physics of a specific photocurable resin (*e.g.*, with reference to that resin's working curve). Moreover, for **any** photocurable resin, the relationship between a cure depth of the resin and energy per unit area is **always** logarithmic.

278. Indeed, the logarithmic relationship between cure depth and energy per unit area is literally a textbook principle that has been extremely known in the field for decades, as evidenced by Jacobs (EX1007), *e.g.* at page 204, inherent to all photocurable resins of the type described by Greene.

279. Therefore, it is my opinion that Greene discloses this limitation of claim 4 of the '511 Patent.

5. Claim 5 – The method of claim 1, wherein the resin is selected from the group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations thereof.

280. Sekine teaches that the resin is selected from a group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations thereof. Sekine specifically contemplates different "resin materials." Sekine (EX1005), [0024]. In this regard, Sekine discusses that "the resin material 10 used in embodiment 1 solidifies by undergoing a radical polymerization reaction due to ultraviolet light, and is a resin material whose radical polymerization reaction is hindered in an oxygen-rich environment. For example, this includes photocuring

polyurethane, photocuring epoxy resin, photocuring urethane, photocuring silicone rubber, or the like." *Id.* at [0024].

281. Therefore, it is my opinion that Sekine discloses this limitation of claim 5 of the '511 Patent.

6. Claim 6 – The method of claim 1, wherein the edge blending bar comprises a blending distance and a function selected from the group consisting of: linear, sigmoid and geometric.

282. Sekine teaches that the edge blending bar comprises a blending distance and a function selected from the group consisting of: linear, sigmoid and geometric. As described above in the context of claim 1, Sekine teaches a mechanism for improving printing resolution by blending the ends of adjacent sub-images. For example, Sekine teaches the use of "grayscaling" or "stepping" of adjacent sub-images where their edges overlap, such that the two sub-images blend into one another gradually. This correction mechanism is described in detail with reference to Figure 17A, for instance, as well as with reference to the schematic of Figure 2. Figure 17A (reproduced above) explicitly depicts the blending distance as overlap region or boundary "KR" (which I have previously discussed). Additionally, as illustrated in Figure 2, the CPU 111 creates exposure images divided for each projector 20 by setting the exposure images of each layer of the shaped product 30. Sekine (EX1005), [0105]. Then, the CPU 111 "extracts the shaping region of the shaped product 30 that spans adjacent exposure images and sets the shaping region

that overflows into the adjacent exposure images." *Id.* at [0105]. Next, "the illuminance of the exposure image in the boundary region is set to gradually decrease within the range where the adjacent projection regions TR overlap." *Id.* at [0105].

283. As well understood in the field, a "gradual decrease" as described by Sekine can be achieved by various standard choices for mathematical functions, including linear, sigmoid, and geometric functions, all of which can provide the "gradual decrease" taught by Sekine, with a linear function being the quintessential example of a "gradual decrease."

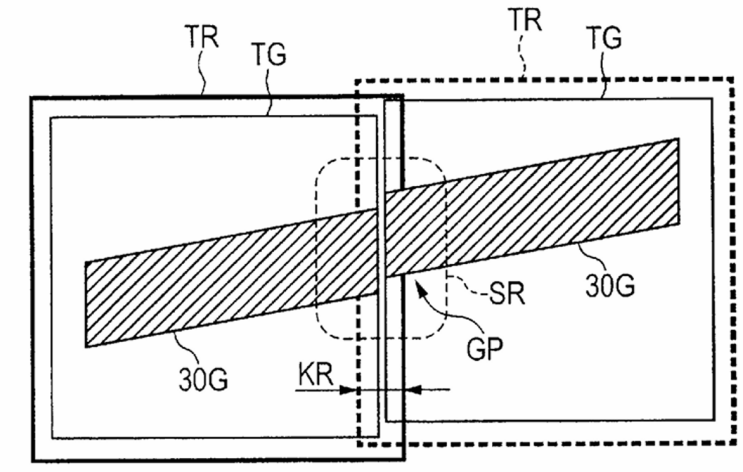
284. Therefore, it is my opinion that Sekine discloses this limitation of claim 6 of the '511 Patent.

7. Claim 7 – The method of claim 1, wherein the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured.

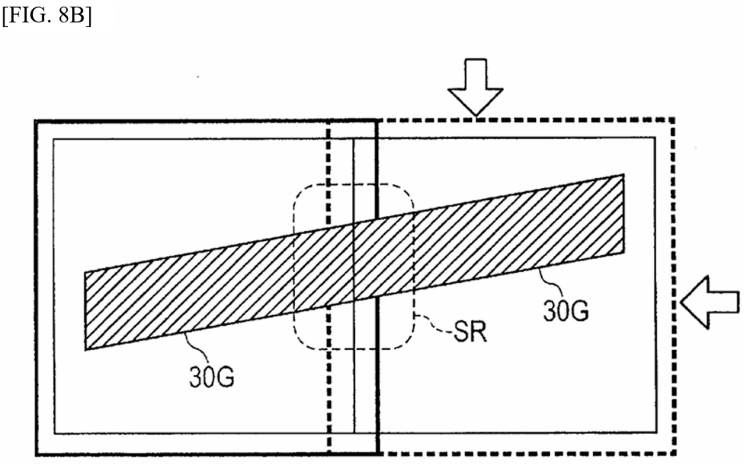
285. Sekine teaches that the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured. As discussed above, Sekine teaches that when multiple sub-images are stitched together to form a composite image, "gaps" or "streaks" may occur due to "brightness differences between **adjacent** projection images" or misalignment. Sekine (EX1005), [0070], [0099]. To address these variations, Sekine teaches a step of normalizing irradiance "to eliminate the brightness difference **between adjacent**

projection images" and "make the illumination distribution **uniform**." *Id.* at [0070]-[0071]. Sekine further explains one way of doing so: "to ensure that the illuminance difference between adjacent projection images TG across the boundary is eliminated, the brightness gradation (duty ratio) of each pixel **in the plane of the image forming element** 23 is controlled to be the same." *Id.* at [0071]. As discussed above, Sekine provides a flowchart (above) in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of adjustment means" for achieving uniform irradiance, whereby each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042]. ("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Sekine specifically discusses that "it is necessary to correct positional displacement between adjacent projection images **and to make the light distribution uniform**." *See id.* at [0035]. It would be clear to a POSITA reading Sekine that the boundary is within the object being manufactured, for example as depicted with respect to FIGS. 8A and 8B. Figures 8A and 8B are reproduced below for convenience.

[FIG. 8A]



[FIG. 8B]



286. Therefore, it is my opinion that Sekine discloses this limitation of claim 7 of the ’511 Patent.

8. Claim 8 – The method of claim 1, further comprising a system controller that synchronizes exposure control of the plurality of image projectors with each other.

287. Sekine teaches a system controller that synchronizes exposure control of the plurality of image projectors with each other. As discussed above, Sekine discusses use of multiple pattern generators simultaneously, for example “four

projectors 20 [that] project the exposure image RG **divided into four to form the projection image TG** at the image formation position 28." *See* Sekine (EX1005), [0043]. Sekine explicitly contemplates that a CPU may set a shaping region and "divide[] such into shaping regions of each projector 20," where the CPU further "sets the exposure images of the photocuring resin material ***for each shaping region*** of the predetermined height increment of the projectors 20." *See id.* at [0028]-[0029]. According to Sekine itself, the "present invention" of Sekine is provided with "first image projection means for projecting a first exposure image into the resin material from the incident surface, second image projection means for projecting a second exposure image **continuous with the first exposure image into the resin material from the incident surface**." *See id.* at [0009]. In this regard, it is clear to a POSITA reading Sekine that the invention of Sekine includes means such as a controller (*i.e.,* a controller) that controls the projection of the divided images and regions such that the corresponding areas are exposed "continuous[ly]" (*i.e.*, simultaneously) with one another.

288. Therefore, it is my opinion that Sekine discloses this limitation of claim 8 of the '511 Patent

9. **Claim 14 – The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image.**

289. Sekine teaches that adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image. As discussed above, Sekine teaches splitting of an exposure image into multiple (*e.g.*, four) sub-images that "form the projection image." *See* Sekine (EX1005), [0043]. As discussed above, Sekine teaches that the "illumination" or "brightness" of an overall or composite image can be non-uniform, and that such lack of uniformity is undesirable. Sekine teaches that when multiple sub-images are stitched together to form a composite image, "gaps" or "streaks" may occur due to "brightness differences between adjacent projection images" or misalignment. *Id.* at [0070], [0099]. To address these variations, Sekine teaches a step of normalizing irradiance "to eliminate the brightness difference between adjacent projection images" and "make the illumination distribution **uniform**." *Id.* at [0070]-[0071]. Sekine further explains one way of doing so: "to ensure that the illuminance difference between adjacent projection images TG across the boundary is eliminated, the brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 is controlled to be the same." *Id.* at [0071]. As discussed above, Sekine provides a flowchart (reproduced above) in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of adjustment means" for achieving uniform irradiance,

whereby each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042]. ("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Sekine specifically discusses that "it is necessary to correct positional displacement between adjacent projection images **and to make the light distribution uniform**." *See id.* at [0035]. Thus, a POSITA would clearly understand that the adjustments being made—specifically to control irradiance to be the same at a sub-image level—would make uniform the irradiance across the composite image as a whole.

290. Therefore, it is my opinion that Sekine discloses the limitations of claim 14 of the '511 Patent.

10. Claim 15 – The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity.

291. Sekine teaches that the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity. By "projector-based spatial energy non-uniformity," a POSITA would understand the '511 Patent

to mean non-uniformities of irradiance energy caused by a projector, for example, "non-uniformities in the projector optics and/or optical path." *See* '511 Patent (EX1001), 11:50-52.

292. These non-uniformities are exactly the same as those accounted for in Sekine. As discussed above, it is well understood that non-uniformities in the optics of projectors can cause illuminance and/or alignment errors, and the correction of such errors is discussed at great length in Sekine, including in paragraphs [0108]-[0111]. Sekine also teaches that various actuators of the system of Sekine (e.g., actuators denoted as 41-48 and 51-53) can be used to adjust optical elements of individual projectors to correct for displacement and angle errors, for instance. *See* Sekine (EX1005), Figure 2 and [0038]-[0041] (reproduced above for convenience).

> [0038]
> (Alignment Mechanism)
> FIGS. 4A to 4C are descriptive diagrams of the alignment mechanism of the image forming element 23. FIG. 4A is a side view, FIG. 4B is a plan view, and FIG. 4C is a front view. As illustrated in FIGS. 4A to 4C, an image display unit 40 holds the image forming element 23 on an inner side of a box-shaped housing 40f so as to be movable by actuators 41 to 48 and 51 to 53 using piezoelectric elements. The actuators 41 to 48 and 51 to 53 expand and contract according to an applied direct current voltage.
>
> [0039] The actuators 41 to 48, which are one example of adjustment means, can adjust the position of the image forming element 23 in a plane that intersects the projection optical axis of the exposure image. The control unit 110 can adjust the relative position at the boundary region KR of the two adjacent projection images TG by controlling the actuators 41 to 48. The actuators 41, 42, 43, and 44 can move the image forming element 23 in a Y direction by

> combining their respective expansions and contractions. The actuators 45, 46, 47, and 48 can move the image forming element 23 in an X direction by combining their respective expansions and contractions. The actuators 41, 42, 43, 44, 45, 46, 47, and 48 can rotate the image forming element 23 in a XY plane to adjust the angle, by combining their respective expansions and contractions.
>
> [0040] The actuators 51, 52, and 53 can move the image forming element 23 in a Z direction by expanding and contracting together. The actuators 51, 52, and 53 can adjust an angle of the image forming element 23 in an XZ plane and a YZ plane by combining their respective expansions and contractions.
>
> [0041] The control unit (110: FIG. 2-below), which is one example of control means, processes the captured image taken by the camera 130 to calculate the amount of pixel displacement in two adjacent projection images and operates the actuators 41 to 48 to offset the displacement amount.

293. As discussed above, Sekine provides a flowchart (reproduced above) in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of adjustment means" for achieving uniform irradiance, whereby each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042]. ("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Sekine specifically discusses that "it is necessary to correct positional displacement between adjacent projection images **and to make the light distribution uniform**." *See id.* at [0035]. Indeed, Sekine explicitly states that the brightness gradation is controlled "to make the illumination distribution uniform," in the same paragraph where Sekine discusses that there may

be "illumination differences" and that "the following are conceivable: (1) **performance differences** of the projection optical system 25 and (2) **performance differences of the light source 21.**" Thus, a POSITA would clearly understand that the adjustments being made—specifically to control irradiance to be the same at a sub-image level—would correct such differences between light sources or the performance difference of the projection optical system (*i.e.*, the "projector-based spatial energy non-uniformity" of a projector).

294. Therefore, it is my opinion that Sekine discloses the additional limitations of claim 15 of the '511 Patent.

C. Motivation to Combine Sekine with Greene and Reasonable Expectation of Success

295. Each of the prior art references addressed above are directed towards improving printing resolution of additive manufacturing systems that use light projection to cure photoactive materials such as photocurable polymer resins. Here, Sekine (which discloses at least three of the four techniques in the '511 Patent) may be predictably combined with Greene (which discloses the fourth technique) to arrive at the claimed invention. Several reasons support this conclusion.

296. First, the references are both directed towards the same purposes and field of endeavor—*i.e.*, improving accuracy in the formation of a 3D printed product formed by light projection. Given the nature of the problem and design needs in the

industry to improve the precision and accuracy of 3D products *vis-à-vis* their ideal digital model, it would be natural for a POSITA to look toward similar references with similar purposes to solve well-known problems in the field. As stated earlier, Sekine provides a "first image projection means" and a "second image projection means" for projecting images "into the resin material from the incident surface to promote fidelity between the 3D product and the 2D schematic from which it is based—*e.g.*, a "three-dimensional shap[ed] device that does not readily form streak patterns or slits . . . on a surface of a shaped product." *Id*. at [0009]-[0010].

297. The purpose of Greene is "to smooth out edges in three-dimensional printing" *Id.* at [0008], while accommodating for the fact that the resins used in the process are different and require varying exposure time. *Id.*, [0037].

298. In view of the fact that the references are directed towards the same field of endeavor—and that there are no teachings in the references that would disparage a combination of the references—the POSITA would be motivated to use them as starting references for the purposes of heightening precision and accuracy of printing 3D products, including to take into account well-known, inherent challenges of light projection systems and the resins used to form 3D products.

299. Second, and as I understand the 'motivation to combine' analysis under U.S. patent law, where a technique has been used to **improve one device** and it would improve a similar device in the same way, such teachings provide a basis to

combine the references. This is precisely the case here with, for example, Greene's disclosure of gamma adjustment and how that same technique could be used in the same way to improve Sekine to arrive at the claimed invention. More specifically, both references are directed towards overall similar purposes, and the specific techniques of the references are **complementary**, with use of gamma adjustment in Greene providing benefit to the techniques taught in Sekine (and vice versa). As noted above, both Greene and Sekine are interested in techniques for improving resolution of articles formed by 3D printing with a projection light source (such as a DLP device). The POSITA would immediately appreciate that various such techniques could be combined. For instance, the POSITA would immediately recognize that the gamma adjustment technique in Greene's system (which improves printing resolution) could be added to the techniques of Sekine for the same purpose (to improve printing resolution). The POSITA would expect that the combination of Greene and Sekine would allow the POSITA to more "accurately represent the digital model"—for example to achieve "a smoother edge . . . rather than a jagged, stair-stepped edge" depicted in non-gamma adjusted products in Greene. *Id.* at [0053]. Indeed, adding the gamma adjustment of Greene to the techniques of Sekine would be very logical, because the gamma adjustment of Greene would improve a similar device (i.e., Sekine) in the same way as that technique improves Greene.

300. As stated above, Sekine teaches a multi-projector system. Each projector 20 projects an image onto the surface of the liquid resin material. Sekine, [0017]. Sekine teaches that to form a large, single product with high resolution, it is possible to divide the overall or composite image 30 into smaller pieces or sub-images, where each sub-image is provided by a separate projector in the array. *Id.* at [0035]. This framework lends itself to the specific benefit afforded by Greene. More specifically, because of Greene's benefits, the POSITA would be motivated to combine and modify Sekine and Greene's systems (i.e., incorporate the gamma adjustment filter of Greene into the multi-projector system disclosed in Sekine) to arrive at the claimed invention because of the added advantages it provides. Further, given that the differences between Sekine and the '511 Patent are limited to one element (gamma adjustment), and the modification to arrive at the claimed invention is relatively minor (i.e., incorporating gamma adjustment into Sekine's multi-projector system), the POSITA would be motivated to combine and modify Sekine and Greene in exactly this manner.

301. The combination of the references would also lead to an expectation of success. Combining Sekine with Greene would simply involve applying known techniques (i.e., gamma adjustment) to a known device ready for improvement (Sekine's multi-projector 3D printing system) to yield predictable results (improved precision and accuracy in a 3D product, particularly with respect to the smoothness

of the product itself). A POSITA would have had a reasonable expectation of success in the combination because Sekine already discloses three of the four techniques typically used in achieving heightened precision and accuracy in 3D product development—and Greene discloses the use of gamma adjustment, which was well-known in the art, and explicitly disclosed in Greene.

302. A POSITA thus would have had a reasonable expectation that the techniques work together because the techniques disclosed are being used in their conventional ways—with the techniques operating as they are expected to function (individually and in combination)—to achieve predictable outcomes that would be expected by those persons skilled in the art. That is, they would have been readily combined due to the predictability of the art and how these techniques were known to improve precision and accuracy in 3D printing.

303. Accordingly, it is my opinion that POSITA would be motivated to combine and modify Sekine's and Greene's systems to arrive at the claimed invention of the '511 Patent.

VIII. GROUND 3: CLAIMS 1-8, 14, AND 15 ARE UNPATENTABLE AS OBVIOUS OVER SHKOLNIK AND SEKINE[21]

A. Shkolnik and Sekine Disclosed All Claimed Limitations

[21]As with the other grounds, I have been informed by counsel and understand that claim terms need not be construed when there is no dispute as to the meaning of a term that could affect the outcome of the proceeding. It is my opinion that none of the claims of the '511 Patent require construction to determine their validity in

1. **Claim 1**

(a) Element 1[a]: A method comprising:

304. Shkolnik is directed to systems and methods for additive manufacturing. Shkolnik (EX1004), 4:22-23. Therefore, it is my opinion that Shkolnik discloses the preamble of claim 1 of the ’511 Patent.

(b) a. providing an additive manufacturing system, comprising:

305. Shkolnik teaches providing an additive manufacturing system. As noted above Shkolnik is directed to systems and methods for additive manufacturing. Shkolnik (EX1004), 4:22-23. Therefore, it is my opinion that Shkolnik discloses this element of claim 1 of the ’511 Patent.

(c) an image projection system comprising a plurality of image projectors; and

306. Shkolnik teaches an image projection system comprising a plurality of image projectors. In general, Shkolnik teaches a system having an image projection system that includes one or more image projectors, such as one or more digital light processing or “DLP” devices. Shkolnik (EX1004), 4:40-44. Such image projectors

view of the prior art I have analyzed in this Declaration. Thus, for purposes of this proceeding, it is my opinion that no formal claim construction is necessary. That is, I have applied the ordinary and customary meaning to my analysis.

are sometimes referred to as "pattern generators" in Shkolnik. *See*, *e.g.*, *id.* 4:41-42; 7:56-57.

307. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(d) an image display subsystem;

308. Shkolnik teaches an image display subsystem. As described in the '511 Patent, an image display subsystem can control the image projection system, including to adjust properties and alignment of a position of each sub-image produced by the image projection system. *See*, *e.g.*, '511 Patent (EX1001), claim 1. Shkolnik teaches that its system can include various components and subsystems for controlling the image projection system and each of the image projectors of Shkolnik to adjust properties and alignment of a position of each sub-image in the array of sub-images described by Shkolnik. For example, Shkolnik teaches a controller that interfaces with multiple pattern generators and an imager "for self-calibration at any time before, during, or after manufacture" such as "image correction mapping…to modify an image or bitmap for positional inaccuracies." *See, e.g.*, Shkolnik (EX1004), 7:10-22; 8:6-32. Such a "controller" is denoted as element 120 in Figure 1A, and such an "imager" is denoted as element 106 in Figure 1A (see reproduction of Figure 1A below for convenience). Additionally, Shkolnik teaches that the imager

106 "may be used for initial alignment and adjustment of pattern generators 102, 104 or for real-time, or near real-time, adjustment." *Id.* at 11:23-35.

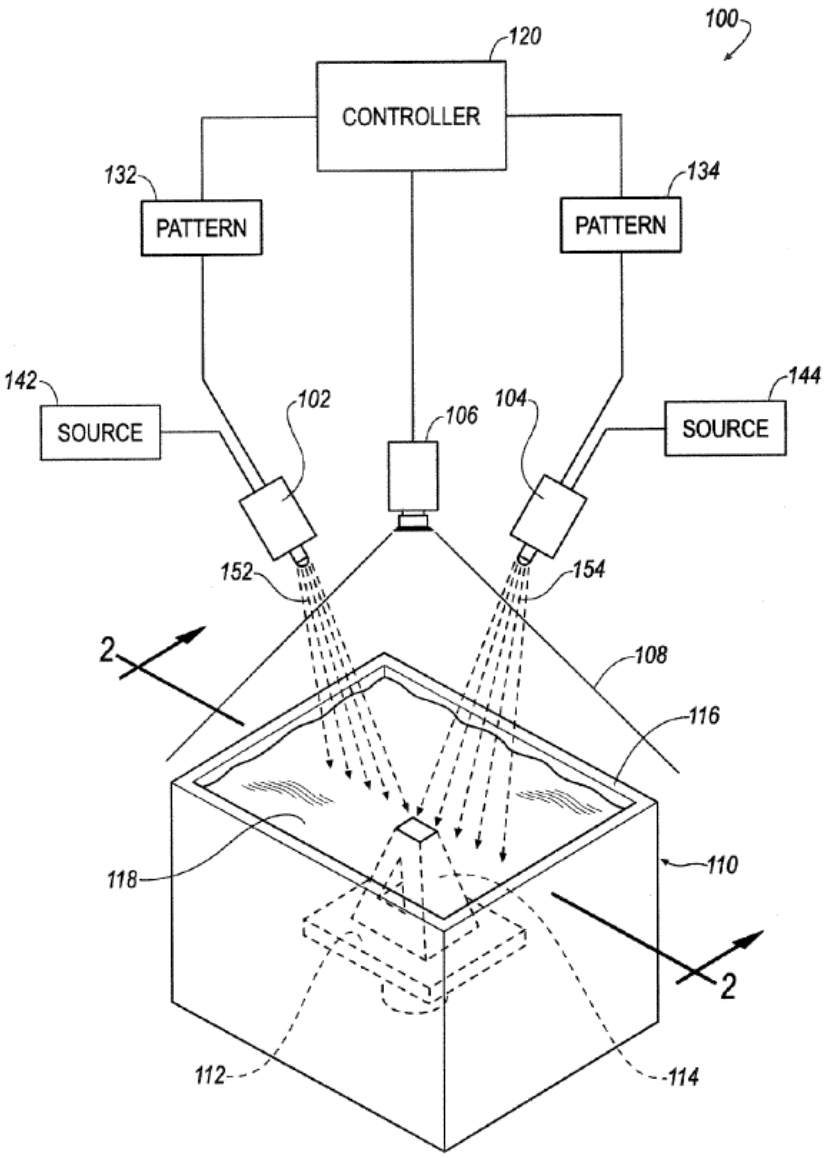


FIG. 1A

309. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(e) b. projecting a composite image onto a build area within a resin pool using the image projection system, wherein:

310. Shkolnik teaches projecting a composite image onto a build area within a resin pool using the image projection system. The image projectors of Shkolnik each project an image onto a reactive material, such as a container of photopolymerizable resin. Shkolnik (EX1004), 5:9-14. For example, Figure 1A of Shkolnik illustrates a system in which multiple image projectors or "pattern generators" (denoted as 102 and 104 in Figure 1A) each project an image or "pattern" (denoted as 152 and 154 in Figure 1A) onto a portion of a reactive material (denoted as 118 in Figure 1A) disposed within a container (denoted as 110 in Figure 1A), thereby forming a composite image (e.g., the complete image of the rabbit in Figure 7). Shkolnik also refers to such individual "patterns" as "sub-images." *See*, *e.g.*, *id.* at 33:59-63. Again, Figure 1A is reproduced above for convenience.

311. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(f) the image projection system is controlled by the image display subsystem;

312. Shkolnik teaches that the image projection system is controlled by the image display subsystem. Shkolnik teaches that its system can include various components and subsystems for controlling the image projection system and each of the image projectors of Shkolnik to adjust properties and alignment of a position of

each sub-image in the array of sub-images described by Shkolnik. Shkolnik specifically teaches a controller that interfaces with multiple pattern generators and an imager "for self-calibration at any time before, during, or after manufacture" such as "image correction mapping…to modify an image or bitmap for positional inaccuracies." *See*, *e.g.*, Shkolnik (EX1004), 7:10-22; 8:6-32; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators."). Such a "controller" is denoted as element 120 in Figure 1A, and such an "imager" is denoted as element 106 in Figure 1A (see reproduction of Figure 1A above for convenience). Additionally, Shkolnik teaches that the imager 106 "may be used for initial alignment and adjustment of pattern generators 102, 104 or for real-time, or near real-time, adjustment." *Id.* at 11:23-35.

313. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

(g) the composite image comprises a plurality of sub-images arranged in an array;

314. Shkolnik teaches the composite image comprises a plurality of sub-images arranged in an array. Shkolnik teaches a system having an image projection system that can include an array of image projectors that each project an image onto

a reactive material. Shkolnik (EX1004), 4:40-44; 5:9-14. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual patterns or "sub-images" provided by the individual image projectors or pattern generators (denoted as 712' and 712" in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). This figure is reproduced below for convenience.

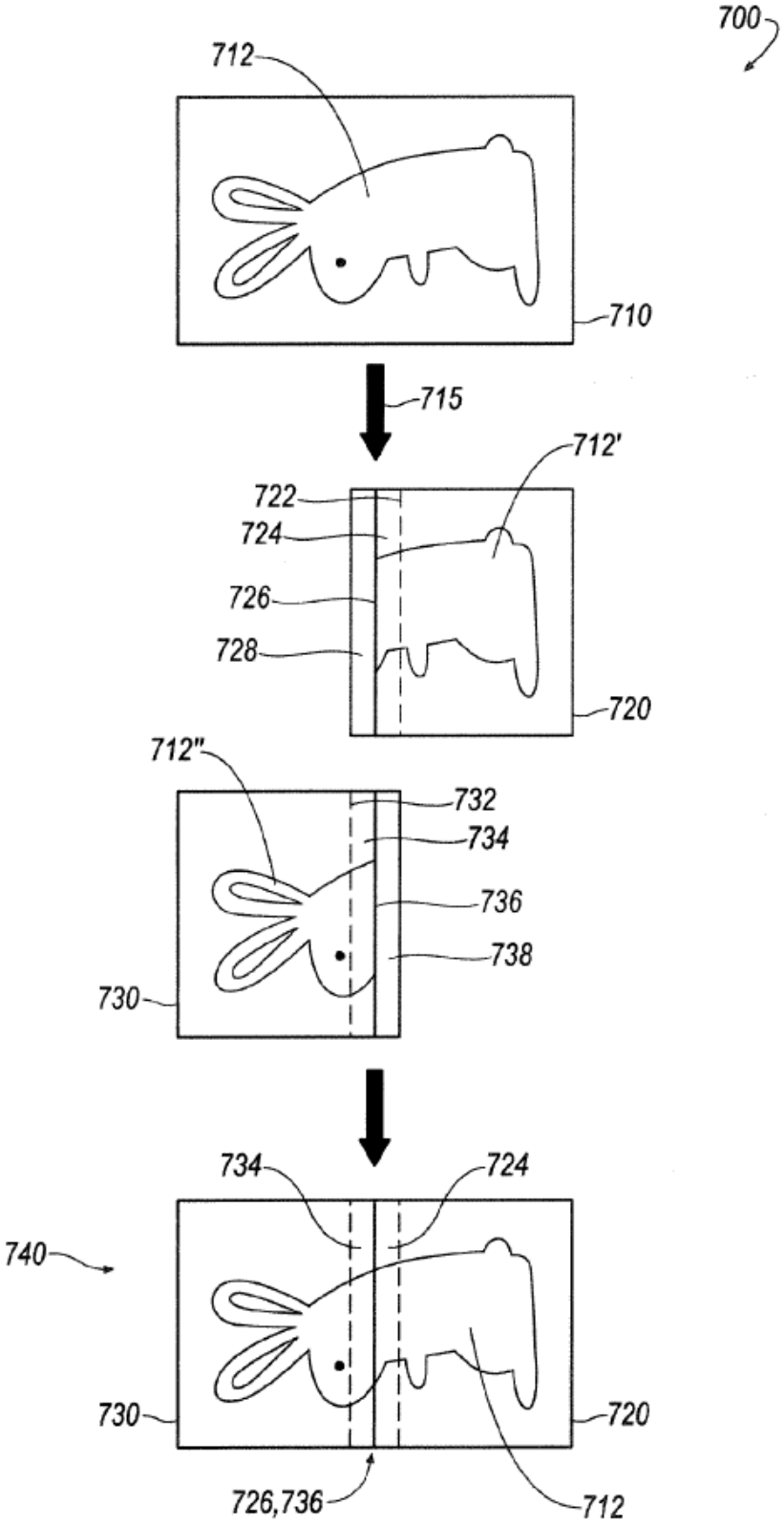

700
712
710
715
712'
722
724
726
728
720
712"
732
734
736
738
730
734
724
740
730
720
726,736
712

FIG. 7A

315. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the ’511 Patent.

(h) two or more adjacent sub-images in the array overlap at two or more sub-image edges; and

316. Shkolnik teaches that two or more adjacent sub-images in the array overlap at two or more sub-image edges. Shkolnik teaches that the images or patterns of an array of image projectors or pattern generators can overlap, including at their edges. Shkolnik (EX1004), 33:45-34:14. Such an overlap is illustrated, for example in Figure 4C and Figure 7A of Shkolnik. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual patterns “sub-images” provided by the individual image projectors or pattern generators (denoted as 712’ and 712” in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). The adjacent sub-images 712’ and 712” in Figure 7A overlap at two edges of the sub-images (e.g., at edges 722/726 and 732/736 in Figure 7A, forming overlap portions 728 and 738). These figures are reproduced below for convenience.

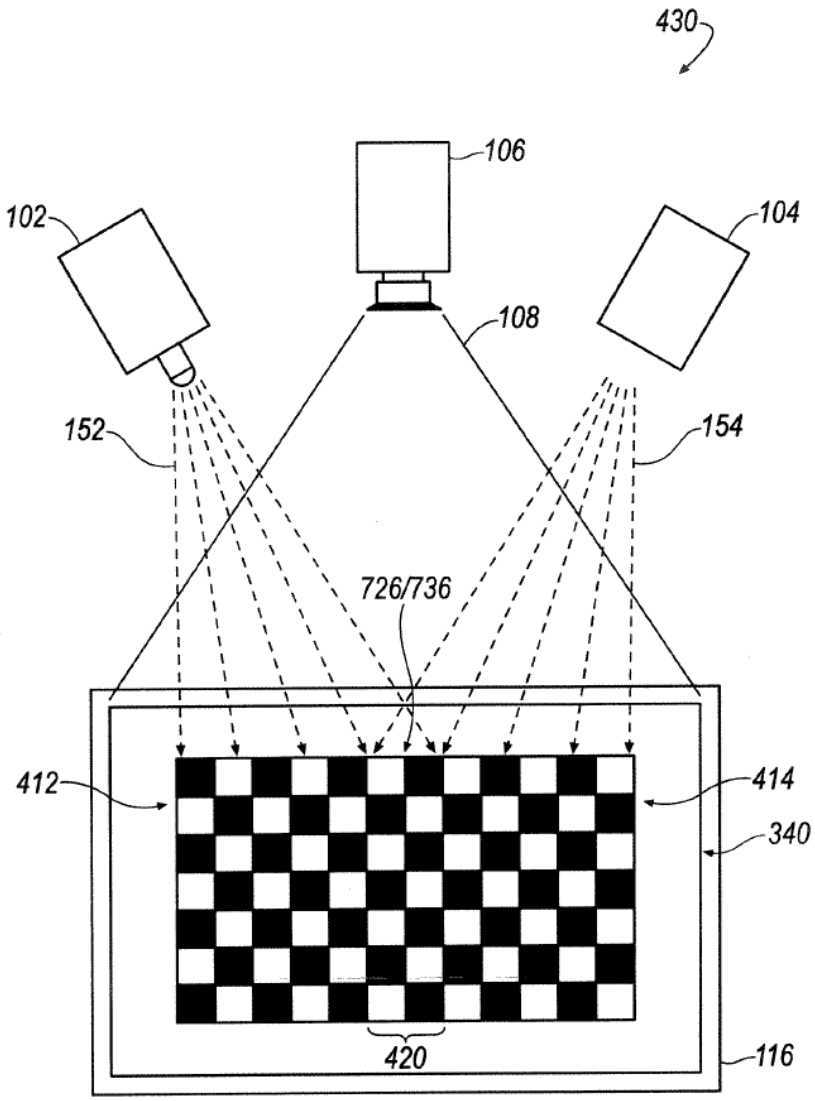


FIG. 4C

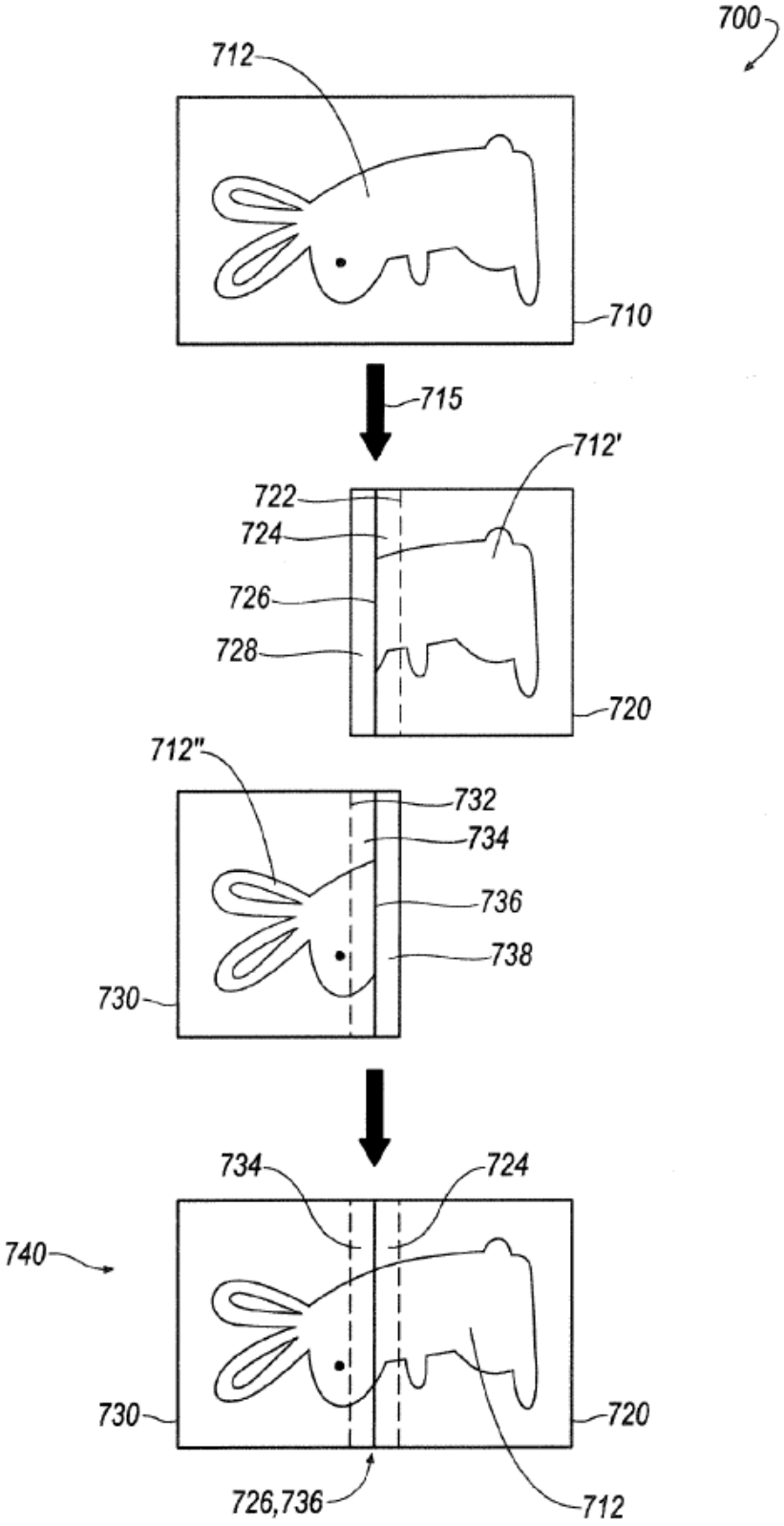

700
712
710
715
712'
722
724
726
728
720
712"
732
734
736
738
730
734
724
740
730
720
726,736
712

FIG. 7A

317. Therefore, it is my opinion that Shkolnik discloses this element of claim 1 of the ’511 Patent.

(i) each sub-image is projected onto a portion of the build area using one of the plurality of image projectors; and

318. Shkolnik teaches that each sub-image is projected onto a portion of the build area using one of the plurality of image projectors. The image projectors of Shkolnik each project an image onto a reactive material, such as a container of photopolymerizable resin. Shkolnik (EX1004), 5:9-14. For example, Figure 1A of Shkolnik illustrates teaches a system in which multiple image projectors or “pattern generators” (denoted as 102 and 104 in Figure 1A) each project an image or “pattern” (denoted as 152 and 154 in Figure 1A) onto a portion of a reactive material (denoted as 118 in Figure 1A) disposed within a container (denoted as 110 in Figure 1A). This figure is reproduced above for convenience.

319. Therefore, it is my opinion that Shkolnik discloses this element of claim 1 of the ’511 Patent.

(j) c. adjusting properties and aligning a position of each sub-image in the array using a set of filters comprising:

320. Shkolnik teaches adjusting properties and aligning a position of each sub-image in the array using a set of filters. Shkolnik teaches that pattern generators such as DLP devices produce “patterns” (e.g., denoted as 132 and 134 throughout

Shkolnik), and that such "patterns" can be "bitmaps (digital information), physical masks (physical patterns), electronic masks (e.g., LCD or transmissive active masks), or other types of information, media, or device(s) that define a pattern." See Shkolnik (EX1004), 10:44-46; 11:4-8. Moreover, Shkolnik teaches that the patterns or sub-images produced by an array of pattern generators (such as DLP devices) can be corrected or "fixed" in various ways, such as to provide positional compensation and intensity compensation. *See*, *e.g.*, *id.*, 14:51-53; 17:24-27. Moreover, Shkolnik teaches that such adjustment can occur within each pattern generator or applied to the pattern generators externally. *See*, *e.g.*, *id.*, 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators."). Thus, the properties of each sub-image are being adjusted.

321. As another example, Shkolnik teaches that adjustments can be made to correct for both linear and non-linear distortions. The corrections or adjustments may also be iterative, undertaken in sequence, or carried out simultaneously. Shkolnik describes such adjustments of sub-images using a combination or "set" of filters, masks, or "maps" in many, many places throughout the 83-page disclosure of Shkolnik (EX1004). *See*, *e.g.*, *id.*, 2:9-11 ("FIG. 1K [below] is an example of a generalized correction map generation system for use with the systems and methods

described herein."); 2:22-26; 2:36-38; 5:38-53; 10:7-13; 14:26-31; 14:51-56; 15:36-57; 17:18-31; 19:38-50; 20:2-11; 28:36-48; 32:40-63; Figures 1K, 1ME, 1MG, 1MFB, 1MGB, 1O, 1Q, 4A, 4B, 4C, and 6. Figure 1K is reproduced below for convenience.

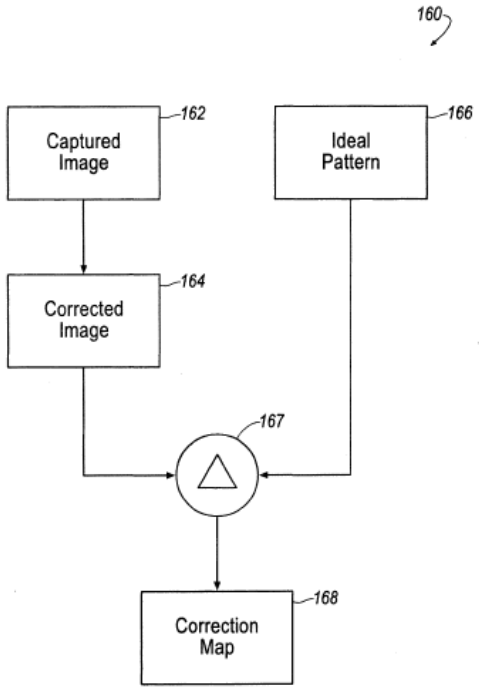


FIG. 1K

322. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

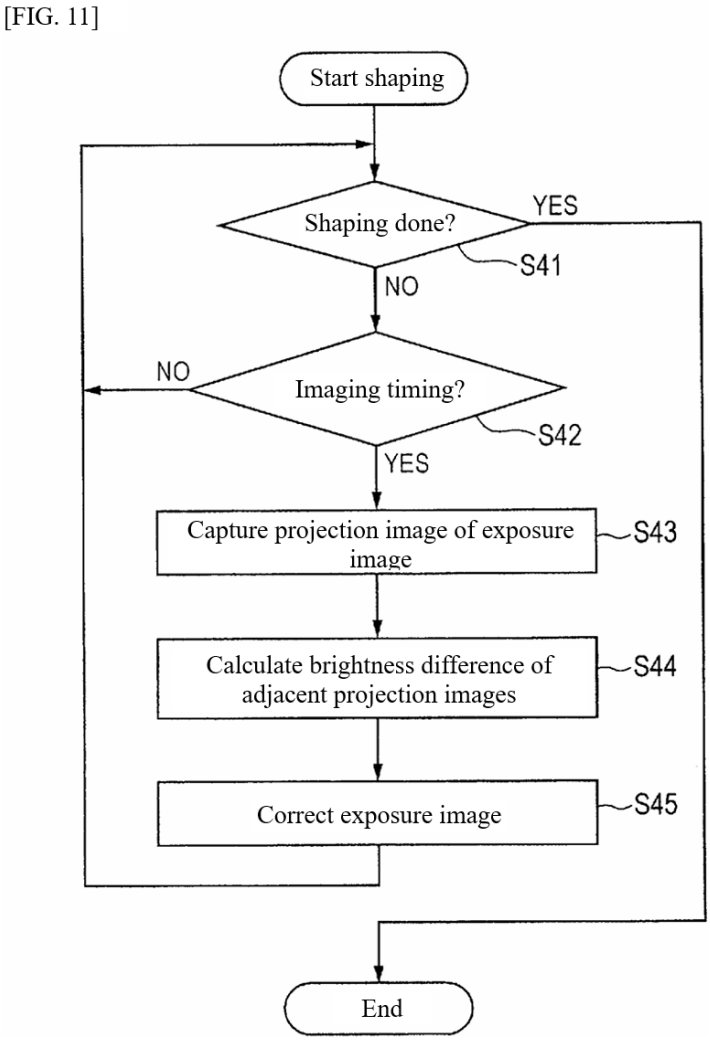
(k) an irradiance mask that normalizes irradiance;

323. Sekine teaches an irradiance mask that normalizes irradiance. One of the correction or adjustment mechanisms taught by Sekine is related to normalizing irradiance. Specifically, Sekine teaches that the "illumination" or "brightness" of an overall or composite image can be non-uniform, and that such lack of uniformity is undesirable. For instance, Sekine teaches that when multiple sub-images are stitched together to form a composite image, "gaps" or "streaks" may occur due to "brightness differences between adjacent projection images" or misalignment. Sekine (EX1005), [0070], [0099]. Moreover, Sekine teaches that brightness differences may be due to "performance differences" within the projection system (e.g., as related to the optics or light sources of the system). *Id.* at [0071].

324. Therefore, to address these variations, Sekine teaches a step of normalizing irradiance "to **eliminate** the brightness **difference between** adjacent projection images" and "make the illumination distribution **uniform**." *Id.* at [0070]-[0071]. Sekine further explains one way of doing so: "to ensure that the illuminance difference between adjacent projection images TG across the boundary is eliminated, the brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 is controlled to be the same." *Id.*, [0071]. Sekine also provides a flowchart (reproduced above) in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of adjustment means" for achieving uniform irradiance, whereby each

projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042].("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Figure 5 is reproduced above, and Figure 11 is reproduced below for convenience.

[FIG. 11]



325. Additionally, these teachings of Sekine are consistent with common knowledge in the field at the time of the filing of the '511 Patent. Practitioners within the digital display and projection community were well-familiar with the concept of

irradiance uniformity, and had access to prior art references (such as Sekine) that disclose irradiance uniformity, both generally as well as providing specific methods, techniques, and algorithms that would enable one to perform irradiance uniformity adjustment.

326. Therefore, it is my opinion that Sekine discloses this limitation of claim 1 of the ’511 Patent.

(l) a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool;

327. Shkolnik teaches a set of filters comprising a gamma adjustment mask that adjusts sub-image energy based on a reactivity of resin in the resin pool. Shkolnik teaches the assignment of an “intensity value” or level to each pixel or voxel of a sub-image. Shkolnik (EX1004), 9:47-51. For example, Shkolnik teaches that for an 8-bit system “intensity ranges of 0 to 255 are convenient.” *Id.* at 9:59-62. Moreover, Shkolnik teaches that “the time and intensity to achieve a particular depth of cure is material dependent,” with the result (explicitly taught by Shkolnik) that a given intensity value that provides a particular curing depth for a specific resin “may not be usable” for a different resin. *Id.* at 10:22-26; *see also id.* at 18:32-37 (“Note, however, that the percent intensity value assigned to a voxel is material dependent, and that there may not be a linear relation between them (e.g., the intensity values for 50% depth of **cure** may be **different** for each **reactive material**).”).

328. In addition, Shkolnik teaches that when a resin (such as "reactive material 118" in Shkolnik) "has a minimum intensity threshold for polymerization or partial-polymerization, the 'off' or zero (0) value intensity (e.g., brightness and/or 'on' time) may be determined **based on the reactive material threshold**." *Id.* at 9:51-55. For example, Shkolnik teaches that "correction" of a pattern for forming an object can be achieved by **mapping the intensity values to the resin reactivity**, resulting in **more accurate additive manufacturing**: "A detailed example of voxelized correction including intensity modification is shown below with respect to FIGS. 1MA-1MG. As discussed herein a voxel data may be expressed as a bitmap with intensities assigned for each pixel in the bitmap, the intensity providing **variable depth of cure for each voxel**." *Id.* at 18:37-42. As noted above on multiple occasions, this correction of a pattern for forming an object can occur at each pattern generator, which means the correction is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

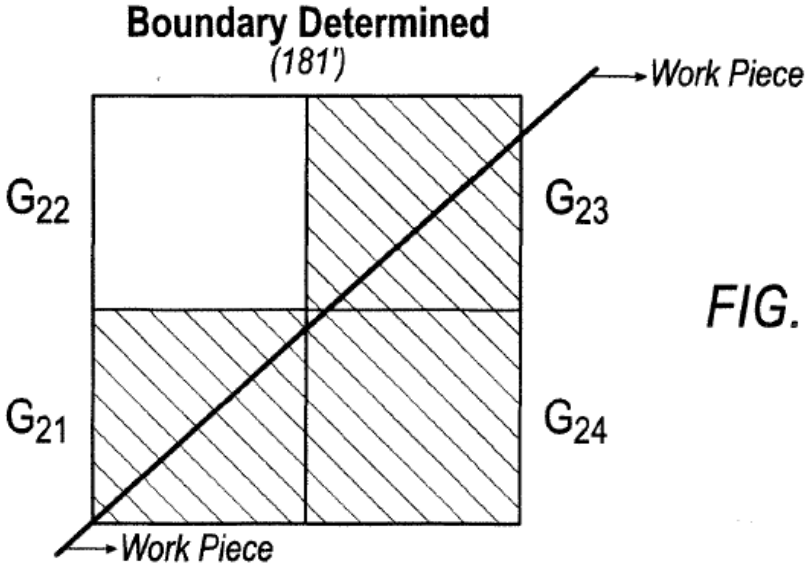


FIG. 1MBB

329. In sum, this discussion of gamma adjustment in Shkolnik is consistent with the POSITA's understanding of the ordinary and customary meaning of the term gamma adjustment in the '511 Patent as set out above. *See*, Section IV. E.2. ("[T]he specification provides that the purpose of the 'gamma correction filter' is to 'enable[] correct smoothing (and/or antialiasing) of pixels by mapping the pixel intensity range (e.g., 0-255) to the minimum and maximum reactivity characteristics of the pixel.'") (quoting '511 Patent at 12:9-12); *see also id.* ("The specification teaches that 'gamma corrections' are '[m]ethods for adjusting the curing time for a specific resin.' *Id*. at 6:3-5. The specification further teaches that such adjustments are need because 'different resin formulations . . . have different curing times.'") (quoting '511 Patent at 5:66-5:67).

330. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the ’511 Patent.

(m) a warp correction filter that provides geometric correction; and

331. Shkolnik teaches a set of filters comprising a warp correction filter that provides geometric correction. As stated above, Shkolnik teaches that pattern generators (such as DLP devices) must be adjusted for distortion, such as distortion caused by defects in micro-mirrors or other optical elements. *See*, *e.g.*, Shkolnik (EX1004), 7:23-37. Shkolnik specifically teaches that mechanical misalignment, misaligned or malformed lenses or mirrors, or changes in hardware caused by heating/cooling “may impart geometric distortion (e.g., where an expected straight line may be curved).” *Id.* at 7:23-31. Shkolnik specifically lists “distortion of a rectangular grid,” “barrel distortion,” and “pincushion (pillow) distortion” as possible types of geometric distortion, “which may be compensated for” by the system of Shkolnik. *Id.* at 7:32-37. Figure 5A of Shkolnik particularly illustrates an example of a “barrel distortion,” *Id.* at 32:64-66. Similarly, Figure 5B illustrates a “pincushion distortion,” and Figure 5C illustrates an example of “a nonlinear and skewed distortion.” *Id.* at 32:67-33:10. Figures 5A, 5B, and 5C of Shkolnik are reproduced below for convenience.

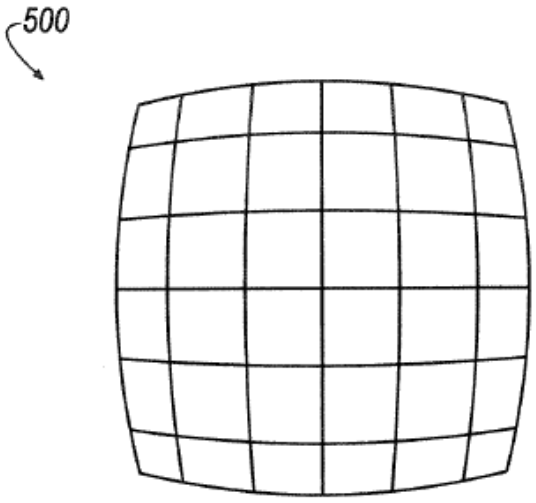


FIG. 5A

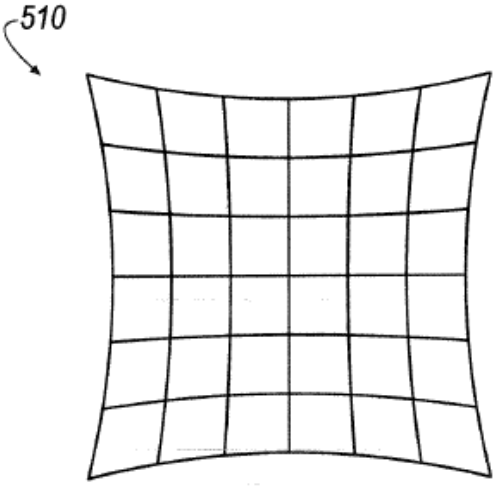


FIG. 5B

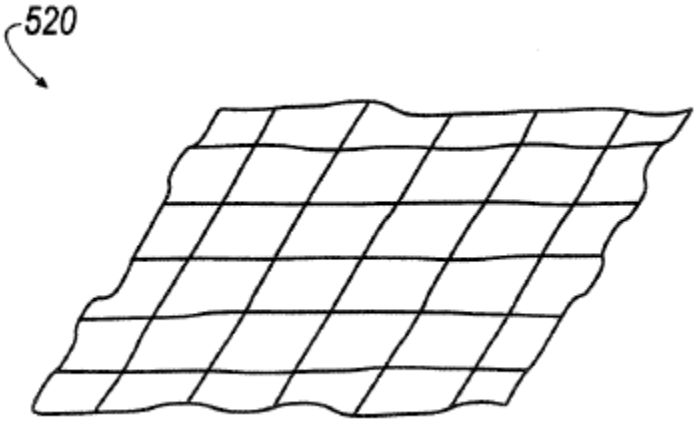


FIG. 5C

332. Shkolnik further teaches that each of these geometric distortion types is "commonly associated with optical systems" that include multiple pattern generators (e.g., DLP devices), such as pattern generators 102 and 104 described above. *Id.* at 32:64-33:10. Additionally, Shkolnik teaches that "[t]he above methods [of image adjustment/correction disclosed by Shkolnik] may be used to correct such distortion." *Id.* at 32:64-33:10. Shkolnik then provides a more detailed description and illustration of how to correct a pincushion distortion: namely, how "to transform the pincushioned output of pattern generators 102, 104 to a more usable output" by using "pattern correction methods 620" and "calibration patterns 612, 614." *Id.* at 33:18-45 and Figure 6. Figure 6 of Shkolnik (EX1004) shows calibration patterns 612, 614 being generated (e.g., from pattern generators 102, 104) as uncompensated patterns. Shkolnik teaches that using the methods of Shkolnik for pattern correction (denoted generically as element 620 in Figure 6), an "adjusted combined image 630 is provided that removes distortion from the system." *Id.* at 33:11-16. As noted above, this 'pattern correction' can occur at each pattern generator, which means that the correction is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators."). Figure 6 is reproduced below for convenience.

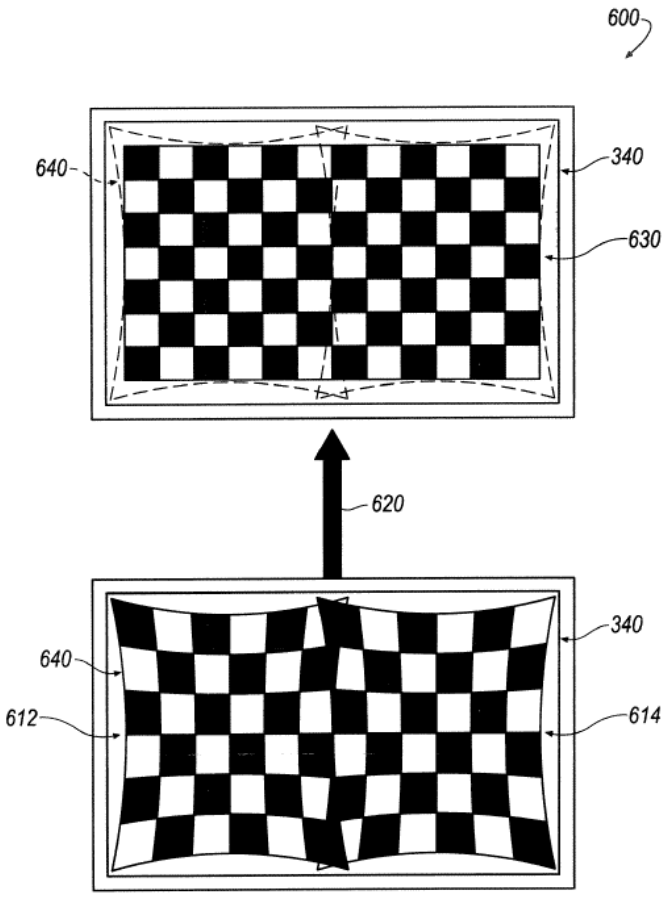


FIG. 6

333. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the ’511 Patent.

(n) an edge blending bar at one or more sub-image edges.

334. Shkolnik teaches a set of filters comprising an edge blending bar at one or more sub-image edges. As described above, an “edge blending bar” is just a name for using one or more edge blending techniques in an area of overlap in two or more sub-images. “Edge blending,” in the context of a multi-projector system, describes

the process or technique of managing areas of the composite projected image that are addressed by more than one projected image. These are the "overlap" areas. Additionally, it is my understanding that there is nothing technologically significant about the phrase "edge blending bars." Other terms such as "edge blending," "pixel blending," "image blending," or "stitching"—or no specific technical term at all—can be used to refer to the same thing—a zone of overlap in which one or more various edge-blending functions are performed.

335. As stated above, Shkolnik teaches a system having an image projection system that includes one or more image projectors or "pattern generators," such as one or more DLP devices. Shkolnik (EX1004), 4:40-44. The plurality of image projectors of Shkolnik each project an image onto a reactive material. *Id.* at 5:9-14. Moreover, Shkolnik teaches that the images or patterns can overlap, including at their edges. *Id.* at 33:45-34:14. Such overlap is illustrated, for example in Figure 4C and Figure 7A of Shkolnik. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual sub-images provided by the individual image projectors (denoted as 712' and 712" in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete image of the rabbit). The adjacent sub-images 712' and 712" in Figure 7A overlap at two edges of the sub-images (e.g., at edges 722/726 and 732/736 in Figure 7A, forming overlap portions 728 and 738). These figures are

reproduced below for convenience. With reference to Figure 7A, Shkolnik teaches that the complete image (e.g., the complete rabbit in Figure 7A) is divided in such a manner that the two sub-images 712' and 712" have overlap portions 728 and 738 between the two sub-images 712' and 712". *Id*. at 33:50-67. Per Shkolnik, the overlap regions "are used to provide a seamless region between the two [sub-images]." *Id.* at 34:2-4. However, Shkolnik expressly warns the reader that there is a "potential for over-exposure of reactive material" due to the overlap of the sub-images. *Id.* at 34:2-14.

336. To solve this problem, Shkolnik teaches an adjustment to the pixels at the edges of the sub-images can be made. Specifically, Shkolnik teaches that "the intensity of pixels from pattern generators 102, 104 that account for overlap pixel region 726, 736 may be reduced in intensity (e.g., 50% from each pattern generator 102, 104) to reduce over-exposure of reactive material 118 at overlap portions 728, 738." *Id.* at 34:10-14. Moreover, Shkolnik teaches that such adjustment can be performed in a dynamic manner: "Potential overlap regions 728, 738 allow for on-the-fly adjustment to image patterns 712', 712" during use that may be desirable to adjust for heat and other changes to the system that may introduce distortion." *Id.* at 34:35-38. Figure 7A is reproduced below for convenience.

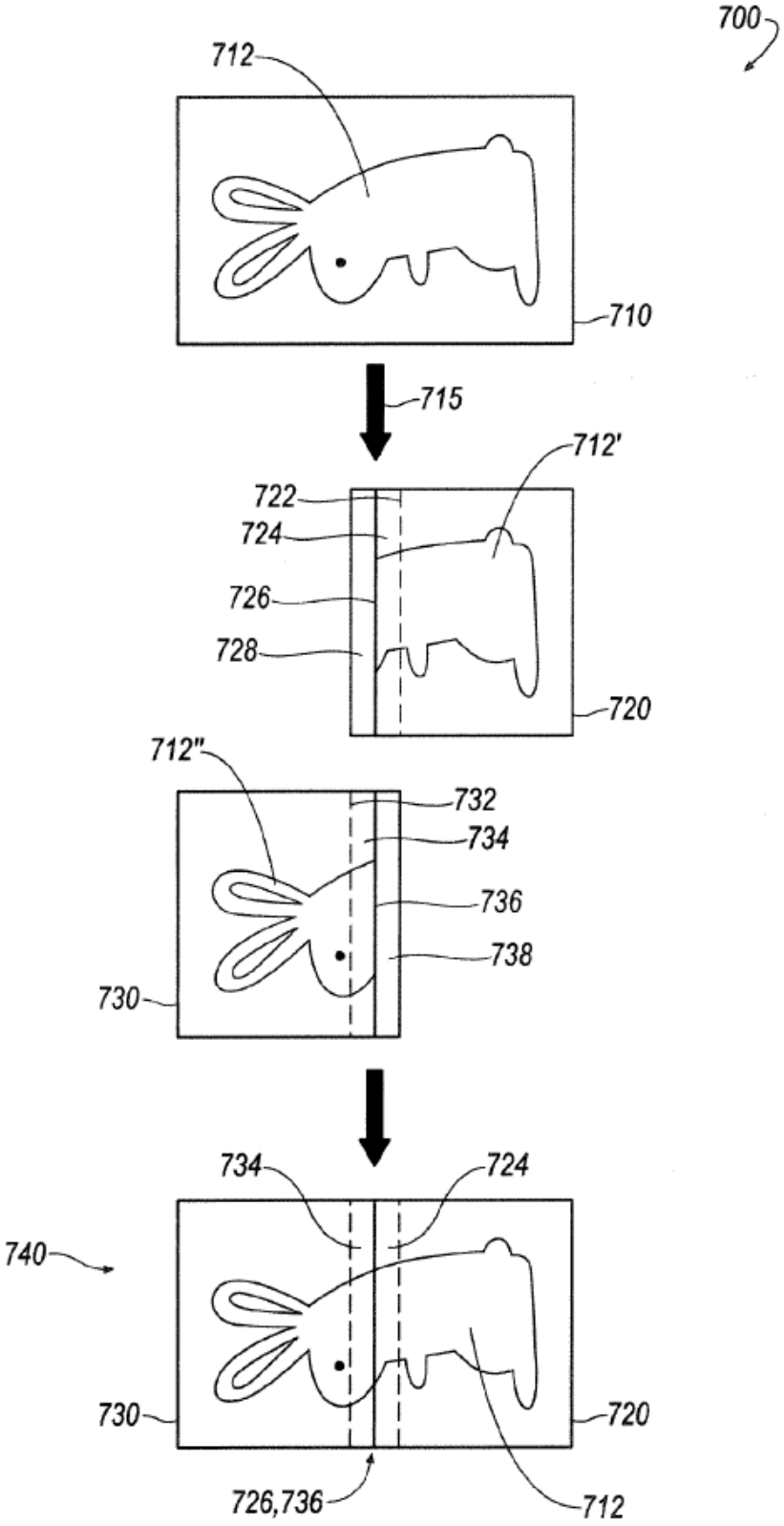

700
712
710
715
712'
722
724
726
728
720
712"
732
734
736
738
730
734
724
740
730
720
726,736
712

FIG. 7A

337. Shkolnik further teaches that if one or both of the pattern generators changes alignment during use, "the areas of potential overlap regions 728, 738 may be used to further adjust the projected image to maintain alignment," with the result that "overlap pixel regions 726, 736 may be moved within potential overlap regions 728, 723 and 724, 734 during operation." *Id.* at 34:38-43. As noted above, this adjustment can occur at each pattern generator, which means that the adjustment is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

338. As noted above, this teaching of Shkolnik is the same as that of the '511 Patent, which teaches, for instance, an "edge blending bar" that accounts for overlap in projection images by, for example, "fad[ing] out" "perimeters of adjacent sub-images" so that "the transition between the adjacent sub-images can be made less noticeable." '511 Patent (EX1001), 9:6-8; *id.* at 10:30-35.

339. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 1 of the '511 Patent.

340. The following dependent claims are also rendered obvious.

2. Claim 2 – The method of claim 1, wherein the image display subsystem controls the image projection system and each of the image projectors using digital light processing.

341. Shkolnik teaches that the image display subsystem controls the image projection system and each of the image projectors using digital light processing. As discussed above with respect to element 1[f] of claim 1, Shkolnik teaches that the image display subsystem controls the image projection system. Specifically, Shkolnik teaches that pattern generators such as DLP devices produce "patterns" (e.g., denoted as 132 and 134 throughout Shkolnik). As additionally discussed above, Shkolnik teaches that its system can include various components and subsystems for controlling the image projection system and each of the image projectors of Shkolnik to adjust properties and alignment of a position of each sub-image in the array of sub-images described by Shkolnik. For example, Shkolnik teaches a controller that interfaces with multiple pattern generators and an imager "for self-calibration at any time before, during, or after manufacture" such as "image correction mapping…to modify an image or bitmap for positional inaccuracies." *See*, *e.g.*, Shkolnik (EX1004), 7:10-22; 8:6-32. Such a "controller" is denoted as element 120 in Figure 1A, and such an "imager" is denoted as element 106 in Figure 1A (see reproduction of Figure 1A above). Additionally, Shkolnik teaches that the imager 106 "may be used for initial alignment and adjustment of pattern generators 102, 104 or for real-time, or near real-time, adjustment." *Id.* at 11:23-35.

342. With respect to "digital light processing" ("DLP"), Shkolnik specifically teaches that the pattern generators may be DLP devices. *See id.* at 7:56-

67 ("Examples of pattern generators may ***include Digital Light Processing technology (DLP) from Texas Instruments®*** or …"); *see also id.* at 8: 63-65 ("In this example, pattern generators 102, 104 may be configured as ***Digital Light Projector (DLP) devices*** that include micro-mirrors to create patterns 132, 134."); and *id*. at 6:43-47 ("In an example where a grayscale value is assigned to a pixel **and a DLP® type pattern generator** is used, the DLP® micro-mirror may be moved so as to expose the pixel at the build surface in an alternating manner to provide an overall grayscale value.").

343. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 2 of the '511 Patent.

3. Claim 3 – The method of claim 1, wherein the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors.

344. Sekine teaches that the irradiance mask additionally adjusts the energy across the build area to compensate for non-uniformities in optics of the plurality of image projectors**.** Sekine discloses multiple types of adjustments of sub-images, including, e.g., "illuminance correction control" or "alignment control." *See*, *e.g.*, Sekine (EX1005), [0042], [0073]. It is of course well understood that non-uniformities in the optics of projectors can cause illuminance and/or alignment

errors, and the correction of such errors is discussed at great length in Sekine (EX1005), including in paragraphs [0108]-[0111].

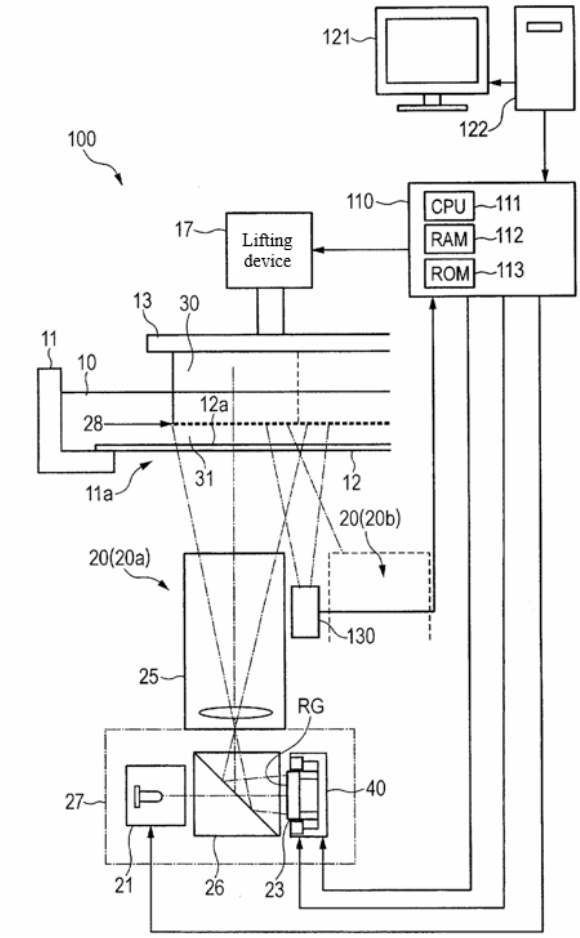
345. As another example, Sekine teaches that various actuators of the system of Sekine (e.g., actuators denoted as 41-48 and 51-53) can be used to adjust optical elements of individual projectors to correct for displacement and angle errors, for instance. *See* Sekine (EX1005), Figure 2 and [0038]-[0041] (reproduced below for convenience).

> [0038]
> (Alignment Mechanism)
> FIGS. 4A to 4C are descriptive diagrams of the alignment mechanism of the image forming element 23. FIG. 4A is a side view, FIG. 4B is a plan view, and FIG. 4C is a front view. As illustrated in FIGS. 4A to 4C, an image display unit 40 holds the image forming element 23 on an inner side of a box-shaped housing 40f so as to be movable by actuators 41 to 48 and 51 to 53 using piezoelectric elements. The actuators 41 to 48 and 51 to 53 expand and contract according to an applied direct current voltage.
>
> [0039] The actuators 41 to 48, which are one example of adjustment means, can adjust the position of the image forming element 23 in a plane that intersects the projection optical axis of the exposure image. The control unit 110 can adjust the relative position at the boundary region KR of the two adjacent projection images TG by controlling the actuators 41 to 48. The actuators 41, 42, 43, and 44 can move the image forming element 23 in a Y direction by combining their respective expansions and contractions. The actuators 45, 46, 47, and 48 can move the image forming element 23 in an X direction by combining their respective expansions and contractions. The actuators 41, 42, 43, 44, 45, 46, 47, and 48 can rotate the image forming element 23 in a XY plane to adjust the angle, by combining their respective expansions and contractions.

[0040] The actuators 51, 52, and 53 can move the image forming element 23 in a Z direction by expanding and contracting together. The actuators 51, 52, and 53 can adjust an angle of the image forming element 23 in an XZ plane and a YZ plane by combining their respective expansions and contractions.

[0041] The control unit (110: FIG. 2-below), which is one example of control means, processes the captured image taken by the camera 130 to calculate the amount of pixel displacement in two adjacent projection images and operates the actuators 41 to 48 to offset the displacement amount.

[FIG. 2]



346. Therefore, it is my opinion that Sekine discloses this limitation of claim 3 of the ’511 Patent.

4. Claim 4 – The method of claim 1, wherein the gamma adjustment mask comprises a logarithmic relationship between a cure depth of the resin and energy per unit area in the build area.

347. As stated above, Shkolnik teaches a gamma adjustment mask. As also stated above, **any** gamma adjustment necessarily includes accounting for the unique chemistry and physics of a specific photocurable resin (e.g., with reference to that resin's working curve). See Shkolnik (EX1004), 10:22-26 ("the time and intensity to achieve a particular depth of cure is material dependent"). Moreover, for **any** photocurable resin, the relationship between a cure depth of the resin and energy per unit area is **always** logarithmic.

348. Indeed, the logarithmic relationship between cure depth and energy per unit area is literally a textbook principle that has been well known in the field for decades, as evidenced by Jacobs (EX1007), e.g. at page 204, inherent to all photocurable resins of the type described by Shkolnik.

349. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 4 of the '511 Patent.

5. Claim 5 – The method of claim 1, wherein the resin is selected from the group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations thereof.

350. Shkolnik teaches that the resin is selected from a group consisting of acrylates, epoxies, methacrylates, urethanes, silicone, vinyls, and combinations

thereof. Specifically, Shkolnik teaches the use of "a material comprising a resin containing at least one ethylenically unsaturated compound (including but not limited to (meth)acrylate monomers and polymers) and/or at least one epoxy group." Shkolnik (EX1004), 5:17-24. Additionally, Shkolnik teaches that "a curable silicone composition" may be used as a reactive material. *Id.* at 4:65-5:8.

351. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 5 of the '511 Patent.

6. Claim 6 – The method of claim 1, wherein the edge blending bar comprises a blending distance and a function selected from the group consisting of: linear, sigmoid and geometric.

352. Shkolnik teaches that the edge blending bar comprises a blending distance and a function selected from a group consisting of linear, sigmoid and geometric. As described above, Shkolnik teaches that sub-images or patterns can overlap, including at their edges. Shkolnik (EX1004), 33:45-34:14. Additionally, Shkolnik teaches that the "overlap regions" or "overlap portions" (e.g., denoted as 726 and 736, or 728 and 738 in Shkolnik)—which are the "blending distance"—can have any desired width, such as "from one pixel to any number of pixels to generate any width of overlap portions." *Id.* at 34:4-7. Edge blending or "fading" of overlap regions is described in significant detail by Shkolnik, such as with reference to Figures 4 and 7 (see discussion above regarding claim 1). Moreover, with reference once again to Figure 7, Shkolnik teaches that the "fading effect" created by the edge

blending of Shkolnik can "use a linear interpolation algorithm to reduce intensity such that when overlapped, the combined intensity is the same as the original image." *Id.* at 34:53-64.

353. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 6 of the '511 Patent.

7. Claim 7 – The method of claim 1, wherein the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured.

354. Shkolnik teaches that the edge blending bar adjusts the one or more sub-image edges based on at least one layer boundary location within an object being manufactured. As an initial matter, a POSITA would understand that locations adjusted by the edge blending bar are "within an object being manufactured." As discussed above with respect to the "edge blending bar" in claim 1, the term—or no specific technical term at all—can be used to refer to a zone of overlap in which one or more various edge-blending functions are performed. The zones are necessarily within the object being manufactured, as other areas (*i.e.*, where an object is not being manufactured), do not need to be blended in any manner and generally correspond to a zero irradiance (*i.e.*, no solidification of resin should occur at such a location). In this regard, it is clear from the context of Shkolnik that the locations are "within an object being manufactured," since the whole process is "for

manufacturing" and for "manufacture of large components." *See* Shkolnik (EX1004), 4:22-4:34.

355. Additionally, as further discussed above, Shkolnik teaches the following regarding boundaries:

> In an example using the original bitmap's pixel information, the boundary of the part may be reconstructed for later use in the geometric correction method. Moreover, using the bitmaps threshold value (in this example 40%), the **boundary of the component** may be reconstructed in a relatively accurate manner for later correction. For example, in FIG. 1MBB, t**he boundary is determined to be a smooth surface, rather than follow the jagged edge that would otherwise be determined by pixels G21 and G23.** The component boundary may be estimated as being nearly through the center of each outer boundary pixel (e.g., G21 and G23) and may also be influenced by neighboring pixels to estimate a **smooth surface**. Here, the component boundary is estimated through nearly the middle of pixels G21, G23 because the "on" threshold **for each pixel is 40%**. Other methods may be applied, however, **using boundary estimation (rather than using the original jagged edge determined by the original bitmap pixels) may provide for improved results** using the geometric correction methods.

Id. at 26:15-33.

356. As stated above, Shkolnik teaches that the images or patterns generated by the pattern generators can overlap, including at their edges. *Id.* at 33:45-34:14. Such overlap is illustrated, for example in Figure 4C and Figure 7A of Shkolnik. Additionally, as shown in Figure 7A, Shkolnik teaches that the individual sub-images provided by the individual image projectors (denoted as 712' and 712" in Figure 7A, referring to two portions of an image of a rabbit) can together form an overall or composite image (denoted as 712 in Figure 7A, referring to the complete

image of the rabbit). The adjacent sub-images 712' and 712" in Figure 7A overlap at two edges of the sub-images (e.g., at edges 722/726 and 732/736 in Figure 7A, forming overlap portions 728 and 738). These figures are reproduced above with respect to claim 1 for convenience. With reference to Figure 7, Shkolnik teaches that the complete image (e.g., the complete rabbit in Figure 7) is divided in such a manner that the two sub-images 712' and 712" have overlap portions 728 and 738 between the two sub-images 712' and 712". *Id*. at 33:50-67. Per Shkolnik, the overlap regions "are used to provide a seamless region between the two [sub-images]," specifically at edges. *Id.* at 34:2-4.

357. To solve the problem of intensity overlap at such boundary locations, Shkolnik teaches an adjustment to the pixels at the sub-images edges can be made. Specifically, Shkolnik teaches that "the intensity of pixels from pattern generators 102, 104 that account for overlap pixel region 726, 736 may be reduced in intensity (e.g., 50% from each pattern generator 102, 104) to reduce over-exposure of reactive material 118 at overlap portions 728, 738." *Id.* at 34:10-14. Moreover, Shkolnik teaches that such adjustment can be performed in a dynamic manner: "Potential overlap regions 728, 738 allow for on-the-fly adjustment to image patterns 712', 712" during use that may be desirable to adjust for heat and other changes to the system that may introduce distortion." *Id.* at 34:35-38. Shkolnik thus adjusts the one or more sub-image edges based on at least one layer boundary location, which are

within an object being manufactured. Further, as noted above, this adjustment can occur at each pattern generator, which means that the adjustment is occurring at least at the sub-image level. *Id.* at 31:51-53; *see also id.* at 7:18-22 ("Note that while the image correction mapping is generally shown and described herein as being external to the pattern generators, the systems and methods, in whole or in part, may also be integrated with the pattern generators.").

358. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 7 of the '511 Patent.

8. Claim 8 – The method of claim 1, further comprising a system controller that synchronizes exposure control of the plurality of image projectors with each other.

359. Shkolnik teaches a system controller that synchronizes exposure control of the plurality of image projectors with each other. As discussed above, Shkolnik discusses use of the pattern generators to simultaneously project multiple sub-images. For example, Shkolnik discusses that "In general, an application of the system and method described herein may ***use a pattern generator*** to build a three-dimensional object by exposing a reactive material (discussed below as e.g., a polymerizable material) to electromagnetic radiation." Shkolnik (EX1004), 4:48-52. Shkolnik discusses a "controller 120" that "receives and sends patterns 132, 134 to pattern generators 102, 104 that selectively produce patterns 132, 134 to produce a work piece 114," where components work "**with controller 120** and **pattern**

generators 102, 104 to produce a solid uninterrupted component." *Id.* at 8:10-17. It would be clear to a POSITA reading Shkolnik that the multiple pattern generators discussed in Shkolnik may be synchronized "as work piece 114 is built layer by layer using pattern generators 102, 104." *See* Shkolnik (EX1004), 35:33-35.

360. Therefore, it is my opinion that Shkolnik discloses this limitation of claim 8 of the '511 Patent.

9. Claim 14 – The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image.

361. Sekine teaches that the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image such that the composite image has a uniform irradiance range across the composite image. As discussed above, Sekine teaches splitting of an exposure image into multiple (*e.g.*, four) sub-images that "form the projection image." *See* Sekine (EX1005), [0043]. As discussed above, Sekine teaches that the "illumination" or "brightness" of an overall or composite image can be non-uniform, and that such lack of uniformity is undesirable. Sekine teaches that when multiple sub-images are stitched together to form a composite image, "gaps" or "streaks" may occur due to "brightness differences between adjacent projection images" or misalignment. *Id.* at

[0070], [0099]. To address these variations, Sekine teaches a step of normalizing irradiance "to eliminate the brightness difference between adjacent projection images" and "make the illumination distribution **uniform**." *Id.* at [0070]-[0071]. Sekine further explains one way of doing so: "to ensure that the illuminance difference between adjacent projection images TG across the boundary is eliminated, the brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 is controlled to be the same." *Id.* at [0071]. As discussed above, Sekine provides a flowchart (**above**) in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of adjustment means" for achieving uniform irradiance, whereby each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042].("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Sekine specifically discusses that "it is necessary to correct positional displacement between adjacent projection images **and to make the light distribution uniform**." *See id.* at [0035]. Thus, a POSITA would clearly understand that the adjustments being made—specifically to control irradiance to be the same at a sub-image level—would make uniform the irradiance across the composite image as a whole.

362. Therefore, it is my opinion that Sekine discloses the limitations of claim 14 of the ’511 Patent.

10. Claim 15 – The method of claim 1, wherein the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity.

363. Sekine teaches that the adjusting properties and aligning the position of each sub-image in the array further comprises applying the irradiance mask to each sub-image to normalize irradiance non-uniformities within the image projection system arising from a projector-based spatial energy non-uniformity. By “projector-based spatial energy non-uniformity,” a POSITA would understand the ’511 Patent to mean non-uniformities of irradiance energy caused by a projector, for example, “non-uniformities in the projector optics and/or optical path.” *See* ’511 Patent (EX1001), 11:50-52.

364. These non-uniformities are exactly the same as those accounted for in Sekine. As discussed above, it is well understood that non-uniformities in the optics of projectors can cause illuminance and/or alignment errors, and the correction of such errors is discussed at great length in Sekine, including in paragraphs [0108]-[0111]. Sekine also teaches that various actuators of the system of Sekine (e.g., actuators denoted as 41-48 and 51-53) can be used to adjust optical elements of

individual projectors to correct for displacement and angle errors, for instance. *See* Sekine (EX1005), Figure 2 and [0038]-[0041] (reproduced above for convenience).

> [0038]
> (Alignment Mechanism)
> FIGS. 4A to 4C are descriptive diagrams of the alignment mechanism of the image forming element 23. FIG. 4A is a side view, FIG. 4B is a plan view, and FIG. 4C is a front view. As illustrated in FIGS. 4A to 4C, an image display unit 40 holds the image forming element 23 on an inner side of a box-shaped housing 40f so as to be movable by actuators 41 to 48 and 51 to 53 using piezoelectric elements. The actuators 41 to 48 and 51 to 53 expand and contract according to an applied direct current voltage.
>
> [0039] The actuators 41 to 48, which are one example of adjustment means, can adjust the position of the image forming element 23 in a plane that intersects the projection optical axis of the exposure image. The control unit 110 can adjust the relative position at the boundary region KR of the two adjacent projection images TG by controlling the actuators 41 to 48. The actuators 41, 42, 43, and 44 can move the image forming element 23 in a Y direction by combining their respective expansions and contractions. The actuators 45, 46, 47, and 48 can move the image forming element 23 in an X direction by combining their respective expansions and contractions. The actuators 41, 42, 43, 44, 45, 46, 47, and 48 can rotate the image forming element 23 in a XY plane to adjust the angle, by combining their respective expansions and contractions.
>
> [0040] The actuators 51, 52, and 53 can move the image forming element 23 in a Z direction by expanding and contracting together. The actuators 51, 52, and 53 can adjust an angle of the image forming element 23 in an XZ plane and a YZ plane by combining their respective expansions and contractions.
>
> [0041] The control unit (110: FIG. 2-below), which is one example of control means, processes the captured image taken by the camera 130 to calculate the amount of pixel displacement in two adjacent projection images and operates the actuators 41 to 48 to offset the displacement amount.

365. As discussed above, Sekine provides a flowchart (**above**) in Figure 11 for such "illuminance correction control," describing adjusting the light source for **each projector** as "one example of adjustment means" for achieving uniform irradiance, whereby each projector is projecting a sub-image within the boundary allotted to that projector—meaning that adjustment is occurring at the sub-image level. *Id.* at [0042]. ("(Alignment Control) FIG. 5 is a schematic diagram of the projection region of the projector."). Sekine specifically discusses that "it is necessary to correct positional displacement between adjacent projection images ***a*nd to make the light distribution uniform**." *See id.* at [0035]. Indeed, Sekine explicitly states that the brightness gradation is controlled "to make the illumination distribution uniform," in the same paragraph where Sekine discusses that there may be "illumination differences" that "the following are conceivable: (1) **performance differences** of the projection optical system 25 and (2) **performance differences of the light source 21.**" Thus, a POSITA would clearly understand that the adjustments being made—specifically to control irradiance to be the same at a sub-image level—would correct such differences between light sources or the performance difference of the projection optical system (*i.e.*, the "projector-based spatial energy non-uniformity" of a projector).

366. Therefore, it is my opinion that Sekine discloses the additional limitations of claim 15 of the '511 Patent.

B. Motivation to Combine Shkolnik with Sekine and Reasonable Expectation of Success

367. Each of the prior art references addressed above in Ground III are directed towards improving printing resolution of additive manufacturing systems that use light projection to cure photoactive materials such as photocurable polymer resins.

368. For the purposes of this ground (Ground III), I understand that Petitioner is relying on Sekine to meet this limitation together with **an alternative claim construction to their primary claim construction position.** Specifically, Petitioner's alternative position applies in circumstances where the Panel both **(a) adopts a much narrower construction** of the irradiance mask filter limitation, **and (b) further concludes** that Shkolnik may not disclose the limitation as narrowly construed. In these circumstances (as unlikely as they may be), [22] Shkolnik would be predictably combined with Sekine to arrive at the claimed invention. Several reasons support this conclusion.

369. First, the references are both directed towards the same purposes and field of endeavor—*i.e.*, improving efficiency and accuracy in the formation of a 3D printed product formed by light projection. Given the nature of the problem and

[22] I understand that this is unlikely because courts afford a heavy presumption to the ordinary and customary meaning of a claim limitation, here, "an irradiance mask configured to normalize irradiance."

design needs in the industry to improve the precision and accuracy of 3D products, it would be natural for a POSITA to look toward similar references with similar purposes to solve well-known problems in the field.

370. Additionally, there are no teachings in the references that would disparage or teach away from a combination of the references. Shkolnik teaches a system that is used for increasing accuracy in the making of 3D components using a multiple pattern generator system.[23] In much the same way as the '511 Patent, Shkolnik discloses techniques to address inaccuracies in 3D printing—specifically in the context of "where a pattern generator provides an image to a reactive material for selective hardening." *Id*. at 4:40-43. Shkolnik teaches that such pattern generators "typically have linear and nonlinear distortions that cause inaccuracies in the resulting part . . . [and the] inaccuracies may be surface defects or more serious flaws that may cause the part to be structurally defective." *Id*. at 4:44-48.

371. As addressed above in Ground III, Shkolnik teaches at least three of the four techniques (filters) used to correct inaccuracies (gamma adjustment, warp correction, and edge blending).

372. Sekine, too, teaches a system that is used for increasing accuracy in the making of 3D articles. And like Shkolnik, a purpose Sekine is to address

[23] A pattern generator in the context of Shkolnik is an image projector/light modulator as used in the '511 Patent.

inaccuracies within a 3D printing system. Specifically, Sekine teaches that the "illumination" or "brightness" of an overall or composite image can be non-uniform, and that such lack of uniformity is undesirable. Sekine (EX1005), [0070], [0099]. Moreover, Sekine teaches that brightness differences may be due to "performance differences" within the projection system (e.g., as related to the optics or light sources of the system). *Id.* at [0071]. Such degradation is also addressed in Section III.B.1. ("Sources of electrical power and sources of light can likewise fail or degrade over time, which may affect all of the mirrors of a given DMD at the same time.").

373. Further, Sekine teaches a step of normalizing irradiance "to eliminate the brightness difference between adjacent projection images" and "make the illumination distribution **uniform**." *Id.* at [0070]-[0071]. Sekine further explains one way of doing so: "to ensure that the illuminance difference between adjacent projection images TG across the boundary is eliminated, the brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 is controlled to be the **same**." *Id.* at [0071]. Sekine also provides a flowchart in Figure 11 for such "illuminance correction control," describing adjusting the light source for each projector as "one example of adjustment means" for achieving uniform irradiance. Accordingly, Sekine not only addresses the well-known problem in the field but

teaches a method to address that problem making it an option for the POSITA to adopt in relation to Shkolnik.

374. Second, and related to the preceding paragraphs—and as I understand the 'motivation to combine' analysis under U.S. patent law—where a technique has been used to **improve one device** and it would improve a similar device in the same way, such teachings provide a basis to combine the references. This is precisely the case here with, for example, Sekine's disclosures in paragraphs [0070]-[0071] summarized above—and how that same technique could be used in the same way to improve Shkolnik to arrive at the claimed invention. More specifically, while both references are directed towards overall similar purposes, the specific technique stated in Sekine—to address variations in irradiance—could be readily implemented in Shkolnik. As would be recognized by the POSITA, the specific technique(s) of ensuring that the "brightness gradation (duty ratio) of each pixel in the plane of the image forming element 23 is controlled to be the **same**" is one technique taught in Sekine that the POSITA would readily adopt to further improve Shkolnik.

375. Adopting the technique of Sekine is consistent with ensuring heightened fidelity with the CAD drawings or other digital images or files on which the three-dimensional article is based—making the combining of the references a

logical one because it would improve a similar device (i.e., Shkolnik) in the same way as that technique improves Sekine.

376. Moreover, the combination of the references would lead to a reasonable expectation of success. Combining Shkolnik with Sekine would simply involve applying known techniques (i.e., normalizing irradiance in Sekine) to a known device ready for improvement (Shkolnik's multi-projector 3D printing system) to yield predictable results (improved precision and accuracy in a 3D product). A POSITA would have had a reasonable expectation of success in the combination because Shkolnik already discloses at least three of the four techniques typically used in achieving heightened precision and accuracy in 3D product development—and Sekine discloses the use of normalizing irradiance, which was well-known in the art for correcting brightness differences due to "performance differences" within the projection system (e.g., as related to the optics or light sources of the system). Sekine (EX1005), [0071].

377. A POSITA thus would have had a reasonable expectation that the features of Shkolnik and Sekine could be combined successfully. In the combination, the individual features of Shkolnik and the individual features of Sekine would **operate exactly as they are expected to function** (individually and in combination) to **achieve predictable results** that would be expected by those persons skilled in the art.

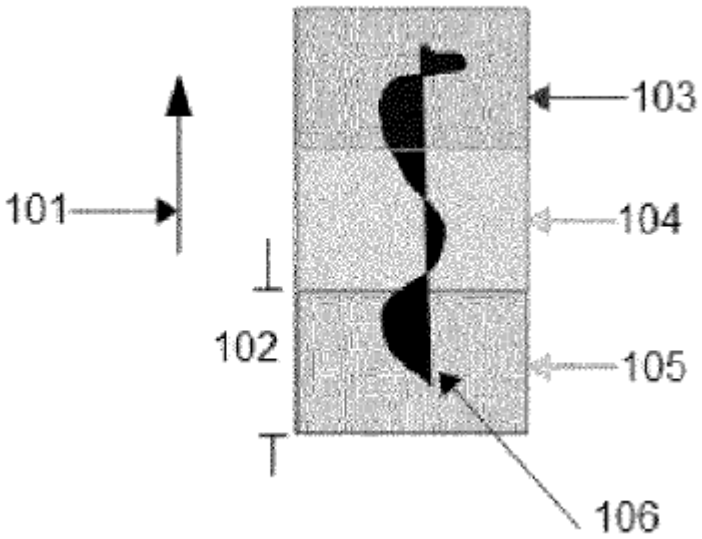
IX. GROUND 4: CLAIMS 9-12 ARE UNPATENTABLE AS OBVIOUS OVER SEKINE AND GREENE AND JØRGENSEN

378. As discussed above with respect to Ground 2, Sekine and Greene disclose all elements of independent claim 1. With respect to the remaining elements of claims 9-12 that depend therefrom, the combination of Sekine, Greene, and Jørgensen teach such elements, as discussed below.

A. Sekine, Greene, and Jørgensen Disclosed All Claimed Limitations

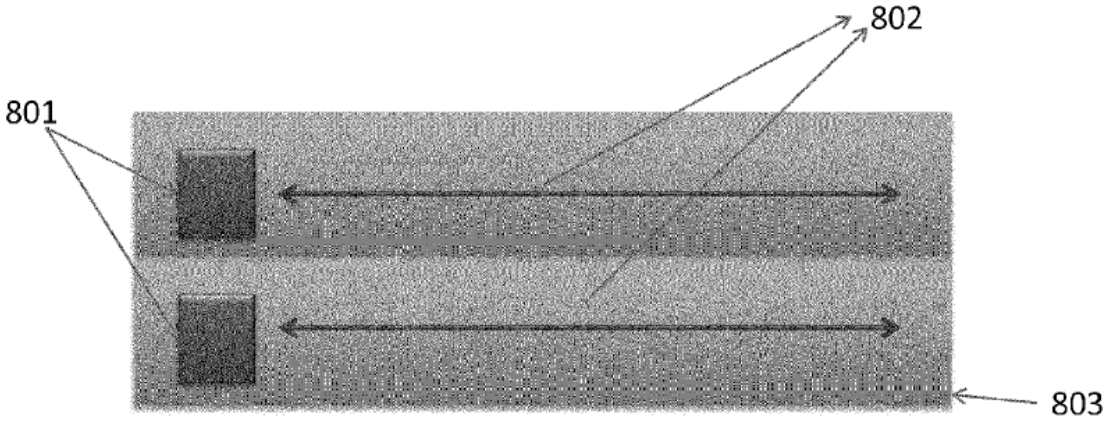
1. Claim 9 – The method of claim 1, wherein the projecting the composite image further comprises moving the plurality of sub-images during an exposure of a layer of an object being manufactured.

379. Jørgensen (EX1028) teaches that an image may be "divided into" sub-images, such as the division of image 106 into sub-images 103, 104, and 105 in Figure 1 (reproduced below). *See* Jørgensen (EX1028), [0013], FIG. 1; *see also id*. at [0015], FIG. 3. Jørgensen further teaches that the sub-images can be moved during exposure of a layer. For instance, Jørgensen teaches that the projection system that produces the sub-images can "be moved relative to the material along the x axis back and forth over the material to be solidificated." *See id.* at [0009], FIG. 4. Jørgensen depicts the movement in several figures, for example in Figures 7, 8, and 9. In Figure 8 (below), for instance, each element "801" represents a "scrolling electronic light projector[]" moving "relative to the light sensitive media 803" in the direction of an "x axis" denoted as "802." Each "scrolling light projector" in Figure 8 corresponds to a sub-image.



FIGURE#1

FIGURE#8



380. Therefore, it is my opinion that Jørgensen discloses the additional limitation of claim 9 of the ’511 Patent.

2. **Claim 10 – The method of claim 9, wherein the movement of the sub-images is either a step-expose-step type movement or a continuous movement.**

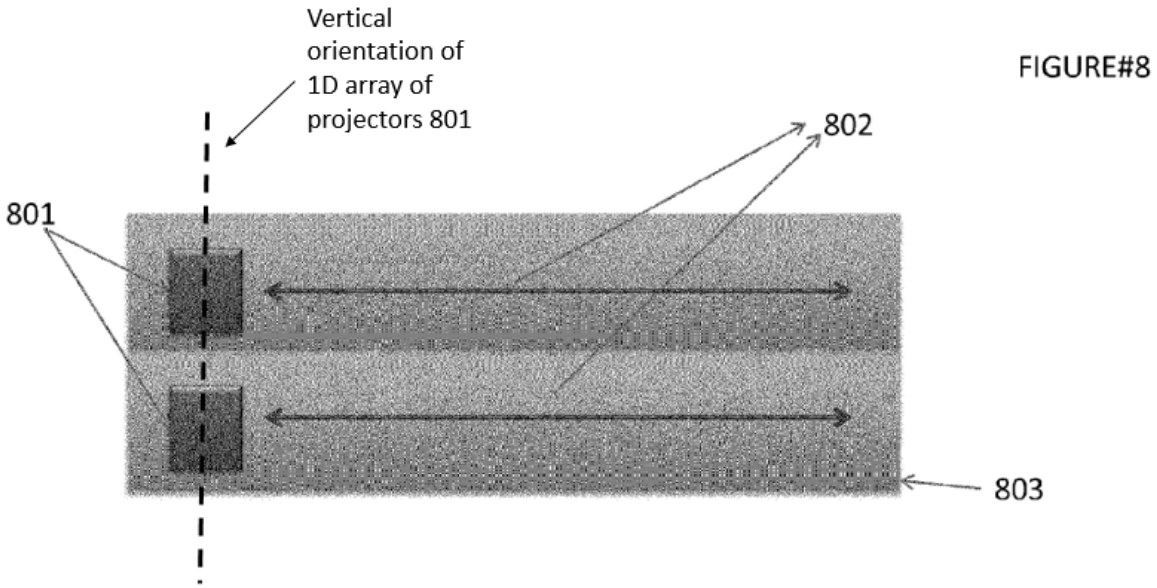
381. Jørgensen teaches that the movement of the sub-images is either a step-expose-step type movement or a continuous movement. Specifically, Jørgensen teaches that to print a "large exposed pattern image," the image may be divided into sub-images and exposed sequentially using a **"step and flash"** procedure, which is the same as a "step-expose-step" type of movement. Jørgensen (EX1028), [0013]. Further, as an alternative to "step and flash," Jørgensen teaches that a composite image may be printed **"in a continuous way,"** in which the "light projector is moving relative to the exposed [photopolymerizable] material" continuously, pixel-by-pixel. *Id.* at [0015].

382. Therefore, it is my opinion that Jørgensen discloses the additional limitation of claim 10 of the '511 Patent.

3. Claim 11 -- The method of claim 9, wherein the plurality of sub-images comprises a 1D array of sub-images oriented in a first direction; and the movement of the sub-images is in a second direction perpendicular to the first direction.

383. Jørgensen teaches that the plurality of sub-images comprises a 1D array of sub-images oriented in a first direction; and the movement of the sub-images is in a second direction perpendicular to the first direction. For example, Jørgensen at Figure 8 depicts two vertically aligned "scrolling electronic light projectors 801." *See* Jørgensen (EX1028), [0020], Figure 8 (reproduced above). As depicted in Figure 8, the projectors "move relative to the light sensitive media 803 back and forth along

the x axis 802." *Id*. As depicted in Figure 8, the x-axis is perpendicular to the vertical orientation of the scrolling electronic projectors 801, where this vertical orientation can be represented by the dashed line superimposed below on Figure 8 of Jørgensen. *Id*.



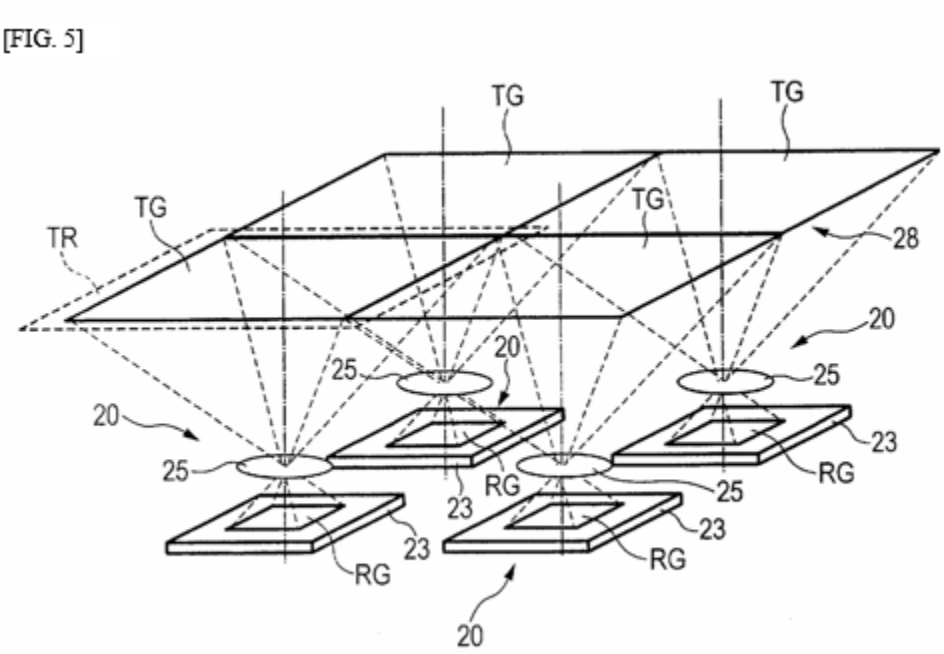
FIGURE#8

384. Therefore, it is my opinion that Jørgensen discloses the additional limitations of claim 11 of the '511 Patent.

4. **Claim 12 – The method of claim 9, wherein the plurality of sub-images comprises a 2D array of sub-images with rows oriented along a first direction and columns oriented along a second direction; and the movement of the sub-images is in either one of the first or second directions, or both the first and second directions.**

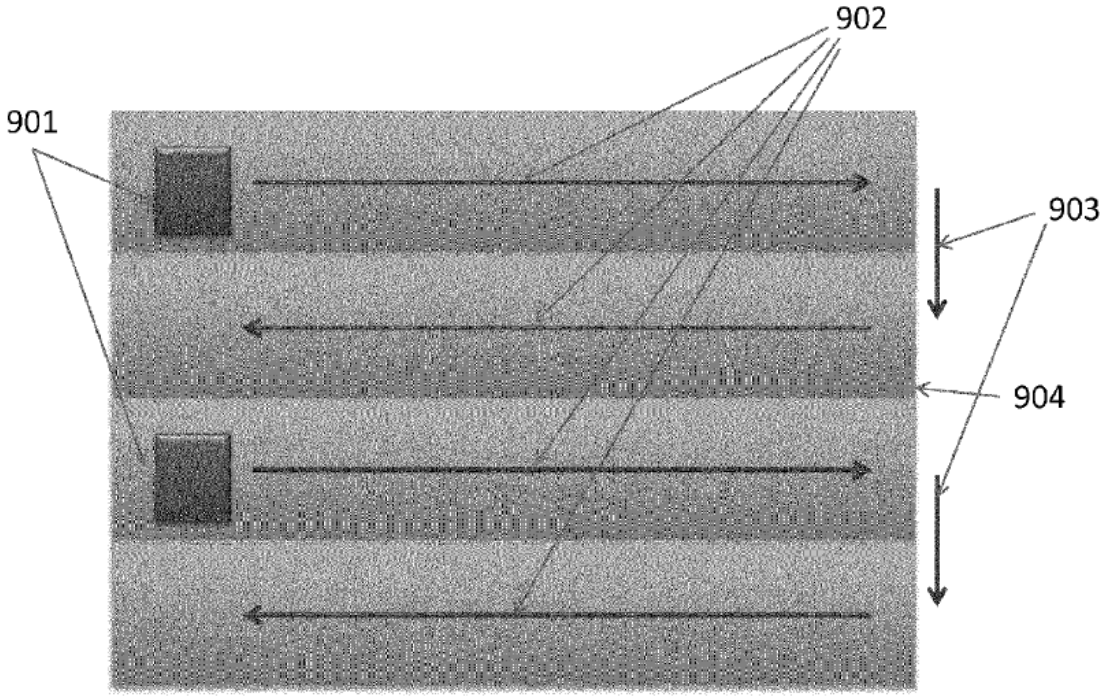
385. As discussed above with respect to claim 1, Sekine teaches that "multiple projectors" project multiple projection images, including "four projectors 20 [that] project the exposure image RG divided into four." *See* Sekine (EX1005), [0043], and Figures 5, 6. Figure 5 clearly depicts the four projectors in a 2 x 2 array (or a "2D array") of sub-images (see below).

[FIG. 5]



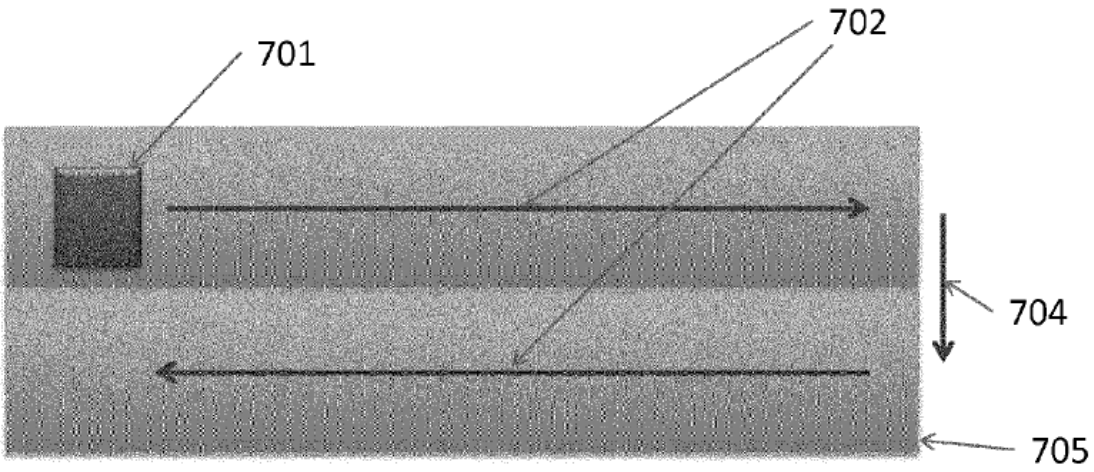
386. As discussed above for claim 9, Jørgensen teaches movement of multiple projectors, each producing a sub-image. For example, with reference to FIG. 9 (reproduced below), Jørgensen teaches multiple projectors/sub-images (denoted as "901") can move "first along the positive x axis 902, then a shift along the y axis 903." *See* Jørgensen (EX1028), [0021], FIG. 9.

FIGURE#9



387. In this regard, a POSITA would appreciate that moving the 2 x 2 array of Sekine in the manner taught by Jørgensen for projectors 901 (or, similarly, for projector 701 in FIG. 7 of Jørgensen, reproduced above in Section V.D. and partially reproduced below for convenience) would necessarily result in the movement described in claim 12. With reference to FIG. 7 or FIG. 9 of Jørgensen, the 2D array of Sekine (e.g., when 'substituted' for projector 701 in FIG. 7 of Jørgensen) would move both 'left-to-right' (the same direction as the row orientation of the 2D array of Sekine) and also 'top-to-bottom' (the same direction as the column orientation of the 2D array of Sekine).

FIGURE#7



388. Notably, Jørgensen specifically teaches that "to speed up the building process even further, one can add multiple light projectors … assembled on the machine," for example where "their motion is parallel along the x-axis." *See* Jørgensen at [0010].

389. Therefore, it is my opinion that the combination of Sekine and Jørgensen discloses the additional limitations of claim 12 of the '511 Patent.

B. Motivation to Combine Sekine and Greene with Jørgensen, and Reasonable Expectation of Success

390. As discussed above with respect to Ground 2, there is appropriate motivation to combine Sekine and Greene. For the reasons set forth below, there is further motivation to combine Sekine and Greene with Jørgensen, with a reasonable expectation of success of such combination.

391. Each of the prior art references addressed above is directed towards improving printing resolution of additive manufacturing systems that use light

projection to cure photoactive materials, such as photocurable polymer resins. Here, Sekine and Greene (which disclose use of image projectors to expose a photocurable resin) may be predictably combined with Jørgensen (which discloses movement patterns for image projectors, including arrays of light projectors) to arrive at the claimed invention. Several reasons support this conclusion.

392. First, the references are each directed towards the same purposes and field of endeavor—*i.e.*, improving efficiency and accuracy in the formation of a 3D printed product formed by light projection. Given the nature of the problem and design needs in the industry to improve the accuracy and efficiency of printing across large building areas, it would be natural for a POSITA to look towards similar references with similar purposes to solve well-known problems in the field. Sekine specifically identifies problems "when attempting to expand the shaping surface area without increasing the projection magnification of the projection optical system." *See* Sekine, [0006]. Likewise, Greene desires to "provide sub-pixel resolution and smoothing capabilities." *See* Greene, [0031].

393. Jørgensen similarly desires "to provide a process capable of increasing the resolution of the solidificated material compared to the static image of projected light," specifically by "using image scrolling while the light projector is in motion relative to the exposed material." *See* Jørgensen, [0003].

394. In view of the fact that the references are directed towards the same field of endeavor—and that there are no teachings in the references that would disparage a combination of the references—the POSITA would be motivated to use them as starting references for the purposes of heightening efficiency and accuracy of printing 3D products, including to take into account well-known, inherent challenges of maintaining resolution when printing in large areas to form 3D products.

395. Second, and as I understand the 'motivation to combine' analysis under U.S. patent law, where a technique has been used to **improve one device** and it would improve a similar device in the same way, such teachings provide a basis to combine the references. This is precisely the case here with, for example, Jørgensen's disclosure of multiple projectors being moved and how that same technique could be used in the same way to improve Sekine to arrive at the claimed invention. More specifically, both references are directed towards overall similar purposes, and the specific techniques of the references are **complementary**, with use of the projector layouts and movements in Jørgensen providing benefit to the techniques taught in Sekine and Greene (and vice versa). As noted above, Jørgensen, Sekine, and Greene are interested in techniques for improving accuracy of articles formed by 3D printing with a projection light source (such as a DLP device) and the efficiency at which such articles are printed. The POSITA would immediately

appreciate that various such techniques could be combined. For instance, the POSITA would immediately recognize that the movement of one or more light projectors (including light projectors in a 1D array) over a build area (which can improve printing resolution and efficiency) could be added to the techniques of Sekine and Greene for the same purpose (to improve printing resolution and efficiency). The POSITA would expect that the combination of Jørgensen and Sekine would allow the POSITA to achieve "increasing the resolution of the solidificated material" and also to "speed up the building process even further" discussed in Jørgensen. *See* Jørgensen, [0006] and [0010]. Indeed, adding the scrolling of multiple projectors of Jørgensen to the techniques of Sekine would be very logical, because the scrolling of multiple projectors of Jørgensen would improve a similar device (*i.e.*, Sekine) in the same way as that technique improves Jørgensen. Further, the addition of the gamma adjustment of Greene is very logical for the reasons discussed above with respect to the motivation to combine Sekine and Greene in Ground 2.

396. As stated above, Sekine teaches a multi-projector system. Each projector 20 projects an image onto the surface of the liquid resin material, for example with a five projectors 20 layout visible and organized in a "5×5 configuration" or four projectors arranged in a 2×2 projector array. Sekine, [0014], [0017], [0043]-[0044], FIG. 1, FIG. 5. Sekine teaches that to form a large, single

product with high resolution, it is possible to divide the overall or composite image 30 into smaller pieces or sub-images, where each sub-image is provided by a separate projector in the array. *Id.* at [0035]. This framework (further combined with the gamma adjustment aspects of Greene, for the reasons discussed above with respect to Ground 2) lends itself to the specific benefit afforded by Jørgensen. More specifically, because of Jørgensen's benefits, the POSITA would be motivated to combine and modify the Sekine, Greene, and Jørgensen systems (*i.e.*, to incorporate the multi-projector movement methods of Jørgensen into the 2D array multi-projector system disclosed in Sekine, and further incorporating the gamma adjustment aspects of Greene) to arrive at the claimed invention because of the added advantages provided by the combination. Given that the differences between the Sekine-Greene combination and claims 9-12 of the '511 Patent, as well as the modifications to arrive at such differences, are relatively minor (*i.e.*, incorporating multi-projector movement into Sekine's 2D multi-projector system), the POSITA would be motivated to combine and modify the Sekine and Greene combination with Jørgensen in exactly this manner.

397. The combination of the references would also lead to an expectation of success. Combining Sekine/Greene with Jørgensen would simply involve applying known techniques (*i.e.*, Jørgensen's multi-projector movement) to a known device ready for improvement (*i.e.*, Sekine's multi-projector 3D printing system modified

with Greene's gamma adjustment) to yield predictable results (*i.e.*, improved precision, accuracy, and efficiency in a 3D product, particularly with respect to accuracy over any size build area). A POSITA would have had a reasonable expectation of success in the combination because Sekine already discloses multiple projectors typically used in achieving heightened precision, accuracy, and efficiency in 3D product development—and Jørgensen discloses the use of movement of multiple projectors, which was well-known in the art and was explicitly disclosed in Jørgensen. The inclusion of the gamma adjustment aspects of Greene in the combination has a similar expectation of success as discussed above.

398. A POSITA thus would have had a reasonable expectation that the techniques work together because the techniques disclosed are being used in their conventional ways—with the techniques operating as they are expected to function (individually and in combination)—to achieve predictable outcomes that would be expected by those persons skilled in the art. That is, they would have been readily combined due to the predictability of the art and how these techniques were known to improve precision and accuracy in 3D printing.

399. Accordingly, it is my opinion that a POSITA would be motivated to combine and modify the system formed from the combination of Sekine and Greene with Jørgensen's system to arrive at the claimed invention of claims 9-12 of the '511 Patent.

X. GROUND 5: CLAIM 13 ARE UNPATENTABLE AS OBVIOUS OVER SEKINE AND GREENE AND JØRGENSEN AND YI

A. Sekine, Greene, Jørgensen, and Yi Disclosed All Claimed Limitations

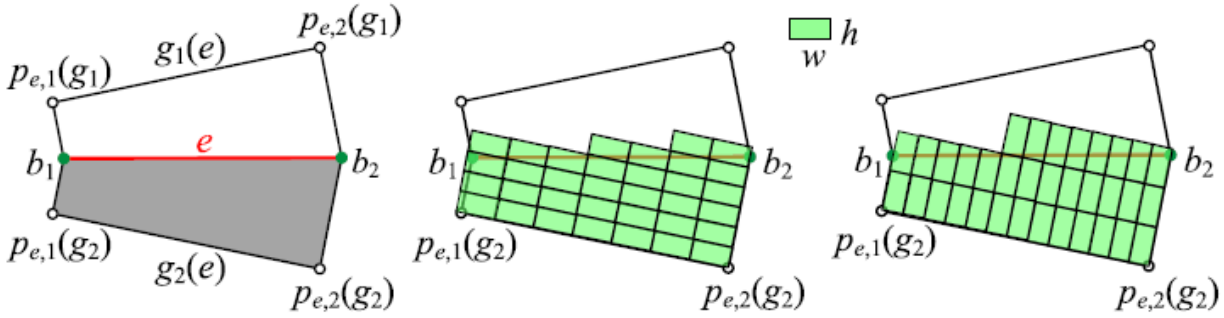
400. As discussed above with respect to Ground 4, Sekine, Greene, and Jørgensen disclose all elements of independent claim 1 and dependent claim 9. With respect to the remaining elements of claim 13 that depends therefrom, the combination of Sekine, Greene, Jørgensen, and Yi teach such elements, as discussed below.

1. Claim 13 – The method of claim 9, wherein the plurality of sub-images arranged in the array comprises one or more rows oriented along a first direction and one or more columns oriented along a second direction; and the movement of the sub-images is in a third direction that is different from both the first and second directions.

401. As explained above, the combination of Sekine, Greene, and Jørgensen teaches the method of claim 9. Yi (EX1029) teaches the additional limitation of claim 13. Specifically, Yi teaches *movement in a third direction that is different from both the first and second directions*. Yi discloses a "new DLP system that allows the platform to move not only vertically (in *z*-axis) but also horizontally (in *x*-*y* plane)." *See* Yi (EX1029), p.1194. In the Yi system, "[i]n addition to moving vertically (along *z*-axis), the working platform holding cured models can **move and rotate horizontally** (i.e., in the *x*-*y* plane)." *Id.*

402. In the figures, Yi represents individual projected images as rectangles, where each such rectangle corresponds to "the maximal area that can be projected by a light source, which is a rectangular region in our delta DLP 3-D printer." *See id*. at p.1196, FIG. 4. Yi refers to each such rectangle as an "elementary rectangle." *Id*. Yi further discloses "sets" or arrays of rectangles having multiple columns and rows. *See*, *e.g.*, *id*. at p.1198, FIG. 7, FIG. 8 (green rectangles). Additionally, Yi teaches that "bigger models are made by multiprojections for each layer." *Id*. at p.1202, FIGS. 13, 14.

403. Notably, the system of Yi is movable and rotatable in the x-y plane such that "the rectangles are allowed to be in **any orientation**," when projected onto the curable material surface, and are not limited to having their "sides parallel to two orthogonal directions." *See id.*, p.1194. Yi depicts one example of such an off-axis orientation in FIG. 7 (reproduced below). *See id.* at p.1198, FIG. 7



404. Therefore, it is my opinion that Yi discloses the additional limitations of claim 13 of the '511 Patent.

B. Motivation to Combine Sekine, Greene, and Jørgensen with Yi and Reasonable Expectation of Success

405. As discussed above with respect to Ground 4, there is appropriate motivation to combine Sekine, Greene, and Jørgensen. Such reasoning applies the same here. For the reasons set forth below, there is further motivation to combine Sekine, Greene, and Jørgensen with Yi, with a reasonable expectation of success of such combination.

406. The references may be predictably combined to arrive at the claimed invention for several reasons. First, each of Sekine, Greene, Jørgensen, and Yi is in a shared field of endeavor—namely, DLP-based additive manufacturing systems that use light projection to cure photoactive materials, such as photocurable polymer resins. They also are directed towards the same purposes of improving efficiency and accuracy in the formation of a 3D printed product formed by the DLP-based light projection. Given the nature of the problem and design needs in the industry to improve the accuracy and efficiency of printing—particularly across large building areas—it would be natural for a POSITA to look towards similar references with similar purposes to solve well-known problems in the field. Each of Sekine, Greene, and Jørgensen seeks to address printing resolution issues. *See e.g.*, Sekine, [0006]; Greene, [0031]; Jørgensen, [0006]. Amongst others, Yi similarly seeks to address issues including that "the resolution of projected masks is limited by the resolution

of a projector," such that a "project mask with a lower resolution will lead to a fabrication result with less geometric detail." *See* Yi, p.1193.

407. A purpose of Yi is to "overcome [the] aforementioned difficulty," specifically by "mak[ing] multiple projections for each layer of the 3-D model to fabricate large models," and to "realize this function of DLP-based 3-D printing with a large size" by having "the working platform holding cured models … move and rotate horizontally (i.e. in the *x-y* plane)." *See id.* at p.1193-1194. The rotation and movement allow Yi's system to reach "any position" in the working area. *See id.* at p.1195.

408. In view of the fact that the references are directed towards the same field of endeavor—and that there are no teachings in the references that would disparage a combination of the references—the POSITA would be motivated to use them as starting references for the purposes of heightening efficiency and accuracy of printing 3D products, including to take into account well-known, inherent challenges of maintaining resolution when printing in large areas is used to form 3D products.

409. Second, and as I understand the 'motivation to combine' analysis under U.S. patent law, where a technique has been used to **improve one device** and it would improve a similar device in the same way, such teachings provide a basis to combine the references. This is precisely the case here with, for example, Yi's

disclosure of sub-images that are rotatable to an off-axis and moved to any position. This technique of Yi could be used in the same way to improve the Sekine-Greene-Jørgensen combination to arrive at the claimed invention. More specifically, the references are directed towards overall similar purposes, and the specific techniques of the references are **complementary**, with use of the "third direction" movements of Yi providing benefit to the techniques taught in Sekine-Greene-Jørgensen (and vice versa).

410. The POSITA would immediately appreciate that various such techniques could be combined. For instance, the POSITA would immediately recognize that the third direction (different from both the first and second directions—the first direction being the orientation of one or more rows and the second direction being the orientation of one or more columns) could be added to the multi-projector array movement techniques of the Sekine-Greene-Jørgensen combination for the same purpose (to improve printing resolution and efficiency). The POSITA would expect that the combination of Yi and Sekine-Greene-Jørgensen would allow the POSITA to address the very issues discussed in Yi, including to "overcome" the issues of "the resolution of projected masks" and "realize this function of DLP-based 3-D printing with a large size." *See* Yi, p.1193-1194. Indeed, adding the third direction movement of Yi to the techniques of Sekine-Greene,-Jørgensen would be very logical, because the third direction movement of Yi would

improve a similar device (*i.e.*, formed by the Sekine-Greene-Jørgensen combination) in the same way as that technique improves the systems of Sekine, Greene, and Jørgensen.

411. Given that Jørgensen discusses movement of an array of multiple projectors already, and is combinable with Sekine in a manner that would result in movement of a 2D array of multiple projectors (both discussed above with respect to Ground 4), this framework lends itself to the specific benefit afforded by Yi. More specifically, because of Yi's benefits, the POSITA would be motivated to combine and modify the Sekine-Greene-Jørgensen system (*i.e.*, incorporate the multi-projector movement methods of Jørgensen, with the multi-projector and various masks and other elements disclosed in Sekine, further incorporating the gamma adjustment in Greene) to arrive at the claimed invention because of the added advantages it provides for achieving the same goal—improved print accuracy and efficiency in DLP-based additive manufacturing. Further, given that the differences between the Sekine-Greene-Jørgensen system and claim 13 of the '511 Patent is limited to one element (the movement of the sub-images is in a third direction that is different from both the first and second directions), and the modification to arrive at the claimed invention is relatively minor (*i.e.*, incorporating the movement and rotation of Yi), the POSITA would be motivated to combine and modify the Sekine-Greene-Jørgensen combination in exactly this manner.

412. Performing such a combination also would lead to an expectation of success, as doing so would simply involve applying known techniques (*i.e.*, Yi's third direction movement) to a known device ready for improvement (*i.e.*, the moving, multi-projector 3D printing system of the Sekine-Greene-Jørgensen combination) to yield predictable results (*i.e.*, improved precision, accuracy, and efficiency in a 3D product, particularly with respect to accuracy over any size build area). As the Sekine-Greene-Jørgensen combination already discloses movement of multiple projectors, a POSITA would have had a reasonable expectation of success in the combination—simply with the third direction of Yi.

413. A POSITA would have had a reasonable expectation that the techniques work together because the techniques disclosed are being used in their conventional ways—with the techniques operating as they are expected to function (individually and in combination)—to achieve predictable outcomes that would be expected by those persons skilled in the art. That is, they would have been readily combined due to the predictability of the art and how these techniques were known to improve precision and accuracy in 3D printing.

414. Accordingly, it is my opinion that POSITA would be motivated to combine and modify the system formed from the combination of Sekine, Greene, and Jørgensen with the Yi system to arrive at the claimed invention of the '511 Patent.

XI. OBJECTIVE INDICIA OF NON-OBVIOUSNESS

415. I am not aware of any licenses of the ’511 Patent in the additive manufacturing industry or media attention or other indication that the industry has taken particular notice of the ’511 Patent or Patent Owner’s technology. Similarly, I am not aware of any long-felt but unmet need satisfied by the ’511 Patent or Patent Owner’s technology, or unexpected results achieved by the ’511 Patent or Patent Owner’s technology. Nonetheless, I reserve the right to respond to any such consideration, if secondary considerations are addressed by the Patent Owner’s expert.

416. There is no objective indicia that support the non-obviousness of the ’511 Patent.

XII. CONCLUSION

417. I hereby declare that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true, and that these statements were made with knowledge that willful false statements and the like are so made punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the Petition for *inter partes* review.

418. For the reasons set forth above, it is my opinion that the Challenged Claims of the ’511 Patent are invalid.

Signature:



…….

Yong Chen, Ph.D.
Professor of Aerospace and Mechanical Engineering
University of Southern California

Date: July 16, 2025

APPENDIX A

CURRICULUM VITAE OF YONG CHEN

CURRICULUM VITAE

YONG CHEN, PH.D.

Department of Aerospace & Mechanical Engineering
Epstein Department of Industrial & Systems Engineering
University of Southern California
3650 McClintock Avenue, OHE 430E, Los Angeles, CA

Tel: (213)740-7829
Fax: (213)740-1120
E-mail: YongChen@usc.edu
https://viterbi-web.usc.edu/~yongchen/

EDUCATION

Ph. D. in Mechanical Engineering, Georgia Institute of Technology, 2001.
Major: *Computer-aided Engineering.*
Dissertation: *Computer-Aided Design for Rapid Tooling: Methods for Mold Design and Design-for-Manufacture.*
Dissertation Advisor: *David W. Rosen*

M. S. in Mechanical Engineering, Huazhong University of Science and Technology, 1996.
Major: *Computer-aided Design.*

B. S. in Mechanical Engineering, Zhejiang University, 1993.
Major: *Manufacturing Engineering.*

PROFESSIONAL EXPERIENCE

12/18~*present*: ***Professor*** (with tenure), Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA.

12/18~*present*: ***Professor*** (joint – 25%), Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA.

08/24~*present*: ***Professor*** (by courtesy), Alfred E. Mann Department of Biomedical Engineering, University of Southern California, Los Angeles, CA.

7/18~06/21: ***Director***, Daniel J. Epstein Institute, Viterbi School of Engineering, University of Southern California, Los Angeles, CA.

1/14~12/18: ***Associate Professor*** (by courtesy), Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA.

6/13~12/18: ***Associate Professor*** (with tenure), Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA.

4/14~6/14: ***Visiting Professor,*** Department of Engineering Design and Production, Aalto University, Espoo, Finland.

3/14~4/14: ***Academic Visitor,*** Department of Mechanical Engineering, National University of Singapore, Singapore.

1/14~3/14: ***Visiting Professor,*** Department of Mechanical and Automation Engineering, Chinese University of Hong Kong, Hong Kong.

7/06~*05/13*: ***Assistant Professor***, Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA.

(Updated: July 2025)

8/06~ *6/07*: ***Consultant,*** 3D Systems Inc., Valencia, CA.

8/01~7/06: ***Senior R&D Engineer,*** 3D Systems Inc., Valencia, CA.

3/98~7/01: ***Doctoral Research Assistant,*** Georgia Institute of Technology, Atlanta, GA.

7/96~2/98: ***Research Scientist,*** CAD Center, Huazhong University of Science and Technology, Wuhan, Hubei, China.

7/96~2/98: ***Lecturer,*** School of Mechanical Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, China.

9/93~6/96: ***Graduate Research Assistant,*** Huazhong University of Science and Technology, Wuhan, Hubei, China.

AWARDS AND HONORS

- 2025: **USC Viterbi Use-inspired Research Award**, University of Southern California, April 2025.
- 2023: **Best Paper Award 2022**, *Research* journal, for the paper "3D Printing of Nacre-inspired Structures with Exceptional Mechanical and Flame-retardant Properties." Vol. 2022, 9840574, 2022.
- 2023: **Invited Participant**, Army Research Lab Mid-term Tech Forecasting Workshop on Additive Manufacturing, March 9-16, Virtual.
- 2022: **Plenary Speaker**, ASME 2022 International Mechanical Engineering Congress & Exposition (IMECE), October 29- November 2, Columbus, Ohio.
- 2022: **Program Chair**, ASME 2022 Manufacturing Science and Engineering Conferences (MSEC), June 27-July 1, West Lafayette, Indiana.
- 2021: **Program co-Chair**, ASME 2021 Manufacturing Science and Engineering Conferences (MSEC), June 22-25, Virtual conference hosted by the University of Cincinnati.
- 2021: **Best Paper Award**, ASME 2021 Manufacturing Science and Engineering Conference (MSEC2021), Virtual (hosted by the University of Cincinnati), June 2021.
- 2020: **Best Paper Award (2nd Place)**, ASME 2020 Manufacturing Science and Engineering Conference (MSEC2020), Cincinnati, Ohio, June 2020.
- 2020: **USC Stevens Center for Innovation Commercialization Award**, University of Southern California, April 2020.
- 2019: **Program co-Chair**, ASME 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE), August 18-21, Anaheim, California.
- 2018: **Fellow**, American Society of Mechanical Engineering (ASME).
- 2018: **Outstanding Paper Award**, SME 46th North American Manufacturing Research Conference (NAMRC), College Station, Texas, June 2018.
- 2018: **USC Stevens Center for Innovation Commercialization Award**, University of Southern California, April 2018.

- 2018: **Outstanding Engineering Merit Award 2017**, Orange County Engineering Council, Santa Ana, California, February 2018.
- 2017: **Plenary Speaker**, The 28th International Solid Freeform Fabrication Symposium, August 7, Austin, Texas.
- 2017: **Outstanding Paper Award**, SME 45th North American Manufacturing Research Conference (NAMRC), Los Angeles, California, June 2017.
- 2017: **Conference Chair**, 2017 International Manufacturing Research Conference (NAMRC/MSEC/ICM&P), June 4-8, Los Angeles, California.
- 2017: **Plenary Speaker**, 11th THU-USC Faculty Research Symposium on the 4th Industrial Revolution: Enabling Tools and Methods, May 17, Tsinghua University, Beijing, China.
- 2016: **Outstanding Paper Award**, SME 44th North American Manufacturing Research Conference (NAMRC), Blacksburg, Virginia, June 2016.
- 2015: **Plenary Speaker**, 2015 SIAM Conference on Geometric and Physical Modeling, October 12, Salt Lake City, Utah.
- 2015: **Keynote Speaker**, China Graphics 2015, August 16, Beijing, China.
- 2015: **Keynote Speaker**, 2015 International Conference on Real-time Computing and Robotics, June 26, Changsha, China.
- 2015: **Session Chair on Advanced Manufacturing**, China-America Frontiers of Engineering Symposium, National Academy of Engineering, June 1-3, Irvine, California.
- 2014: **Keynote Speaker**, 4th International Conference on Additive Manufacturing and Bio-Manufacturing, November 13, Beijing, China.
- 2014: **Invited Participant**, Dagstuhl Seminar Series: "Computational Aspects of Fabrication," September 2-5, Leibniz-Zentrum für Informatik, Wadern, Germany.
- 2014: **Best Application Paper Award Finalist**, IEEE International Conference on Automation Science and Engineering (CASE 2014), Taipei, Taiwan, August 2014.
- 2014: **Invited Participant**, NSF US-South Korea Workshop on Advanced Manufacturing, August 11-12, Reno, NV.
- 2014: **Keynote Speaker**, 11th Annual International CAD Conference and Exhibition, June 23, Hong Kong, China.
- 2013: **Invited Participant**, Defense Advanced Research Project Agency (DARPA) ISAT workshop *Rethinking CAD*, October 24-25, Arlington, VA.
- 2013: **Outstanding Paper Award**, SME 41st North American Manufacturing Research Conference (NAMRC), Madison, Wisconsin, June 2013.
- 2013: **Invited Speaker**, NSF Summer Institute on Additive Manufacturing, May 29-31, Northwestern University, Evanston, IL.
- 2013: **Selected Participant**, German-America Frontiers of Engineering Symposium, National Academy of Engineering, April 26-28, Irvine, California.
- 2013: **Honorable Mention Paper Award**, 8th International Conference on MicroManufacturing (ICOMM 2013), Victoria, BC, Canada, March 2013.

- 2012: **Best Paper Award (3rd Place)**, ASME 2012 Manufacturing Science and Engineering Conference (MSEC2012), Notre Dame, IN, June 2012.
- 2012: **Faculty Early Career Development (CAREER) Award**, National Science Foundation (NSF), January 2012.
- 2012: **CAPPD Best Paper Award**, ASME 32nd Computers and Information in Engineering Conference, Chicago, IL, August 2012.
- 2012: **Outstanding Paper Award - Winner**, *Rapid Prototyping Journal*, Emerald Group Publishing Limited, for the paper "A Layerless Additive Manufacturing Process based on CNC Accumulation." Vol. 17, No. 3, pp. 218-227, 2011.
- 2011: **CAPPD Best Paper Award**, ASME 31st Computers and Information in Engineering Conference, Washington DC, August 2011.
- 2011: **Outstanding Paper Award**, SME 39th North American Manufacturing Research Conference (NAMRC), Corvallis, Oregon, June 2011.
- 2010: **Leadership and Service Award**, Computer-aided Product and Process Development Technical Committee, ASME CIE Division, August 16, 2010, Montreal, Quebec, Canada.
- 2010: **Symposium Outstanding Paper**, 21st International Solid Freeform Fabrication (SFF) Symposium, Austin, Texas, August 2010.
- 2009: **Invited Participant**, National Science Foundation (NSF) workshop on developing *Roadmap for Additive Manufacturing*, March 30-31, Arlington, VA.
- 2009: **Selected Participant**, U.S. Frontiers of Engineering Symposium, National Academy of Engineering, September 10-12, Irvine, California.
- 2008: **Best Paper Award**, ASME 28th Computers and Information in Engineering Conference, Brooklyn, New York, August 2008.
- 2008: **Outstanding Young Manufacturing Engineer Award**, Society of Manufacturing Engineers (SME).
- 2007: **Zumberge Award** for Individual Research and Innovation, USC.
- 2007: **Research Initiation Award**, Society of Manufacturing Engineers (SME).
- 2005: **Best Paper Award**, ASME 25th Computers and Information in Engineering Conference, Long Beach, California, September 2005.

RESEARCH

PRIMARY RESEARCH INTERESTS

My research interests are advanced manufacturing and design, especially additive manufacturing (a.k.a., 3D printing). Additive manufacturing (AM) is a manufacturing method that can directly convert a computer-aided design model into a physical object. It has been widely recognized as a disruptive manufacturing technology for a wide variety of applications, including aerospace, defense, dental,

biomedical, and consumer products. Also, additive manufacturing enables revolutionary new designs by using complex three-dimensional shapes, heterogeneous material properties, and multi-functionality.

My research focuses on the following areas related to AM technologies: (1) novel process and machine development for additive manufacturing and functional materials; (2) new modeling and control methodologies and techniques for accurate, reliable, and fast manufacturing processes; and (3) innovative design and computational tools for AM-enabled products and applications. My research would contribute to the development of AM technologies to enable people to revolutionize future engineering systems.

PUBLICATIONS

(Names listed in the order of authorship – a total of nearly 200 published journal and conference papers. My Google Scholar profile is at: https://scholar.google.com/citations?hl=en&user=qAKY6NAAAAAJ with the citation of **15,525**, the h-index of **57**, and the i10-index of **152** until July 2, 2025).

Book:

B1. Hugh Bruck, **Yong Chen**, Satyandra K. Gupta, *Recent Advances in Additive Manufacturing*, World Scientific Publishing Co., 2020.

Book Chapters:

B2. Yang Yang, Xiangjia Li, **Yong Chen**, "Additive Manufacturing of Bio-inspired Structures via Nanocomposite 3D Printing." Recent Advances in Additive Manufacturing, World Scientific Publishing Co., 2020.

B3. Xiangjia Li, **Yong Chen**, "Vat Photopolymerization based Ceramic Manufacturing." ASM Handbook on Additive Manufacturing Processes, Vol. 24, ASM International, 2020.

B4. Tsz-Ho Kwok, **Yong Chen**, Charlie C. L. Wang, "Geometric Analysis and Computation Using Layered Depth-Normal Images for Three-Dimensional Microfabrication." Three-Dimensional Microfabrication Using Two-Photon Polymerization, Elsevier, 2015.

B5. Pu Huang, Charlie C. L. Wang, **Yong Chen**, "Algorithms for Layered Manufacturing in Image Space." Advances in Computers and Information in Engineering Research, ASME Press, 2014.

Refereed Journal Articles Published or Accepted for Publication:

J1. Han Xu, Qizhou Li, Shangxiong Zhang, Changyuan Pu, Yizhu Chen, **Yong Chen**, "Feature-oriented Vibrations in LCD-based Vat Photopolymerization." ***Journal of Manufacturing Processes***, 148, 224-236, 2025.

J2. Yi Zhu, Dengting Li, Chao Zhang, Fangye Lin, **Yong Chen**, "Abrasive Flow Machining of Laser Powder Bed Fusion Fabricated Mini-channels: Modelling and Verification." ***Journal of Manufacturing Processes***, 141, 36-47, 2025.

J3. Joshua Vandervelde, Yeowon Yoon, Rifat Shahriar, Stephen B. Cronin, **Yong Chen**, "Additive and Laser Manufacturing for Multifunctional Electronics on High-performance Polymers." ***Small Science***, 2500022, 2025.

J4. Han Xu, Renzhi Hu, Shuai Chen, Junhong Zhu, Chi Zhou, **Yong Chen**, "Vibration-assisted Vat Photopolymerization for Pixelate-aliasing-free Surface Fabrication." ***International Journal of Extreme Manufacturing***, 6(3), 035004, 2024.

J5. Zhongkun Zhao, Haoqing Yang, Manqi Li, Chandan Gudi, Kamal Varma Kanumuru, Robert Voigt, Olalekan Babaniyi, Tengxiao Liu, **Yong Chen**, Hongtao Sun, "Engineering Heterogeneous Domains and Interfaces in Shape Memory Fibers for Tunable Responsive Behaviors." ***Chemical Engineering Journal***, Vol. 480, 147936, 2024.

J6. Jie Jin, Fangzhou Zhang, Yulong Yang, Chengqian Zhang, Haidong Wu, Yang Xu, **Yong Chen**, "Hybrid Multi-material 3D Printing Using Photocuring-while-dispensing." ***Small***, 2302405, 2023.

J7. Han Xu, Shuai Chen, Renzhi Hu, Muqun Hu, Yang Xu, Yeowon Yoon, **Yong Chen**, "Continuous Vat Photopolymerization for Optical Lens Fabrication." ***Small***, 19(40), 2300517, 2023.

J8. Hong Sun, Yuxuan Sun, Chayut Buranabunwong, Xingxiang Li, Shiwu Zhang, **Yong Chen**, Mujun Li, "Flexible Capacitive Sensor Based on Miura-ori Metamaterial." ***Chemical Engineering Journal***, Vol. 468, 143514, 2023.

J9. Yuxuan Sun, Liu Wang, Yangyang Ni, Huajian Zhang, Xiang Cui, Jiahao Li, Yin-Bo Zhu, Ji Liu, Shiwu Zhang, **Yong Chen**, Mujun Li, "3D Printing of Thermosets with Diverse Rheological and Functional Applicabilities." ***Nature Communications***, 14(1), 245, 2023.

J10. Gisele Ragusa, Satyandra K. Gupta, Qiang Huang, **Yong Chen**, Azad M. Madni, Sven Koenig, Lilian Leung, "Use of a Delphi Research Process for Designing, Developing, and Assessing the Importance of Contemporary Advanced Manufacturing Curriculum." ***International Journal of Engineering Education***, Vol. 39, No., 2, pp. 1-12, 2023.

J11. Haidong Wu, Wei Liu, Lifu Lin, **Yong Chen**, Yuerui Xu, Shanghua Wu, Zhenzhong Sun, Di An, Sai Wei, Zhipeng Xie, "Realization of Complex-shaped and High-performance Alumina Ceramic Cutting Tools via Vat Photopolymerization based 3D Printing: A Novel Surface Modification Strategy through Coupling Agents Aluminic Acid Ester and Silane Coupling Agent", ***Journal of the European Ceramic Society***, 43(3), 1051-1063, 2023.

J12. Yeowon Yoon, Yang Xu, **Yong Chen**, "Hierarchical Porous Structure Fabrication Via Hybrid Stereolithography and Inkjet Printing with Sacrificial Liquid." ***ASME Journal of Manufacturing Science and Engineering***, 145(1), 011010-1, 2023.

J13. **Yong Chen**, Albert Shih, "Guest Editorial - Special Issue: Manufacturing Science Engineering Conference 2022." ***ASME Journal of Manufacturing Science and Engineering***, 145(1), 010301, 2023.

J14. Yang Xu, Huachao Mao, Cenyi Liu, Zhengyu Du, Weijia Yan, Zhuoyuan Yang, Jouni Partanen, **Yong Chen**, "Hopping Light Vat Photopolymerization for Multiscale Fabrication." ***Small***, 19(11), 2205784, 2023.

J15. Cory K. Mayfield, Mina Ayad, Elizabeth Lechtholz-Zey, **Yong Chen**, Jay R. Lieberman, "3D Printing for Critical Sized Bone Defects: Current Concepts and Future Directions." ***Bioengineering***, 9, 680, 2022.

J16. Laiming Jiang, Gengxi Lu, Yushun Zeng, Yizhe Sun, Haochen Kang, James Burford, Chen Gong, Mark S. Humayun, **Yong Chen**, Qifa Zhou, "Flexible Ultrasound-induced Retinal Stimulating Piezo-Arrays for Biomimetic Visual Prostheses." ***Nature Communications***, 13, 3853, 2022.

J17. Xiangjia Li, Tommaso Baldacchini, **Yong Chen**, "An Investigation of Integrated Multi-scale 3D Printing for Hierarchical Structures Fabrication." ***ASME Journal of Micro and Nano-Manufacturing***, 9(4), 041005, 2022.

J18. Yang Xu, Fangjie Qi, Huachao Mao, Songwei Li, Yizhen Zhu, Jingwen Gong, Lu Wang, Noah Malmstadt, **Yong Chen**, "In-situ-transfer Vat Photopolymerization for Transparent Microfluidic Channels." ***Nature Communications***, Vol. 13, 1-11, 2022.

J19. Yang Yang, Ziyu Wang, Qingqing He, Xiangjia Li, Gengxi Lu, Laiming Jiang, Yushun Zeng, Brandon Bethers, Jie Jin, Shuang Lin, Siqi Xiao, Yizhen Zhu, Xianke Wu, Wenwu Xu, Qiming Wang, **Yong Chen**, "3D Printing of Nacre-inspired Structures with Exceptional Mechanical and Flame-retardant Properties." ***Research***, Vol. 2022, 9840574, 2022.

J20. Lifu Lin, Haidong Wu, Peishen Ni, **Yong Chen**, Zhaoquan Huang, Yehua Li, Kunji Lin, Pengfei Sheng, Shanghua Wu, "Additive Manufacturing of Complex-Shaped and High-Performance Aluminum Nitride-Based Components for Thermal Management." ***Additive Manufacturing***, Vol. 52, 102671, 2022.

J21. Jiawei Tian, Manqi Li, Zhonghao Han, **Yong Chen**, Xianfeng David Gui, Q. J. Ge, Shikui Chen, "Conformal Topology Optimization of Multi-material Ferromagnetic Soft Active Structures Using an Extended Level Set Method." ***Computer Methods in Applied Mechanics and Engineering***, vol. 389, 114394, 2022.

J22. Ye Yang, Songwei Li, Han Xu, Yang Xu, **Yong Chen**, "Fabrication of Flexible Microheater with Tunable Heating Capabilities by Direct Laser Writing and Selective Electrodeposition." ***Journal of Manufacturing Processes***, vol. 74, 88-99, 2022.

J23. Wenxuan Jia, Yuen-shan Leung, Huachao Mao, Han Xu, Chi Zhou, **Yong Chen**, "Hybrid-light-source Stereolithography for Fabricating Macro-objects with Micro-textures." ***ASME Journal of Manufacturing Science and Engineering***, 144(3), 031003, 2022.

J24. Yushun Zeng, Laiming Jiang, Qingqing He, Robert Wodnicki, Yang Yang, **Yong Chen**, Qifa Zhou, "Recent Progress in 3D-printing Piezoelectric Materials for Biomedical Applications." ***Journal of Physics D: Applied Physics***, 55, 013002, 2022.

J25. Laiming Jiang, Gengxi Lu, Yang Yang, Yang Xu, Fangjie Qi, Jiapu Li, Benpeng Zhu, **Yong Chen**, "Multi-channel Piezo-ultrasound Implant with Hybrid Waterborne Acoustic Metastructure for Selective Wireless Energy Transfer at Megahertz Frequencies." ***Advanced Materials***, 2104251, 2021.

J26. Jie Jin, Huachao Mao, **Yong Chen**, "Photocuring-while-writing: a 3D Printing Strategy to Build Free Space Structure and Freeform Surface Texture." ***Manufacturing Letters***, 29, 113-116, 2021.

J27. Huachao Mao, Wenxuan Jia, Yuen-shan Leung, Jie Jin, **Yong Chen**, "Multi-material Stereolithography Using Curing-on-demand Printheads." ***Rapid Prototyping Journal***, 27/5, 861-871, 2021.

J28. Yang Xu, Fangjie Qi, Xiangyun Gao, Yujie Shan, Yun Zhou, **Yong Chen**, "Direct Droplet Writing – A Novel Droplet-punching Capillary-splitting 3D Printing Method for Highly Viscous Materials." ***Procedia Manufacturing***, 53, 472-483, 2021.

J29. Chi Zhou, Han Xu, **Yong Chen**, "Spatiotemporal Projection-Based Additive Manufacturing: A Data-driven Image Planning Method for Subpixel Shifting in a Split Second." ***Advanced Intelligent Systems***, 2100079, 2021.

J30. Eric O. Potma, David Knez, **Yong Chen**, Yulia Davydova, Amanda Durkin, Alexander Fast, Mihaela Balu, Brenna Norton-Baker, Rachel W. Martin, Tommaso Baldacchini, Dmitry A. Fishman, "Rapid chemically selective 3D imaging in the mid-infrared." ***Optica***, 8(7), 995-1002, 2021.

J31. Chengqian Zhang, Xiangjia Li, Laiming Jiang, Daofan Tang, Han Xu, Peng Zhao, Jianzhong Fu, Qifa Zhou, **Yong Chen**, "3D Printing of Functional Magnetic Materials: From Design to Applications." ***Advanced Functional Materials***, 2102777, 2021.

J32. Zoe Johnson, Xiangjia Li, Tea Jashashvili, Yuan Yuan, Michael Jamieson, Mark Urata, **Yong Chen**, Yang Chai, "Mesenchymal Stem Cells and 3D-osteoconductive Scaffold Regenerate Calvarial Bone in Critical Sized Defects in Swine." ***Stem Cells Translational Medicine***, 10(8), 1170-1183, 2021.

J33. Xiangjia Li, **Yong Chen**, "Vat Photopolymerization based Ceramic Manufacturing." ***Journal of Materials Engineering and Performance***, 20, 4819-4836, 2021.

J34. Laiming Jiang, Genxi Lu, Yushun Zeng, Yizhe Sun, Runze Li, Yang Yang, Mark S. Humayun, **Yong Chen**, Qifa Zhou, "Photoacoustic and Piezo-ultrasound Hybrid-induced Energy Transfer for 3D Twining Wireless Multifunctional Implants." ***Energy and Environmental Science***, 14(3), 1490-1505, 2021.

J35. Eder Sales, Tsz-Ho Kwok, **Yong Chen**, "Function-aware Slicing Using Principle Stress Line for Toolpath Planning in Additive Manufacturing." ***Journal of Manufacturing Processes***, 64, 1420-1433, 2021.

J36. Yang Xu, Ziqi Wang, Siyu Gong, **Yong Chen**, "Reusable Supports for Additive Manufacturing." ***Additive Manufacturing***, 39, 101840, 2021.

J37. Yang Xu, Yizhen Zhu, Yifeng Sun, Jie Jin, **Yong Chen**, "A Vibration-assisted Separation Method for Constrained-surface-based Stereolithography." ***ASME Journal of Manufacturing Science and Engineering***, 143(5), 051008, 2021.

J38. Xiangjia Li, Weitong Shan, Yang Yang, Dylan Joralmon, Yizhen Zhu, Yiyu Chen, Yuan Yuan, Han Xu, Jiahui Rong, Rui Dai, Qiong Nian, Yang Chai, **Yong Chen**, "Limpet Teeth Inspired Painless Microneedles Fabricated by Magnetic Field Assisted 3D Printing." ***Advanced Functional Materials***, 31(5), 2003725, 2021 (featured as the **Inside Back Cover** of the issue).

J39. Han Xu, Shuai Chen, Huachao Mao, Fuyan Luo, **Yong Chen**, "A Numerically Controlled Shape Memory Alloy Wire Bending Process Using Vat Photopolymerization." ***Journal of Manufacturing Processes***, 56, 1322-1330, 2020.

J40. Laiming Jiang, Yang Yang, **Yong Chen**, Qifa Zhou, "Ultrasound-induced Wireless Energy Harvesting: From Materials Strategies to Functional Applications." ***Nano Energy***, 77, 105131, 2020.

J41. An Xin, Kunhao Yu, Runrun Zhang, Bingyuan Ruan, Allyson L. McGaughey, Zhangzhengrong Feng, Kyung Hoon Lee, Liming Xiong, **Yong Chen**, Amy Childress, Qiming Wang, "Bone-inspired Healing of 3D-printed Ceramics at Room Temperature." ***Materials Horizons***, 7, 2130-2140, 2020.

J42. Yang Yang, Zeyu Chen, Hongjie Hu, Ziyu Wang, Laiming Jiang, Gengxi Lu, Xiangjia Li, Ruimin Chen, Jie Jin, Haochen Kang, Hengxi Chen, Shuang Lin, Hanyu Zhao, Qifa Zhou, Sheng Xu, **Yong Chen**, "A Stretchable and Shape-conformable Thermoelectric Generator." ***Nano Letters***, 20, 4445-4453, 2020.

J43. Yushun Zeng, Laiming Jiang, Yizhe Sun, Yang Yang, Yi Quan, Shuang Wei, Gengxi Lu, Runze Li, Jiahui Rong, **Yong Chen**, Qifa Zhou, "3D-printing Piezoelectric Composite with Honeycomb Structure for Ultrasonic Devices." ***Micromachines***, 11(8), 713, 2020.

J44. Kunhao Yu, Haixu Du, An Xin, Kyung Hoon Lee, Zhangzhengrong Feng, Sami F. Masri, **Yong Chen**, Guoliang Huang, Qiming Wang, "Healable, Memorable, and Transformable Lattice Structures." ***Nature Asia Materials***, 12:26, 2020.

J45. Xiangjia Li, Yuan Yuan, Luyang Liu, Yuen-Shan Leung, Yiyu Chen, Yuxing Guo, Yang Chai, **Yong Chen**, "3D Printing of Hydroxyapatite/β-tricalcium Phosphate Scaffold with Hierarchical Porous Structure for Bone Regeneration." ***Bio-Design and Manufacturing***, 3, 15-29, 2020.

J46. Xiangjia Li, Yang Yang, Luyang Liu, Yiyu Chen, Ming Chu, Haofan Sun, Weitong Shan, **Yong Chen**, "3D Printed Cactus-inspired Spine Structures for Highly Efficient Water Collection." ***Advanced Materials Interfaces***, 7, 1901752, 2020 (featured as the **Front Cover** of the issue).

J47. Jiapu Li, Yang Yang, Zeyu Chen, Shuang Lei, Maokang Shen, Tao Zhang, Xuekai Lan, YiJie Qin, Jun Ou-Yang, Xiaofei Yang, **Yong Chen**, Ziyu Wang, Benpeng Zhu, "Self-healing: A New Skill Unlocked for Ultrasound Transducer." ***Nano Energy***, 68, 104348, 2020.

J48. Yanhui Li, Minglang Wang, Haidong Wu, Fupo He, **Yong Chen**, Shanghua Wu, "Cure Behavior of Colorful ZrO2 Suspensions During Digital Light Processing (DLP) based Stereolithography Process." ***Journal of the European Ceramic Society***, 39, 4921-4927, 2019.

J49. Ram Alluri, Xuan Song, Sofia Bougioukli, William Pannell, Venus Vakhshori, Osamu Sugiyama, Amy Tang, Sang-hyun Park, **Yong Chen**, Jay Lieberman, "Regional Gene Therapy with 3D Printed Scaffold to Heal Critical Sized Bone Defects in a Rat Model." ***Journal of Biomedical Materials Research: Part A***, 107(10), 2174-2182, 2019.

J50. Laiming Jiang, Yang Yang, Ruimin Chen, Genxi Lu, Runze Li, Jie Xing, Kirk Shung, Mark S. Humayun, Jianguo Zhu, **Yong Chen**, Qifa Zhou, "Ultrasound-induced Energy from Lead-free Piezoelectric Composite for Potential Retinal Electrical Stimulation Application." ***Advanced Functional Materials***, 29(33), 1902522, 2019 (featured as the **Back Cover** of the issue).

J51. Yuen-Shan Leung, Tsz-Ho Kwok, Huachao Mao, **Yong Chen**, "Digital Material Design Using Tensor-based Error Diffusion for Additive Manufacturing." ***Computer-aided Design***, 114, 224-235, 2019.

J52. Xiangjia Li, Huachao Mao, Yayue Pan, **Yong Chen**, "Mask Video Projection based Stereolithography with Continuous Resin Flow to Build Digital Models in Minutes." ***ASME Journal of Manufacturing Science and Engineering***, 141, 081007, 2019.

J53. Yang Yang, Xiangjia Li, Ming Chu, Haofan Sun, Jie Jin, Kunhao Yu, Qiming Wang, Qifa Zhou, **Yong Chen**, "Electrically Assisted 3D Printing of Nacre-inspired Structure with Self-sensing Capability." ***Science Advances***, 5(4), eaau9490, 2019.

J54. Yuen-Shan Leung, Tsz-Ho Kwok, Xiangjia Li, Yang Yang, Charlie C. L. Wang, **Yong Chen**, "Challenges and Status on Design and Computation for Emerging Additive Manufacturing Technologies." ***ASME Journal of Computing and Information Science in Engineering***, 19, 021013, 2019.

J55. Zeyu Chen, Xuejun Qian, Xuan Song, Qiangguo Jiang, Rongji Huang, Yang Yang, Runze Li, Kirk Shung, **Yong Chen**, and Qifa Zhou, "Three-dimensional Printed Piezoelectric Array for Improving Acoustic Field and Spatial Resolution in Medical Ultrasonic Imaging." ***Micromachines***, 10, 170, 2019.

J56. Yuanrui Li, Huachao Mao, Pan Hu, Mark Hermes, Haneol Lim, Jongseung Yoon, Mitul Luhar, **Yong Chen**, and Wei Wu, "Bio-inspired Functional Surfaces Enabled by Multiscale Stereolithography." ***Advanced Materials Technologies***, 1800638, 2019 (featured as the **Back Cover** of the issue).

J57. Yanhui Li, **Yong Chen**, Minglang Wang, Lian Li, Haidong Wu, Fupo He, Shanghua Wu, "The Cure Performance of Modified ZrO2 Coated by Paraffin Via Projection based Stereolithography." ***Ceramics International***, 45, pp. 4084-4088, 2019.

J58. Laiming Jiang, Yang Yang, Zeyu Chen, Ruimin Chen, Gengxi Lu, Runze Li, Di Li, Xiaoyang Chen, K. K. Shung, Jianguo Zhu, **Yong Chen**, and Qifa Zhou, "Flexible Piezoelectric Ultrasonic Energy Harvester Array for Bio-implantable Wireless Generator." ***Nano Energy***, 56, pp. 216-224, 2019.

J59. Huachao Mao, Tsz-Ho Kwok, **Yong Chen**, Charlie Wang, "Adaptive Slicing based on Efficient Profile Analysis." ***Computer-aided Design***, 107, pp. 89-101, 2019.

J60. Jun Zhang, Yang Yang, Benpeng Zhu, Xiangjia Li, Jie Jin, Zeyu Chen, **Yong Chen**, and Qifa Zhou, "Multifocal Point Beam Forming by a Single Ultrasonic Transducer with 3D Printed Holograms." ***Applied Physics Letters***, 113, 243502, 2018.

J61. Xiangjia Li, Yang Yang, Benshuai Xie, Ming Chu, Haofan Sun, Siyang Hao, Yiyu Chen, **Yong Chen**, "3D Printing of Flexible Liquid Sensor based on Swelling Kinetics of Hydrogel with Carbon Nanotubes." ***Advanced Materials Technologies***, 1800476, 2018.

J62. Xiangjia Li, Benshuai Xie, Jie Jin, Yang Chai, **Yong Chen**, "3D Printing Temporary Crown and Bridge by Temperature-controlled Mask Image Projection Stereolithography." ***Procedia Manufacturing***, pp. 1023-1033, 2018.

J63. Jie Jin, Jinfan Yang, Huachao Mao, **Yong Chen**, "A Vibration-assisted Method to Reduce Separation Force for Stereolithography." ***SME Journal of Manufacturing Processes***, 34, pp. 793-801, 2018.

J64. Yang Yang, Xuan Song, Xiangjia Li, Zeyu Chen, Chi Zhou, Qifa Zhou, **Yong Chen**, "Recent Progress in Biomimetic Additive Manufacturing Technology: From Materials to Functional Structures." ***Advanced Materials***, 30(36), 1706539, 2018.

J65. William Giannobile, Yang Chai, **Yong Chen**, Kevin Healy, Nancy Lane, Michael Longaker, David Mooney, Charles Sfeir, Mark Urata, William Wagner, Ben Wu, David Kohn, "Dental, Oral and Craniofacial Regenerative Medicine." ***Journal of Dental Research***, 97(4), pp. 361-363, 2018.

J66. Yang Yang, Xiangjia Li, Xuan Zheng, Zeyu Chen, Qifa Zhou, **Yong Chen**, "3D-printed Biomimetic Superhydrophobic Structures for Microdroplet Manipulation and oil/water separation." ***Advanced Materials***, 30, pp. 1704912, 2018 (featured as the **Back Cover** of the issue).

J67. Huachao Mao, Yuen-Shan Leung, Yuanrui Li, Pan Hu, Wei Wu, **Yong Chen**, "Multiscale Stereolithography Using Shaped Beams." ***ASME Journal of Micro and Nano Manufacturing***, 5(4), 040905, 2017.

J68. Tsz-Ho Kwok, **Yong Chen**, "GDFE: Geometry-driven Finite Element for Four-dimensional Printing." ***ASME Journal of Manufacturing Science and Engineering***, 139, 111006, 2017.

J69. Xiangjia Li, **Yong Chen**, "Micro-scale Feature Fabrication Using Immersed Surface Accumulation." ***SME Journal of Manufacturing Processes***, Vol. 28, pp. 531-540, 2017.

J70. Jie Jin, **Yong Chen**, "Highly Removable Water Support for Stereolithography." ***SME Journal of Manufacturing Processes***, Vol. 28, pp. 541-549, 2017.

J71. Dongping Deng, Yang Yang, **Yong Chen**, Xing Lan, Jesse Tice, "Accurately Controlled Sequential Self-folding Structures by Polystyrene Film." ***Smart Materials and Structures***, 26, 085040, 2017.

J72. Yanzhou Ji, Zhuo Wang, Bo Wang, **Yong Chen**, Tu Zhang, Long-Qing Chen, Xuan Song, Lei Chen, "Effect of Meso-scale Geometry on Piezoelectric Performance of Additively Manufactured Flexible Polymer-Pb(ZrxTi1−x)O3 Composites." ***Advanced Engineering Materials***, pp. 1600803, 2017.

J73. Yang Yang, Zeyu Chen, Xuan Song, Zuofeng Zhang, Jun Zhang, Kirk Shung, Qifa Zhou, **Yong Chen**, "Biomimetic Anisotropic Reinforcement Architectures by Electrically Assisted Nanocomposite 3D Printing." ***Advanced Materials***, 29, pp. 1605750, 2017 (featured as the **Inside Back Cover** of the issue).

J74. Dongping Deng, Tsz-Ho Kwok, **Yong Chen**, "4D printing: Design and Fabrication of Smooth Curved Surface using Controlled Self-folding." ***ASME Journal of Mechanical Design***, 139, 081702, 2017.

J75. Haidong Wu, Wei Liu, Rongxuan He, Ziwei Wu, Qiangguo Jiang, Xuan Song, **Yong Chen**, Yanling Cheng, Shanghua Wu, "Fabrication of Dense Zirconia-toughened Alumina Ceramics through a Stereolithography-based Additive Manufacturing." ***Ceramics International***, 43(1), pp. 968-972, 2017.

J76. Tsz-Ho Kwok, Hang Ye, **Yong Chen**, Chi Zhou, Wenyao Xu, "Mass Customization: Reuse of Digital Slicing for Additive Manufacturing." ***ASME Journal of Computing and Information Science in Engineering***, 17(2), 021009, 2017.

J77. Yayue Pan, **Yong Chen**, Zuyao Yu. "Fast Mask Image Projection based Micro-stereolithography Process for Complex Geometry". ***ASME Journal of Micro- and Nano-Manufacturing***, 5(1), 014501, 2017.

J78. Xuan Song, Zeyu Chen, Liwen Lei, Kirk Shung, Qifa Zhou, **Yong Chen**, "Piezoelectric Component Fabrication Using Projection Stereolithography of Barium Titanate Ceramic Suspensions." ***Rapid Prototyping Journal***, 23, 1, 2017.

J79. Kai Xu, Tsz-Ho Kwok, Zhengcai Zhao, **Yong Chen**, "A Reverse Compensation Framework for Shape Deformation Control in Additive Manufacturing." ***ASME Journal of Computing and Information Science in Engineering***, 17(2), 021009, 2017.

J80. Xuan Song, Zhuofeng Zhang, Zeyu Chen, **Yong Chen**, "Porous Structure Fabrication Using a Stereolithography-based Sugar Foaming Method." ***ASME Journal of Manufacturing Science and Engineering***, 139(3), 031015, 2016.

J81. Yayue Pan, **Yong Chen**. "Meniscus Process Optimization for Smooth Surface Fabrication in Stereolithography". ***Additive Manufacturing***, 12, pp. 321-333, 2016.

J82. Kai Xu, **Yong Chen**. "Photocuring Temperature Study for Curl Distortion Control in Projection based Stereolithography". ***ASME Journal of Manufacturing Science and Engineering***, 139(2), 021002, 2016.

J83. Huachao Mao, Chi Zhou, **Yong Chen**, "LISA: Linear Immersed Sweeping Accumulation." ***SME Journal of Manufacturing Processes***, 24, p. 406-415, 2016.

J84. Wei Liu, Haidong Wu, Maopeng Zhou, Rongxuan He, Qiangguo Jiang, Ziwei Wu, Yanling Cheng, Xuan Song, **Yong Chen**, Shanghua Wu, "Fabrication of Fine-grained Alumina Ceramics by a Novel Process Integrating Stereolithography and Liquid Precursor Infiltration Processing." ***Ceramics International***, 42, p. 17736-17741, 2016.

J85. Haidong Wu, Yanling Cheng, Wei Liu, Maopeng Zhou, Shanghua Wu, Xuan Song, **Yong Chen**, "Effect of the particle size and the debinding process on the density of alumina parts fabricated by 3D printing based on stereolithography." ***Ceramics International***, 42, p. 17290-17294, 2016.

J86. Tsz-Ho Kwok, Yongqiang Li, **Yong Chen**, "A Structural Topology Design Method Based on Principal Stress Line." ***Computer-aided Design***, Vol. 80, p. 19-31, 2016.

J87. Maopeng Zhou, Wei Liu, Haidong Wu, Xuan Song, **Yong Chen**, Lixia Cheng, Fupo He, Shixi Chen, Shanghua Wu, "Preparation of a Defect-free Alumina Cutting Tool via Additive Manufacturing based on Stereolithography – Optimization of the Drying and Debinding Processes." ***Ceramics International***, Vol. 42(10), p. 11598-11602, 2016.

J88. Haishen Zhao, Fanglin Gu, Qi-Xing Huang, Jorge Garcia, **Yong Chen**, Changhe Tu, Bedrich Benes, Hao Zhang, Daniel Cohen-Or, Baoquan Chen, "Connected Fermat Spirals for Layered Fabrication." ***ACM Transactions on Graphics***, Vol. 35 (4), No. 100, 2016.

J89. Zeyu Chen, Xuan Song, Liwen Lei, Xiaoyang Chen, Chunlong Fei, Chi Tat Chiu, Xuejun Qian, Teng Ma, Yang Yang, Kirk Shung, **Yong Chen**, Qifa Zhou, "3D Printing of Piezoelectric Element for Energy Focusing and Ultrasonic Sensing." ***Nano Energy***, 27, p. 78-86, 2016.

J90. Yuanrui Li, Huachao Mao, He Liu, Yuhan Yao, Yifei Wang, Boxiang Song, **Yong Chen**, Wei Wu, "Stereolithography with Variable Resolutions Using Optical Filter with High-contrast Gratings." ***Journal of Vacuum Science & Technology B***, Vol. 33, No. 06, 2015.

J91. Xuan Song, **Yong Chen**, Tae Woo Lee, Shanghua Wu, Lixia Cheng, "Ceramic Fabrication Using Mask-image-projection-based Stereolithography Integrated with Tape-casting." ***SME Journal of Manufacturing Processes***, Vol. 20, pp. 456-464, 2015.

J92. Yang Yang, Zeyu Chen, Xuan Song, Benpeng Zhu, Tzung Hsiai, Pin-I Wu, Rui Xiong, Jing Shi, **Yong Chen**, Qifa Zhou, K. Kirk Shung, "Three-Dimensional Printing of High Dielectric Capacitor Using Projection based Stereolithography Method." ***Nano Energy***, 22, p.414-421, 2016.

J93. Tsz-Ho Kwok, Charlie C. L. Wang, Dongping Deng, Yunbo Zhang, **Yong Chen** , "4D Printing for Freeform Surfaces: Design Optimization of Origami and Kirigami Structures." ***ASME Journal of Mechanical Design***, Vol. 137, pp. 111712, 2015.

J94. Wei Gao, Yunbo Zhang, Devarajan Ramanujan, Karthik Ramani, **Yong Chen**, Christopher B. Williams, Charlie C. L. Wang, Yung C. Shin, Song Zhang, Pablo D. Zavattieri, "The Status, Challenges, and Future of Additive Manufacturing in Engineering." ***Computer-aided Design***, Vol. 69, 65-89, 2015.

J95. Kai Xu, **Yong Chen**, "Mask Image Planning for Deformation Control in Projection-based Stereolithography Process." ***ASME Journal of Manufacturing Science and Engineering***, 137(3), 031014, 2015.

J96. Charlie C. L. Wang, **Yong Chen**, "Geometric and Physical Modeling for Additive Manufacturing." ***Computer-aided Design***, Vol. 69, 63-64, 2015.

J97. Yayue Pan, **Yong Chen**, "Smooth Surface Fabrication based on Controlled Meniscus and Curing-depth in Micro-Stereolithography." ***ASME Journal of Micro- and Nano-Manufacturing***, 3(3), 031001, 2015.

J98. Xuan Song, Yayue Pan, **Yong Chen**, "Development of a Low-cost Parallel Kinematic Machine for Multi-directional Additive Manufacturing." ***ASME Journal of Manufacturing Science and Engineering***, 137 (2), 021007, 2015.

J99. Hongyi Xu, Yijing Li, **Yong Chen**, Jernej Barbic, "Interactive Material Design Using Model Reduction." ***ACM Transactions on Graphics***, Vol. 34, No. 2, Article 18, 2015.

J100. Pu Huang, **Yong Chen**, Yongqiang Li, Charlie C. L. Wang, "Shape Acquiring and Editing Through Augmented Reality based 3D CAD System." ***Computer-aided Design and Application***, Vol. 12, No. 6, 683-692, 2015.

J101. Dongping Deng, **Yong Chen**, "Origami-based Self-folding Structure Design and Fabrication Using Projection based Stereolithography." ***ASME Journal of Mechanical Design***, 137(2), 021701, 2015.

J102. Qiang Huang, Hadis Nouri, Kai Xu, **Yong Chen**, Sobambo Sosina, Tirthankar Dasgupta, "Statistical Predictive Modeling and Compensation of Geometric Deviations of Three-dimensional Printed Products." ***ASME Journal of Manufacturing Science and Engineering***, 136 (6), 061008, 2014.

J103. Xuejin Zhao, Yayue Pan, Chi Zhou, **Yong Chen**, Charlie C. L. Wang, "An Integrated CNC Accumulation System for Automatic Building-around-inserts." ***SME Journal of Manufacturing Processes***, Vol. 15, pp. 432-443, 2013.

J104. Yayue Pan, Chi Zhou, **Yong Chen**, Jouni Partanen, "Multi-tool and Multi-axis CNC Accumulation for Fabricating Conformal Features on Curved Surfaces." ***ASME Journal of Manufacturing Science and Engineering***, Vol. 136, No. 3, 2014.

J105. **Yong Chen**, Kang Li, Xiaoping Qian, "Direct Geometry Processing for Tele-fabrication." ***ASME Journal of Computing and Information Science in Engineering***, Vol. 13, No. 4, pp. 041002, 2013.

J106. **Yong Chen**, Stephen Stoyan. "Optimal Multi-Piece Mold Design Based on a Mixed-Integer Programming Method." ***International Journal of Computer Integrated Manufacturing***, Vol. 26, No. 10, pp. 939-954, 2013.

J107. Charlie C. L. Wang, **Yong Chen**, "Thickening Freeform Surface for Solid Fabrication." ***Rapid Prototyping Journal***, Vol. 19, No. 6, pp. 395-406, 2013.

J108. Pu Huang, Charlie C. L. Wang, **Yong Chen**, "Intersection-Free and Topologically Faithful Slicing of Implicit Solid." ***ASME Journal of Computing and Information Science in Engineering***, Vol. 13, No. 2, 2013.

J109. **Yong Chen**, Charlie C. L. Wang, "Regulating Complex Geometries Using Layer Depth-Normal Images for Rapid Prototyping and Manufacturing." ***Rapid Prototyping Journal***, Vol. 19, No. 4, pp. 253-268, 2013.

J110. Yuen-Shan Leung, Charlie C. L. Wang, **Yong Chen**, "GPU-based Super-union for Minkowski Sum." ***Computer-aided Design and Application***, Vol. 10, No. 3, pp. 475-487, 2013.

J111. Chi Zhou, **Yong Chen**, Zhigang Yang, Behrokh Khoshnevis, "Digital Material Fabrication Using Mask-Image-Projection-based Stereolithography." ***Rapid Prototyping Journal***, Vol. 19, No. 3, pp. 153-165, 2013.

J112. Yayue Pan, Xuejin Zhao, Chi Zhou, **Yong Chen**, "Smooth Surface Fabrication in Mask Projection based Stereolithography." ***SME Journal of Manufacturing Processes***, Vol. 14, No. 4, pp. 460-470, 2012.

J113. Yayue Pan, Chi Zhou, **Yong Chen**, "A Fast Mask Projection Stereolithography Process for Fabricating Digital Models in Minutes." ***ASME Journal of Manufacturing Science and Engineering***, Vol. 134, No. 5, pp. 051011, 2012.

J114. Chi Zhou, **Yong Chen**, "Additive Manufacturing based on Optimized Mask Video Projection for Improved Accuracy and Resolution." ***SME Journal of Manufacturing Processes***, Vol. 14, No. 2, pp. 107-118, 2012.

J115. Behrokh Khoshnevis, Mahdi Yoozbashizadeh, **Yong Chen**, "Metallic Part Fabrication Using Selective Inhibition Sintering (SIS)." ***Rapid Prototyping Journal***, Vol. 18, No. 2, pp. 144-153, 2012.

J116. **Yong Chen**, Jinho Jung, Yongqiang Li, "A Rapid Shape Acquisition Method by Integrating User Touching Input." ***Virtual and Physical Prototyping***, Vol. 6, No. 3, pp. 133-147, 2011.

J117. Hanli Zhao, Charlie C. L. Wang, **Yong Chen**, Xiaogang Jin, "Parallel and Efficient Boolean on Polygonal Solids." ***Visual Computer***, Vol. 27, No. 6-8, pp. 507-517, 2011.

J118. **Yong Chen**, Chi Zhou, Jingyuan Lao, "A Layerless Additive Manufacturing Process based on CNC Accumulation." ***Rapid Prototyping Journal***, Vol. 17, No. 3, pp. 218-227, 2011 (**RPJ Outstanding Paper Award 2012**).

J119. **Yong Chen**, Charlie C. L. Wang, "Uniform Offsetting of Polygonal Model based on Layered Depth-Normal Images." ***Computer-aided Design***, Vol. 43, No. 1, pp. 31-46, 2011.

J120. Charlie C. L. Wang, Yuen-Shan Leung, **Yong Chen**, "Solid Modeling by Layered Depth-Normal Images on the GPU." ***Computer-aided Design***, Vol. 42, No. 6, pp. 535-544, 2010.

J121. Chi Zhou, **Yong Chen**, Richard A. Waltz, "Optimized Mask Image Projection for Solid Freeform Fabrication." ***ASME Journal of Manufacturing Science and Engineering***, Vol. 131, No. 6, pp. 061004-1~12, 2009.

J122. Chi Zhou, **Yong Chen**, "Three-Dimensional Digital Halftoning for Layered Manufacturing Based on Droplets." ***Transactions of the North American Manufacturing Research Institution of SME***, Vol. 37, pp. 175-182, 2009.

J123. **Yong Chen**, Shanglong Wang, "Computer-aided Product Design with Performance-tailored Meso-structures." ***Computer-aided Design and Application***, Vol. 5, No. 1-4, pp. 565-576, 2008.

J124. **Yong Chen**, "An Accurate Sampling-based Method for Approximating Geometry." ***Computer-aided Design***, Vol. 39, No. 11, pp. 975-986, 2007.

J125. **Yong Chen**, "3D Texture Mapping for Rapid Manufacturing." ***Computer-aided Design and Application***, Vol. 4, No. 6, pp. 761-771, 2007.

J126. Shiva Sambu, **Yong Chen**, and David Rosen. "Geometric Tailoring: A Design For Manufacturing Method for Rapid Prototyping and Rapid Tooling." ***ASME Journal of Mechanical Design***, Vol. 126(4), pp. 571-580, 2004.

J127. **Yong Chen** and David Rosen. "A Reverse Glue Approach to Automated Construction of Multi-Piece Molds with Application to Rapid Tooling." ***ASME Journal of Computing and Information Science in Engineering***, Vol. 3(3), pp. 219-230, 2003.

J128. David Rosen, **Yong Chen**, Shiva Sambu, Janet Allen, and Farrokh Mistree. "The Rapid Tooling Testbed: A Distributed Design-For-Manufacturing System". ***Rapid Prototyping Journal***, Vol. 9(3), pp. 122-132, 2003.

J129. **Yong Chen** and David Rosen. "A Region Based Method to Automated Design of Multi-Piece Molds with Application to Rapid Tooling". ***ASME Journal of Computing and Information Science in Engineering***, Vol. 2(2), pp. 86-97, 2002.

Refereed Conference Proceedings (full paper review):

C1. **Yong Chen**, Han Xu, Yang Xu. "DMD-based Additive Manufacturing: Spatiotemporal Properties and Motion-assisted Image Projection Methods." SPIE Photonics West, 12900-18, San Francisco, CA, January 27- February 1, 2024.

C2. Yeowon Yoon, Yang Xu, **Yong Chen**, "Hierarchical Porous Structure Fabrication Via Hybrid Stereolithography and Inkjet Printing with Sacrificial Liquid." Proceeding of the 2022 International Manufacturing Science and Engineering Conference, MSEC2022-78358, West Lafayette, Indiana, June 27- July 1, 2022.

C3. Yang Xu, Fangjie Qi, Xiangyun Gao, Yujie Shan, Yun Zhou, **Yong Chen**, "Direct Droplet Writing – A Novel Droplet-punching Capillary-splitting 3D Printing Method for Highly Viscous Materials." Proceeding of 49th SME-North American Manufacturing Research Conference, NAMRC49, Cincinnati, Ohio, June 21-25, 2021.

C4. Wenxuan Jia, Yuen-shan Leung, Huachao Mao, Han Xu, Chi Zhou, **Yong Chen**, "Hybrid-light-source Stereolithography for Fabricating Macro-objects with Micro-textures." Proceeding of the 2021 International Manufacturing Science and Engineering Conference, MSEC2021-63717, Cincinnati, Ohio, June 21-25, 2021 (**Best Paper Award**).

C5. Han Xu, Shuai Chen, Huachao Mao, Fuyan Luo, **Yong Chen**, "A Numerically Controlled Shape Memory Alloy Wire Bending Process Using Vat Photopolymerization." Proceeding of 48th SME-North American Manufacturing Research Conference, NAMRC48, Cincinnati, Ohio, June 22-26, 2020.

C6. Yang Xu, Yizhen Zhu, Yifeng Sun, Jie Jin, **Yong Chen**, "A Vibration-assisted Separation Method for Constrained-surface-based Stereolithography." Proceeding of the 2020 International Manufacturing Science and Engineering Conference, MSEC2020-10246, Cincinnati, Ohio, June 22-26, 2020 (**Best Paper Award – 2nd Place**).

C7. Eder Sales, Tsz-Ho Kwok, **Yong Chen**, "Toolpath Generation for Additive Manufacturing Considering Structural Performance." Proceeding of the 2020 International Manufacturing Science and Engineering Conference, MSEC2020-10246, Cincinnati, Ohio, June 22-26, 2020.

C8. Yang Yang, Jie Jin, Xiangjia Li, **Yong Chen**, "Electrically Assisted 3D Printing of Bioinspired Structures." 2019 World Congress on Micro and Nano Manufacturing, Raleigh, NC, U.S.A., September 10-12, 2019.

C9. Yuen-Shan Leung, Tsz-Ho Kwok, Huachao Mao, **Yong Chen**, "Digital Material Design Using Tensor-based Error Diffusion for Additive Manufacturing." Symposium on Solid and Physical Modeling, Vancouver, Canada, June 17-19, 2019.

C10. Akshay Bharadwaj, Yang Xu, Atin Angrish, **Yong Chen**, Binil Starly, "Development of a Pilot Manufacturing Cyberinfrastructure with an Information Rich Mechanical CAD 3D Model Repository" Proceeding of the 2019 International Manufacturing Science and Engineering Conference, MSEC2019-2882, Erie, Pennsylvania, June 10 – 14, 2019.

C11. Yuen-shan Leung, Huachao Mao, **Yong Chen**, "Approximate Functionally Graded Materials for Multi-material Additive Manufacturing" Proceeding of ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2018-86391, Quebec, Canada, August 26-29, 2018.

C12. Xiangjia Li, **Yong Chen**, "Multi-scale 3D Printing of Bioinspired Structures with Functional Surfaces." Proceeding of 2018 International Symposium on Flexible Automation, Kanazawa, Japan, July 15 – 19, 2018.

C13. Xiangjia Li, Benshuai Xie, Jie Jin, Yang Chai, **Yong Chen**, "3D Printing of Temporary Crown and Bridge in Minutes by Temperature-Controlled Mask Image Projection Stereolithography." Proceeding of 46th SME-North American Manufacturing Research Conference, NAMRC46, College Station, TX, June 18 – 22, 2018.

C14. Jie Jin, Jinfan Yang, Huachao Mao, **Yong Chen**, "A Vibration-assisted Method to Reduce Separation Force for Stereolithography." Proceeding of 46th SME-North American Manufacturing Research Conference, NAMRC46, College Station, TX, June 18 – 22, 2018 (**Outstanding Paper Award**).

C15. Xiangjia Li, Huachao Mao, Yayue Pan, **Yong Chen**, "Mask Video Projection based Stereolithography with Continuous Resin Flow to Build Digital Models in Minutes." Proceeding of the 2018 International Manufacturing Science and Engineering Conference, MSEC2018-6708, College Station, Texas, June 18 – 22, 2018.

C16. Yuanrui Li, Pan Hu, Mao Huachao, Mark Hermes, Lucas Zhang, Haneol Lim, Mitul Luhar, Jongseung Yoon, **Yong Chen**, Wei Wu, "Multi-Scale Manufacture for Bio-Inspired Structure Enabled by Variable Voxel Stereolithography." Proceeding of the 2017 IEEE International Conference on Nanotechnology, Pittsburgh, PA, July 25-28, 2017.

C17. Huachao Mao, Yuen-Shan Leung, Yuanrui Li, Pan Hu, Wei Wu, **Yong Chen**, "Multi-scale Stereolithography Using Shaped Beams." Proceeding of the 2017 International Manufacturing Science and Engineering Conference, MSEC2017-3031, Los Angeles, CA, June 4 – 8, 2017.

C18. Xiangjia Li, **Yong Chen**, "Micro-scale Texture Fabrication Using Immersed Surface Accumulation." Proceeding of 45th SME-North American Manufacturing Research Conference, NAMRC45, Los Angeles, CA, June 4 – 8, 2017.

C19. Zhengcai Zhao, Yucan Fu, Jiuhua Xu, **Yong Chen**, "Measurement-based Adaptive Machining by Direct Spatial Deformation of Template CAM Data." Proceeding of the 2017 International Manufacturing Science and Engineering Conference, MSEC2017-2773, Los Angeles, CA, June 4 – 8, 2017.

C20. Jie Jin, **Yong Chen**, "Highly Removable Water Support for Stereolithography." Proceeding of 45th SME-North American Manufacturing Research Conference, NAMRC45, Los Angeles, CA, June 4 – 8, 2017 (**Outstanding Paper Award**).

C21. Xiangjia Li, Yang Yang, **Yong Chen**, "Bio-inspired Micro-scale Texture Fabrication based on Immersed Surface Accumulation Process." 2017 World Congress on Micro and Nano Manufacturing, Kaohsiung, Taiwan, March 27 ~ 30, 2017.

C22. Tsz-Ho Kwok, Hang Ye, **Yong Chen**, Chi Zhou, Wenyao Xu, "Mass Customization: Reuse of Digital Slicing for Continuous Liquid Interface Production." Proceeding of ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC2016-60140, Charlotte, NC, August 21 – 24, 2016.

C23. Pu Huang, Yongqiang Li, **Yong Chen**, Jun Zeng, "A Digital Material Design Framework for 3D Printed Heterogeneous Objects." Proceeding of ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC2016-60181, Charlotte, NC, August 21 – 24, 2016.

C24. Dongping Deng, Archit Jain, Narut Yodvanich, Arthur Araujo, **Yong Chen**, "Three-dimensional Circuit Fabrication Using Four-dimensional Printing and Direct Ink Writing." Proceeding of 2016 International Symposium on Flexible Automation, Cleveland, Ohio, August 1 – 3, 2016.

C25. Haishen Zhao, Fanglin Gu, Qi-Xing Huang, Jorge Garcia, **Yong Chen**, Changhe Tu, Bedrich Benes, Hao Zhang, Daniel Cohen-Or, Baoquan Chen, "Connected Fermat Spirals for Layered Fabrication." Proceeding of SIGGRAPH 2016 Conference, Anaheim, CA, July 24-28, 2016.

C26. Yuanrui Li, Huachao Mao, Yuhan Yao, He Liu, Yifei Wang, Boxiang Song, **Yong Chen**, Wei Wu, "Multiscale Porous Structure Enabled by Variable Voxel Stereolithography." 60th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN), Pittsburgh, PA, May 31- June 3, 2016.

C27. Huachao Mao, Chi Zhou, **Yong Chen**, "LISA: Linear Immersed Sweeping Accumulation." Proceeding of 44th SME-North American Manufacturing Research Conference, NAMRC44, Blacksburg, VA, June 27 – July 1, 2016 (**Outstanding Paper Award**).

C28. Kai Xu, Tsz-Ho Kwok, **Yong Chen**, "A Reverse Compensation Framework for Shape deformation in Additive Manufacturing." Proceeding of the 2016 International Manufacturing Science and Engineering Conference, MSEC2016-8815, Blacksburg, VA, June 27 – July 1, 2016.

C29. Xuan Song, Zhuofeng Zhang, Zeyu Chen, **Yong Chen**, "Porous Structure Fabrication Using a Stereolithography-based Sugar Foaming Method." Proceeding of the 2016 International Manufacturing Science and Engineering Conference, MSEC2016-8826, Blacksburg, VA, June 27 – July 1, 2016.

C30. Tsz-Ho Kwok, Weiwei, Wan, Jia Pan, Charlie Wang, Jianjun Yuan, Kensuke Harada, **Yong Chen**, "Rope Caging and Grasping." Proceeding of IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, May 16-21, 2016.

C31. Xiangjia Li, Tommaso Baldacchini, Xuan Song, **Yong Chen**, "Multi-scale Additive Manufacturing: An Investigation on Building Objects with Macro-, Micro- and Nano-scales Features." The 11th International Conference on MicroManufacturing (ICOMM 2016), Irvine, CA, March 29 ~ 31, 2016.

C32. Dongping Deng, **Yong Chen**, "4D Printing: Design and Fabrication of Low Curvature 3D Shell Structures Using Controlled Self-Folding Method." ASME Manufacturing Science and Engineering Conference, MSEC2015-9459, Charlotte, NC, June 8 -12, 2015.

C33. Xuan Song, **Yong Chen**, Tae Woo Lee, Shanghua Wu, Lixia Cheng, "Ceramic Fabrication Using Mask-image-projection-based Stereolithography Integrated with Tape-casting." Proceeding of 43rd SME-North American Manufacturing Research Conference, NAMRC43, Charlotte, NC, June 8 -12, 2015.

C34. Qiang Huang, Hadis Nouri, Kai Xu, **Yong Chen**, Sobambo Sosina, and Tirthankar Dasgupta, "Predictive Modeling of Geometric Deviations of 3D Printed Products – A Unified Modeling Approach for Cylindrical and Polygon Shapes." The 2014 IEEE International Conference on Automation Science and Engineering (CASE 2014), Taipei, Taiwan, August 18-22, 2014 (**Best Application Paper Award Finalist)**.

C35. Dongping Deng, **Yong Chen**, "Origami-based Self-folding Structure Fabrication based on 3D Printing on Polystyrene Film." ASME Mechanism and Robotics Conference, DETC2014-34901, Buffalo, NY, USA, Aug. 17 ~ 20, 2014.

C36. Kai Xu, **Yong Chen**, "Curing Temperature Study for Curl Distortion Simulation in Mask Image Projection based Stereolithography." ASME Computers and Information in Engineering Conference, DETC2014-34908, Buffalo, NY, USA, Aug. 17 ~ 20, 2014.

C37. Kai Xu, **Yong Chen**, "Deformation Control Based on In-situ Sensors for Mask Projection based Stereolithography." Proceeding of the 2014 International Manufacturing Science and Engineering Conference, MSEC2014-4055, Detroit, Michigan, June 9 - 13, 2014.

C38. Yayue Pan, **Yong Chen**, "Smooth Surface Fabrication based on Controlled Meniscus in Micro-Stereolithography." The 9th International Conference on MicroManufacturing (ICOMM 2014), Singapore, March 25 ~ 28, 2014.

C39. Dongping Deng, **Yong Chen**, "An Origami Inspired Additive Manufacturing Process for Building Thin-shell Structures." International Mechanical Engineering Congress and Exposition, IMECE2013-65720, San Diego, CA, USA, Nov. 15 ~ 21, 2013.

C40. Tony Di Carlo, Behrokh Khoshnevis, **Yong Chen**, "Manufacturing Additively with Fresh Concrete." International Mechanical Engineering Congress and Exposition, IMECE2013-63996, San Diego, CA, USA, Nov. 15 ~ 21, 2013.

C41. Pu Huang, Dongping Deng, **Yong Chen**, "Modeling and Fabrication of Heterogeneous Three-dimensional Objects based on Additive Manufacturing." International Mechanical Engineering Congress and Exposition, IMECE2013-65724, San Diego, CA, USA, Nov. 15 ~ 21, 2013.

C42. Xuejin Zhao, Yayue Pan, Chi Zhou, **Yong Chen**, Charlie C. L. Wang, "An Integrated CNC Accumulation System for Automatic Building-around-inserts." Proceeding of 41st SME-North American Manufacturing Research Conference, NAMRC41-1574, Madison, WI, June 10 -14, 2013 (**Outstanding Paper Award**).

C43. Yayue Pan, **Yong Chen**, "Fast Micro-Stereolithography Process based on Bottom-up Projection for Complex Geometry." The 8th International Conference on MicroManufacturing (ICOMM 2013), Victoria, Canada, March 25 ~ 28, 2013 (**Honorable Mention Paper Award)**.

C44. Kai Xu, **Yong Chen**, "Mask Image Planning for Deformation Control in Projection-based Stereolithography Process." ASME Computers and Information in Engineering Conference, DETC2012-71523, Chicago, IL, USA, Aug. 12 ~ 15, 2012.

C45. Dongping Deng, **Yong Chen**, "Design of Origami Sheets for Foldable Object Fabrication." ASME Design Automation Conference, DETC2012-71530, Chicago, IL, USA, Aug. 12 ~ 15, 2012.

C46. **Yong Chen**, Kang Li, Xiaoping Qiang, "Direct Geometry Processing for Tele-fabrication." ASME Computers and Information in Engineering Conference, DETC2012-71483, Chicago, IL, USA, Aug. 12 ~ 15, 2012 (**CAPPD Best Paper Award**).

C47. Xuan Song, **Yong Chen**, "Joint Design for 3-D Printing Non-assembly Mechanism." ASME Design for Manufacturing and the Life Cycle Conference, DETC2012-71528, Chicago, IL, USA, Aug. 12 ~ 15, 2012.

C48. Yayue Pan, **Yong Chen**, Chi Zhou, "Fast Recoating Methods for the Projection-based Stereolithography Process in Micro- and Macro-scales." Proceedings of Solid Freeform Fabrication Symposium, Austin, Texas, August 8~10, 2012.

C49. Dongping Deng, **Yong Chen**, Chi Zhou, "Investigation on PEEK Fabrication Using Mask-image-projection-based Stereolithography." Proceedings of Solid Freeform Fabrication Symposium, Austin, Texas, August 8~10, 2012.

C50. Yuen-Shan Leung, Charlie C. L. Wang, **Yong Chen**, "GPU-based Minkowski Sum with Enclosed Voids." International CAD Conference and Exhibition, Niagara Falls, Canada, June 11 ~ 14, 2012.

C51. Hamid Chabok, Chi Zhou, **Yong Chen**, Arash Eskandarinazhad, Qifa Zhou, and Kirk Shung, "Ultrasound Transducer Array Fabrication Based on Additive Manufacturing of Piezocomposites." ASME/ISCIE International Symposium on Flexible Automation (ISFA), St. Louis, Missouri, June 18-20, 2012.

C52. Yayue Pan, Chi Zhou, **Yong Chen**, "Rapid Manufacturing in Minutes: The Development of a Mask Projection Stereolithography Process for High-speed Fabrication." Proceeding of the 2012 International Manufacturing Science and Engineering Conference, MSEC2012-7232, Notre Dame, Indiana, June 4 - 8, 2012 (**Best Paper Award – 3rd Place**).

C53. Yayue Pan, Xuejin Zhao, Chi Zhou, **Yong Chen**, "Smooth Surface Fabrication in Mask Projection based Stereolithography." Proceeding of 40th SME-North American Manufacturing Research Conference, NAMRC40-7715, Notre Dame, Indiana, June 4 - 8, 2012.

C54. Behrokh Khoshnevis, Mahdi Yoozbashizadeh, **Yong Chen**, "Bronze and Titanium Fabrication by the Concept of Selective Inhibition Sintering." The Minerals, Metals & Materials Society (TMS) 141st Annual Meeting and Exhibition, Orlando, FL, March 11-15, 2012.

C55. Pu Huang, Charlie C. L. Wang, **Yong Chen**, "Self-Intersection Free and Topologically Faithful Slicing of Implicit Solid." ASME Computers and Information in Engineering Conference, DETC2011-47661, Washington, DC, USA, Aug. 28 ~ 31, 2011 (**CAPPD Best Paper Award**).

C56. Yayue Pan, **Yong Chen**, Chi Zhou, "Fabrication of Smooth Surfaces based on Mask Projection Stereolithography." Proceedings of Solid Freeform Fabrication Symposium, pp. 263-278, Austin, Texas, August 8~10, 2011.

C57. Chi Zhou, **Yong Chen**, Zhigang Yang, Behrokh Khoshnevis, "Development of Multi-material Mask-Image-Projection-based Stereolithography Process for the Fabrication of Digital Materials." Proceedings of Solid Freeform Fabrication Symposium, pp. 65-80, Austin, Texas, August 8~10, 2011.

C58. Yayue Pan, Chi Zhou, **Yong Chen**, Jouni Partanen, "Fabrication of Conformal Ultrasound Transducer Arrays and Horns Based on Multi-axis CNC Accumulation." Proceeding of the 2011 International Manufacturing Science and Engineering Conference, MSEC2011-50139, Corvallis, Oregon, June 13 - 17, 2011.

C59. Chi Zhou, **Yong Chen**, "Additive Manufacturing based on Optimized Mask Video Projection for Improved Accuracy and Resolution." Proceeding of 39th SME-North American Manufacturing Research Conference, NAMRC39-4725, Corvallis, Oregon, June 13 - 17, 2011 (**Outstanding Paper Award**).

C60. Hanli Zhao, Charlie C. L. Wang, **Yong Chen**, Xiaogang Jin, "Parallel and Efficient Boolean on Polygonal Solids." Computer Graphics International (CGI) 2011, Ottawa, Canada, June 12 - 15, 2011.

C61. Behrokh Khoshnevis, Mahdi Yoozbashizadeh, **Yong Chen**, "Metallic Part Fabrication Using Selective Inhibition Sintering (SIS)." Materials Science & Technology 2011 - Proceedings: Additive Manufacturing of Metals, Editors: I. Harris, U. Ackelid, O. Harrysson, S. Babu, and B. Stucker, Columbus, OH, Oct. 16-20, 2011.

C62. **Yong Chen**, Xiaoshu Xu, "Robust Geometric Computation for Complex Component Design and Manufacturing." Proceeding of 2011 NSF Engineering Research and Innovation Conference, Atlanta, Georgia, January 4 - 7, 2011.

C63. Stephen Stoyan, **Yong Chen**. "Multi-Piece Mold Design Based on Linear Integer Programming Toward Guaranteed Optimality." Int'l Conference on Manufacturing Automation (ICMA 2010), Hong Kong, China, Dec. 13~15, 2010.

C64. **Yong Chen**, Xiaoshu Xu. "Manufacturability Analysis of Infeasible Features in Polygonal Models for Web-based Rapid Prototyping." Int'l Conference on Manufacturing Automation (ICMA 2010), Hong Kong, China, Dec. 13~15, 2010.

C65. Hamid Reza Chabok, Chi Zhou, Shima Alagha, **Yong Chen**, Qifa Zhou, and Kirk K. Shung, "Development of a Digital Micro-Manufacturing Process for High-Frequency Ultrasound Transducers." IEEE International Ultrasonics Symposium, San Diego, California, October 11 ~ 14, 2010.

C66. Chi Zhou, **Yong Chen**, "Additive Manufacturing based on Multiple Calibrated Projectors and Its Mask Image Planning." ASME Design Automation Conference, DETC2010-28922, Montreal, Quebec, Canada, Aug. 15 ~ 18, 2010.

C67. Yongqiang Li, **Yong Chen**, "Five-axis Manufacturing Simulation based on Normal Arc Mapping and Offset Volume Computation." ASME Computers and Information in Engineering Conference, DETC2010-29051, Montreal, Quebec, Canada, Aug. 15 ~ 18, 2010.

C68. **Yong Chen**, Charlie C. L. Wang, "Contouring of Structured Points with Small Features." ASME Computers and Information in Engineering Conference, DETC2010-29094, Montreal, Quebec, Canada, Aug. 15 ~ 18, 2010.

C69. Yongqiang Li, **Yong Chen**, "Beam Structure Optimization for Additive Manufacturing based on Principal Stress Lines." Proceedings of Solid Freeform Fabrication Symposium, Austin, Texas, August 8~11, 2010.

C70. **Yong Chen**, Chi Zhou, Jingyuan Lao, "Additive Manufacturing without Layers: A New Solid Freeform Fabrication Process based on CNC Accumulation." Proceedings of Solid Freeform Fabrication Symposium, Austin, Texas, August 8~11, 2010 (**SFF Symposium Outstanding Paper**).

C71. Yongqiang Li, **Yong Chen**, Chi Zhou, "Design of Flexible Skin for Target Displacements based on Meso-Structures." ASME Computers and Information in Engineering Conference, DETC2009/CIE-87137, San Diego, California, Aug. 30 ~ Sept. 2, 2009.

C72. Chi Zhou, **Yong Chen**, Richard A. Waltz, "Optimized Mask Image Projection for Solid Freeform Fabrication." ASME Design Automation Conference, DETC2009/DAC-86268, San Diego, California, Aug. 30 ~ Sept. 2, 2009.

C73. Chi Zhou, **Yong Chen**, "Calibrating Large-area Mask Projection Stereolithography for Its Accuracy and Resolution Improvements." Proceedings of Solid Freeform Fabrication Symposium, Austin, Texas, August 2009.

C74. Behrokh Khoshnevis, Mahdi Yoozbashizadeh, **Yong Chen**, "Metallic Parts Fabrication with Selective Inhibition Sintering." Supplemental Proceedings: Volume 1: Fabrication, Materials, Processing and Properties, The Minerals, Metals, & Materials Society (TMS) 2009, pp. 381~388.

C75. **Yong Chen**, Charlie C. L. Wang, "Layer Depth-Normal Images for Complex Geometries – Part One: Accurate Modeling and Adaptive Sampling." ASME Computers and Information in Engineering Conference, DETC2008-49432, Brooklyn, New York, August 3 ~ 6, 2008 (**Best Paper Award**).

C76. Charlie C. L. Wang, **Yong Chen**, "Layer Depth-Normal Images for Complex Geometries – Part Two: Manifold-Preserved Adaptive Contouring." ASME Computers and Information in Engineering Conference, DETC2008-49576, Brooklyn, New York, August 3 ~ 6, 2008.

C77. **Yong Chen**, Shanglong Wang, "Computer-aided Product Design with Performance-tailored Mesostructures." International CAD Conference and Exhibition, Orlando, Florida, June 23 ~ 27, 2008.

C78. **Yong Chen**, "Accurate and Robust Boolean Operations on Polygonal Models." ASME Computers and Information in Engineering Conferences, DETC2007-35731, Las Vegas, Nevada, Sept. 4 ~ 7, 2007.

C79. **Yong Chen**, "Non-uniform Offsetting for Laser Path Planning of Solid Freeform Fabrication Machines." Proceedings of Solid Freeform Fabrication Symposium, pp. 174-186, Austin, Texas, August 6 ~ 8, 2007.

C80. **Yong Chen**, "3D Texture Mapping for Rapid Manufacturing." International CAD Conference and Exhibition, Honolulu, Hawaii, June 25 ~ 29, 2007.

C81. **Yong Chen**, "A Mesh-based Geometric Modeling Method for General Structures." ASME Computers and Information in Engineering Conferences, DETC2006-99513, Philadelphia, Pennsylvania, Sept. 10 ~ 13, 2006.

C82. **Yong Chen**, Hongqing Wang, David Rosen, and Jarek Rossignac, 2005, "Filleting and Rounding Using A Point-Based Method." ASME Design Automation Conference, DETC2005/DAC-85408, Long Beach, California, Sept. 24 ~ 28, 2005.

C83. Hongqing Wang, **Yong Chen**, and David Rosen, 2005, "A Hybrid Geometric Modeling Method for Large Scale Conformal Cellular Structures." ASME Computers and Information in Engineering Conference, DETC2005/CIE-85366, Long Beach, California, Sept. 24 ~ 28, 2005 (**Best Paper Award**).

C84. **Yong Chen** and David Rosen. "A Reverse Glue Approach to Automated Construction of Multi-Piece Molds." ASME Computers and Information in Engineering Conference, DETC2003/CIE-48171, Chicago, Illinois, Sept. 9-12, 2003.

C85. David Rosen, **Yong Chen**, Shiva Sambu, Janet Allen, and Farrokh Mistree, 2002. "The Rapid Tooling Testbed: A Distributed Design-For-Manufacturing System." Int'l Conference on Manufacturing Automation (ICMA 2002), Hong Kong, China, Dec. 10~12, 2002.

C86. Shiva Sambu, **Yong Chen**, and David Rosen. "Geometric Tailoring: A Design For Manufacturing Method for Rapid Prototyping and Rapid Tooling." ASME Design for Manufacturing Conference, DETC2002/DFM-34169, Montreal, Canada, Sept. 29 ~ Oct. 2, 2002.

C87. **Yong Chen** and David Rosen. "A Region-based Method to Automated Design of Multi-Piece Molds with Application to Rapid Tooling." ASME Computers and Information in Engineering Conference, DETC2001/CIE-21294, Pittsburgh, Pennsylvania, Sept. 9-12, 2001.

C88. **Yong Chen** and David Rosen. "Problem Formulation and Basic Elements for Automated Multi-Piece Mold Design." ASME Computers and Information in Engineering Conference, DETC2001/CIE-21293, Pittsburgh, Pennsylvania, Sept. 9-12, 2001.

C89. David Rosen, **Yong Chen**, Jonathan Gerhard, Janet Allen, and Farrokh Mistree, 2000, "Design Decision Templates and Their Implementation for Distributed Design and Fabrication." ASME DETC 2000 Conference, DAC-14293, Baltimore, Maryland, Sept. 10-13, 2000.

C90. Jonathan Gerhard, Scott Duncan, **Yong Chen**, Janet Allen, David Rosen, Farrokh Mistree and Andrew Dugenske. 1999. "Towards a Decision-Based, Distributed Product Realization Environment for Engineering Systems." ASME DETC 1999 Conference, CIE-9085, Las Vegas, Nevada, Sept. 14-17, 1999.

Non-refereed Conference Proceedings (Presentation only):

C91. Yeowon Yoon, Yang Xu, **Yong Chen**. "On-demand Printing of Metallic Polymer Composite Microstructures via Hybrid 3D Printing." Material Research Society (MRS) Fall Meeting & Exhibit, Boston, MA, November 26- December 1, 2023.

C92. **Yong Chen**. "Device Design Enabled by Multi-scale, Multi-material, and Multi-functional Vat Photopolymerization." ASTM International Conference on Advanced Manufacturing (ICAM 2023), Washington D.C, October 30 - November 3, 2023.

C93. **Yong Chen**, "In-situ Transfer Vat Photopolymerization for Super High-resolution Gaps." International Conference of Additive Manufacturing for a Better World, Session Polymer AM, Singapore, August 23, 2022.

C94. William Pannell, Sofia Bougioukli, Xuan Song, B Ortega, Osamu Sugiyama, Amy Tang, **Yong Chen**, Jay Lieberman. "Three-Dimensionally Printed Calcium Phosphate Scaffolds with Gene Therapy for Difficult Bone Graft Scenarios in a Rodent Model." American Academy of Orthopaedic Surgeons Annual Meeting, San Diego, CA, March 14-17, 2017.

C95. Stephen Stoyan, **Yong Chen**. "Mixed-integer Programming Approach to Multi-piece Mold Design and Supply Chain Extensions." Institute of Operational Research and Management Science (INFORMS) Annual Meeting 2011, Charlotte, NC, Nov. 15, 2011.

C96. Behrokh Khoshnevis, Anahita Afshin Navid, Mahdi Yoozbashizadeh, **Yong Chen**, "Moldless Powder Metallurgy by Sintering Inhibition." Proceedings of Industrial Engineering Research Conference, Nashville, Tennessee, May 19 ~ 23, 2007.

Theses:

Yong Chen, "Computer-aided Design for Rapid Tooling: Methods for Mold Design and Design-for-Manufacture." Ph.D. Dissertation, G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 2001.

PATENTS

Patents Issued:

P1. William Pannell, Jay Lieberman, **Yong Chen**, Xuan Song, Sofia Bougioukli, "Growth Factor Transduced Cell-loaded Ceramic Scaffold for Bone Regeneration and Repair." University of Southern California. USP 12,016,779, June 2024.

P2. Yang Chai, **Yong Chen**, Yuan Yuan, Yuxing Gao, Xiangjia Li, Zoe Johnson, "Stem Cells and Devices for Bone Regeneration." University of Southern California. EP 3707240, April 24, 2024.

P3. **Yong Chen**, Jie Jin, "Methods and Apparatus for Vibration-assisted Stereolithography." University of Southern California. USP 11858213B2, Granted date: January 2024.

P4. **Yong Chen**, Huachao Mao, "Sliding Window Screen for Reducing Resin Refilling Time in Stereolithography." University of Southern California. USP 11,707,884, Granted date: July 2023.

P5. Yang Chai, **Yong Chen**, Yuan Yuan, Yuxing Gao, Xiangjia Li, "Stem Cells and Devices for Bone Regeneration." University of Southern California. USP 11,484,625, November 2022.

P6. **Yong Chen**, Yang Xu, "Automatic Reusable Support for 3D Printing." University of Southern California. USP 11485091B2, Granted date: November 2022.

P7. **Yong Chen**, Yuanrui Li, Huachao Mao, Wei Wu, "3D Printing with Variable Voxel Sizes." USP 11,230,057, Granted date: January 2022.

P8. **Yong Chen**, Xiangjia Li, "Surface Projection Tool for Multi-axis Additive Manufacturing." University of Southern California. USP 11,214,005, Granted date: January 2022.

P9. **Yong Chen**, Jie Jin, "SLA Additive Manufacturing Using Frozen Supports on Non-SLA Material." University of Southern California. USP 10,894,354, Granted date: January 2021.

P10. **Yong Chen**, Huachao Mao, "Linear-immersed Sweeping Accumulation for 3D Printing." University of Southern California. USP 10,814,546, Granted date: October 2020.

P11. Wei Wu, **Yong Chen**, Yuanrui Li, Huachao Mao, "3D Printing with Variable Voxel Sizes based on Optical Filter." USP 10,688,771, Granted date: June 2020.

P12. **Yong Chen**, Huachao Mao, Xiangjia Li, "Mask Video Projection based Stereolithography with Continuous Resin Flow." University of Southern California. USP10,308,007, Granted date: 06/04/2019.

P13. **Yong Chen**, Yayue Pan, "Process Planning of Meniscus Shapes for Fabricating Smooth Surfaces in Mask Image Projection based Additive Manufacturing." University of Southern California. USP 9,943,996, Granted date: April 2018.

P14. Thomas A. Kerekes, Jouni P. Partanen, **Yong Chen** and Charles W. Hull. "Improved Wall Smoothness, Feature Accuracy and Resolution in Projected Images Via Exposure Levels in Solid Imaging." 3D Systems, Inc. EP 189404B1, Granted date: 06/28/2017.

P15. Behrokh Khoshnevis, Hongsheng Tong, **Yong Chen**, John Pham, Robert Lee. "Orthodontic Appliance with Snap Fitted, Non-Sliding Archwire." University of Southern California. USP 9,427,291, Granted date: 8/30/2016.

P16. Thomas A. Kerekes, Jouni P. Partanen, **Yong Chen** and Charles W. Hull. "Wall Smoothness, Feature Accuracy and Resolution in Projected Images Via Exposure Levels in Solid Imaging." 3D Systems, Inc. USP patent No. 9,415,544, Granted date: 8/16/2016.

P17. **Yong Chen**, Chi Zhou. "Computer Numerical Control (CNC) Additive Manufacturing." University of Southern California. USP Patent No. 9,221,216, Granted date: 12/29/2015.

P18. **Yong Chen**, Chi Zhou. "Digital Mask-image-projection-based Additive Manufacturing that Applied Shearing Force to Detach Each Added Layer." University of Southern California. USP Patent No. 9,120,270, Granted date: 9/1/2015.

P19. **Yong Chen** and Rajeev Kulkarni. "Support Volume Calculation for a CAD Model." 3D Systems, Inc. USP patent No. 6,907,307, Granted date: 6/14/2005.

Patent Applications:

P20. **Yong Chen**, Huachao Mao, "Hopping Light Additive Manufacturing." University of Southern California. November 2024, US Application No. 18/836,456.

P21. **Yong Chen**, Han Xu, "Continuous Vat Photopolymerization for Three-dimensional Printing." University of Southern California. April 2024, PCT/US2024/024690.

P22. **Yong Chen**, Yang Xu, Huachao Mao, "Vat Photopolymerization 3D Printing Method and Apparatus." University of Southern California. February 2024, US Application No. 18/294,990.

P23. **Yong Chen**, Huachao Mao, "Curing-on-demand Printheads for Multi-material 3D Printing." University of Southern California. US 17504169, April 2022 (Applied).

INVITED TALKS (WITHIN LAST FIVE YEARS)

T1. "Multi-scale, Multi-material, and Multi-functional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Industrial and Systems Engineering, Hong Kong Polytechnical University, Hong Kong, April 22, 2025.

T2. "Advancing Mechanical and Aerospace Systems through Multi-scale, Multi-material, and Multi-functional Additive Manufacturing." Department of Mechanical and Aerospace Engineering, Hong Kong University of Science and Technology, Hong Kong, February 17, 2025.

T3. "Physical Field-assisted Additive Manufacturing of Bio-inspired Structures." Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, December 25, 2024.

T4. "Multi-material Additive Manufacturing of Programmable Metallic Polymer Composite." Department of Mechanical Engineering, University of California – Riverside, Riverside, CA, November 7, 2024.

T5. "Hybrid Additive Manufacturing of Programmable Metallic Polymer Composite." Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK, October 7, 2024.

T6. "(Keynote) Mechatronics Design Enabled by Multi-scale, Multi-material, and Multi-functional Additive Manufacturing." 30th IEEE International Conferences on Mechatronics and Machine Vision in Practice, M2VIP 2024, Leeds, UK, October 4, 2024.

T7. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Aerospace and Mechanical Engineering, University of Norte Dame, Norte Dame, IN, September 3, 2024.

T8. "Device Designs Enabled by Multi-scale, Multi-material, and Multi-functional Vat Photopolymerization." Monash Center for Additive Manufacturing, Monash University, Clayton, Victoria, Australia, March 12, 2024.

T9. "3D Printing Multi-scale, Multi-material, and Multi-functional Structures and Devices for Biomedical Engineers." Alfred E. Mann Department of Biomedical Engineering, University of Southern California, Los Angeles, CA, January 26, 2024.

T10. "Device Designs Enabled by Multi-scale, Multi-material, and Multi-functional Vat Photopolymerization." Invited talk, Design for Additive Manufacturing Track, International Conference on Advanced Manufacturing (ICAM) 2023, Washington D.C., November 1, 2023.

T11. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Printed Electronics team meeting (online), Northrop Grumman Corportion, October 10, 2023.

T12. "Projection-based Additive Manufacturing: Spatiotemporal Properties and Data-driven Image Planning Methods." Farsoon, Changsha, Hunan, China, July 13, 2023.

T13. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Precision Machinery and Instrumentation, University of Science and Technology of China, Hefei, China, July 11, 2023.

T14. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." ZSFab Inc., Tongxiang, Zhejiang, China, July 7, 2023.

T15. "Projection-based Additive Manufacturing: Spatiotemporal Properties and Data-driven Image Planning Methods." Systems Hub - Thrust of Smart Manufacturing, Hong Kong University of Science and Technology (Guangzhou), Guangdong, June 29, 2023.

T16. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Mechanical Engineering, Michigan State University, Lansing, MI, April 18, 2023.

T17. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Mechanical Engineering, Iowa State University, Ames, Iowa, March 7, 2023.

T18. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Fowler School of Engineering, Chapman University, Orange, CA, February 6, 2023.

T19. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Production Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, November 9, 2022.

T20. "Projection-based Additive Manufacturing: Spatiotemporal Properties and Data-driven Image Planning Methods." Invited Plenary Talk, The International Mechanical Engineering Congress & Exposition (IMECE), Columbus, Ohio, November 1, 2022.

T21. "3D Printing and Digital Dentistry." USC Viterbi Expo, Los Angeles, CA, October 23, 2022.

T22. "Multiscale and Multimaterial Additive Manufacturing of Bio-inspired Structures and Entrepreneurship." USC Engineering Honors Colloquium, Los Angeles, CA, October 7, 2022.

T23. "Projection-based Additive Manufacturing: Spatiotemporal Properties and Process Innovations." Invited Talk, International Journal of Extreme Manufacturing (IJEM) Online Forum on Additive Manufacturing, June 10, 2022.

T24. "3D Printing from Rapid Prototyping to Rapid Manufacturing." Invited Short Course, The 65th International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication (EIPBN), New Orleans, LA, May 31, 2022.

T25. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." School of Power and Mechanical Engineering, Wuhan University, Wuhan, Hubei, China, February 24, 2022.

T26. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen, China, January 11, 2022.

T27. "Multiscale, Multimaterial, and Multifunctional Additive Manufacturing of Bio-inspired Structures and Smart Devices." Department of Mechanical and Aerospace Engineering, Hong Kong University of Science and Technology, Hong Kong, China, January 5, 2022.

T28. "Multi-material Fabrication via Hybrid Vat Photopolymerization." School of Mechanical and Electrical Engineering, Guangdong University of Technology, Guangzhou, Guangdong, China, December 31, 2021.

T29. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." School of Mechanical Engineering, Zhejiang University, Hangzhou, China, December 24, 2021.

T30. "Multi-material Fabrication via Hybrid Vat Photopolymerization." School of Mechanical Engineering, Jiangnan University, Wuxi, China, December 12, 2021.

T31. "Multi-material Fabrication via Hybrid Additive Manufacturing." Department of Mechanical and Electrical Engineering, Xiamen University, Xiamen, Fujian, China, December 1, 2021.

T32. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." Department of Mechanical Engineering Distinguished Speaker Series, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 4, 2021.

T33. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." Department of Mechanical Engineering, University of Nevada, Reno, Nevada, September 10, 2021.

T34. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, California, January 20, 2021.

T35. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, Kansas, November 3, 2020.

T36. "Additive Manufacturing of Bio-inspired Structures via Multiscale, Multimaterial, and Multifunctional 3D Printing." Department of Industrial and Systems Engineering, Texas A&M University, College Station, Texas, October 30, 2020.

CONFERENCE PRESENTATIONS

T37. (Invited) "Hybrid 3D Printing Empowering Programmable Metallic Polymer Composite Design." Society of Engineering Science (SES) 2024 Annual Technical Meeting, Session 6.5: Soft Electronics: Mechanics, Materials, Manufacturing and Devices, Hangzhou, Zhejiang, China, August 22, 2024.

T38. (Invited) "In-situ Transfer Vat Photopolymerization for Super High-resolution Gaps." International Conference of Additive Manufacturing for a Better World, Session Polymer AM, Singapore (Hybrid Conference), August 23, 2022.

T39. "Approximate Functionally Graded Materials for Multi-material Additive Manufacturing." ASME 2018 Computers and Information in Engineering Conference (CIE), Session 8-3: Materials Modeling and Process Quality, Quebec City, Canada, August 28, 2018.

T40. "Multi-scale 3D Printing of Bioinspired Structures with Functional Surfaces." 2018 International Symposium on Flexible Automation, OS1: Additive Manufacturing Sensing and Control I, Kanazawa, Japan, July 16, 2018.

T41. "(Plenary) Automatic and Reusable Metal Support for 3D Printing." The 28th International Solid Freeform Fabrication Symposium, Plenary Session, Austin, Texas, August 7, 2017.

T42. "Invited talk: Additive Manufacturing of Controlled Anisotropic Materials via Electrically Assisted Nanocomposite Fabrication." Symposium M, 9th International Conference on Materials for Advanced Technologies (ICMAT), Singapore, June 21, 2017.

T43. "Bio-inspired Micro-scale Texture Fabrication based on Immersed Surface Accumulation Process." 2017 World Congress on Micro and Nano Manufacturing (WCMNM), Session 10: Additive Manufacturing II, Kaohsiung, Taiwan, March 29, 2017.

T44. "3D Circuit Fabrication Using 4D Printing and Direct Ink Writing." 2016 International Symposium on Flexible Automation, T2: Flexible Automation in Manufacturing Systems II, Cleveland, Ohio, August 2, 2016.

T45. "An Interactive Structural Topology Design Method based on Principal Stress Line for Additive Manufacturing." 2015 SIAM Conference on Geometric and Physical Modeling, Additive Manufacturing, MS13: Geometric Modeling and Processing in Additive Manufacturing, Salt Lake City, Utah, October 14, 2015.

T46. "Piezoelectric Device Fabrication Based on 3D Printing Barium Titanate Ceramics." International Solid Freeform Fabrication Symposium, Applications III: Electronics, Mechatronics, Robotics, Austin, Texas, August 11, 2015.

T47. "A Digital Material Design Framework for 3D Printed Heterogeneous Objects." International Solid Freeform Fabrication Symposium, CAD/CAE, Austin, Texas, August 10, 2015.

T48. "Shape Acquiring and Editing Through an Augmented Reality based 3D CAD System." 11th International CAD Conference and Exhibition (CAD2014), Virtual and Augmented Reality, Hong Kong, China, June 23, 2014.

T49. "Smooth Surface Fabrication based on Controlled Meniscus in Micro-Stereolithography." International Conference on Micromanufacturing, Additive Manufacturing, Singapore, March 26, 2014.

T50. "Micro-scale Fabrication in Large Area: Investigation on Integrating Large-Area and Micro-scale Mask Projection Stereolithography." International Solid Freeform Fabrication Symposium, Micro- and Nano-Additive Manufacturing, Austin, Texas, August 14, 2013.

T51. "An Integrated CNC Accumulation System for Automatic Building-around-inserts." SME-North American Manufacturing Research Conference, Manufacturing Systems, Madison, WI, June 11, 2013.

T52. "Fast Micro-Stereolithography Process based on Bottom-up Projection for Complex Geometry." International Conference on Micromanufacturing, Additive Manufacturing, Victoria, Canada, March 27, 2013.

T53. "Fast Recoating Methods for the Projection-based Stereolithography Process in Micro- and Macro-scales." International Solid Freeform Fabrication Symposium, Process Development I, Austin, Texas, August 7, 2012.

T54. "Investigation on PEEK Fabrication Using Mask-image-projection-based Stereolithography." International Solid Freeform Fabrication Symposium, Materials II, Austin, Texas, August 7, 2012.

T55. "Development of a Direct 3D Interface for Computer-aided Design Systems to Enable Personal Manufacturing." International Solid Freeform Fabrication Symposium, Molding I, Austin, Texas, August 6, 2012.

T56. "Ultrasound Transducer Array Fabrication based on Additive Manufacturing of Piezocomposites." ASME/ISCIE International Symposium on Flexible Automation, Applications of Additive Manufacturing Session, St. Louis, Missouri, June 18, 2012.

T57. "Rapid Manufacturing in Minutes: The Development of a Mask Projection Stereolithography Process for High-speed Fabrication." International Manufacturing Science and Engineering Conference, Layer Manufacturing Session, Notre Dame, Indiana, June 5, 2012.

T58. "Direct Digital Manufacturing of Structured Points with Complex Geometries." International Solid Freeform Fabrication Symposium, Modeling I Session, Austin, Texas, August 9, 2011.

T59. "Development of a Mask-Image-Projection based Additive Manufacturing Process for the Fabrication of Digital Materials." International Solid Freeform Fabrication Symposium, Process Development I (Plenary Session), Austin, Texas, August 8, 2011.

T60. "High-frequency Ultrasound Transducer Fabrication based on additive Manufacturing of Piezo-Composites." International Solid Freeform Fabrication Symposium, Application I Session, Austin, Texas, August 8, 2011.

T61. "Fabrication of Conformal Ultrasound Transducer Arrays and Horns Based on Multi-axis CNC Accumulation." ASME Manufacturing Science and Engineering Conference (MSEC) 2011, Corvallis, Oregon, June 16, 2011.

T62. "Multi-Piece Mold Design Based on Linear Mixed-Integer Program Toward Guaranteed Optimality." International Conference on Manufacturing Automation (ICMA) 2010, Hong Kong, China, December 14, 2010.

T63. "Manufacturability Analysis of Infeasible Features in Polygonal Models for Web-based Rapid Prototyping." International Conference on Manufacturing Automation (ICMA) 2010, Hong Kong, China, December 14, 2010.

T64. "Contouring of Structured Points with Small Features." ASME Computer in Engineering Conference, Montreal, Canada, August 18, 2010.

T65. "Five-Axis Manufacturing Simulation Based on Normal Arc Mapping, Continuous Offsetting, and Discrete Computation." ASME Computer in Engineering Conference, Montreal, Canada, August 18, 2010.

T66. "Additive Manufacturing based on Multiple Calibrated Projectors and Its Mask Image Planning." ASME Design Automation Conference, Montreal, Canada, August 17, 2010.

T67. "Additive Manufacturing without Layers: A New Solid Freeform Fabrication Process Based on CNC Accumulation." SFF Symposium, Process I Session, Austin, Texas, August 9, 2010.

T68. "Touch-RE: A Touch-based Model Acquiring Method for Personal Manufacturing." SFF Symposium, Modeling II Session, Austin, Texas, August 11, 2010.

T69. "Beam Structure Optimization for Additive Manufacturing based on Principal Stress Lines." SFF Symposium, Design Session, Austin, Texas, August 11, 2010.

T70. "Optimized Mask Image Projection for Solid Freeform Fabrication." ASME Design Automation Conference, San Diego, California, Sept. 1, 2009.

T71. "Design of Flexible Skin for Target Displacements based on Meso-Structures." ASME Computers and Information in Engineering Conference, San Diego, California, Aug. 31, 2009.

T72. "Adaptive Cells and Anisotropic Mapping for Designing Complex Structures." SFF Symposium, Modeling II Session, Austin, Texas, August 5, 2009.

T73. "Calibrating Large-area Mask Projection Stereolithography for Its Accuracy and Resolution Improvements." SFF Symposium, Process Development II Session, Austin, Texas, August 4, 2009.

T74. "A Contour-based Support Generation Method for Solid Freeform Fabrication of Complex Parts." SFF Symposium, Modeling I Session, Austin, Texas, August 3, 2009.

T75. "3-Dimensional Digital Halftoning for Layered Manufacturing based on Droplets". SME North American Manufacturing Research Conference (NAMRC), Session B-3-1, Greenville, South Carolina, May 22, 2009.

T76. "Layer Depth-Normal Images for Complex Geometries – Part One: Accurate Modeling and Adaptive Sampling." ASME Computers and Information in Engineering Conference (CIE), Session 12-1, Brooklyn, New York, August 6, 2008.

T77. "Computer-aided Product Design with Performance-tailored Mesostructures." International CAD Conference and Exhibition, Orlando, Florida, June 24, 2008.

T78. "Robust and Accurate Boolean Operations on Polygonal Models." ASME Computers and Information in Engineering Conference (CIE), Las Vegas, Nevada, Sept. 5, 2007.

T79. "Non-uniform Offsetting for Laser Path Planning of Solid Freeform Fabrication Machines." SFF Symposium, Modeling Session, Austin, Texas, August 8, 2007.

T80. "3D Texture Mapping for Rapid Manufacturing". International CAD Conference and Exhibition, Honolulu, Hawaii, June 25, 2007.

T81. "A Mesh-based Geometric Modeling Method for General Structures." ASME Computers and Information in Engineering Conference (CIE), Session 4-2, Philadelphia, PA, Sept. 11, 2006.

TEACHING AND EDUCATION

TEACHING AND COURSE DEVELOPMENT

University of Southern California

- AME510, *Advanced Computational Design and Manufacturing* (graduate), 4 unit, Fall 2025.
- AME490, *B.S. Direct Research*, 2 unit, Spring 2025 (Sparsh Goyal).
- AME590, *M.S. Direct Research*, 1 unit, Spring 2025 (Tejashree Sandeep Raverkar).
- AME790, *Ph.D. Direct Research*, 4 unit, Spring 2025 (Jian Ni).
- AME790, *Ph.D. Direct Research*, 3 unit, Spring 2025 (Yichen Cui).
- AME790, *Ph.D. Direct Research*, 6 unit, Spring 2025 (Manqi Li).
- AME504, *Mechatronics Systems Engineering* (graduate), 4 unit, Spring 2025. **Instr. Eval.:** 4.14/5.
- AME790, *Ph.D. Direct Research*, 2 unit, Fall 2024 (Manqi Li).
- ISE232L /AME232L, *Manufacturing Processes* (undergraduate), 4 unit, Fall 2024. **Instr. Eval.:** 4.50/5.
- ENGR596, *M.S. Curricular Practical Training*, 1 unit, Summer 2024 (Manqi Li).
- ENGR596, *M.S. Curricular Practical Training*, 1 unit, Summer 2024 (Sahil Parmar).
- ENGR596, *M.S. Curricular Practical Training*, 1 unit, Summer 2024 (Manank Patel).
- AME490, *B.S. Direct Research*, 2 unit, Spring 2024 (Charlie Welland).
- AME790, *Ph.D. Direct Research*, 2 unit, Spring 2024 (Yichen Cui).
- AME790, *Ph.D. Direct Research*, 2 unit, Spring 2024 (Manqi Li).
- AME790, *Ph.D. Direct Research*, 6 unit, Spring 2024 (Yeowon Yoon).
- AME504, *Mechatronics Systems Engineering* (graduate), 4 unit, Spring 2024. **Instr. Eval.:** 4.40/5.
- AME790, *Ph.D. Direct Research*, 6 unit, Fall 2023 (Yeowon Yoon).
- AME490, *B.S. Direct Research*, 3 unit, Fall 2023 (Charlie Welland).
- AME504, *Mechatronics Systems Engineering* (graduate), 4 unit, Fall 2023. **Instr. Eval.:** 5.00/5.
- AME790, *Ph.D. Direct Research*, 5 unit, Spring 2023 (Yeowon Yoon).
- AME790, *Ph.D. Direct Research*, 3 unit, Spring 2023 (Manqi Li).
- AME590, *M.S. Direct Research*, 3 unit, Spring 2023 (Youngwoo Lee).
- AME596, *M.S. Curricular Practical Training*, 1 unit, Spring 2023 (Santosh V. Narayan).
- ISE790, *Ph.D. Direct Research*, 4 unit, Spring 2023 (Han Xu).
- ISE232L /AME232L, *Manufacturing Processes* (undergraduate), 3 unit, Spring 2023. **Instr. Eval.:** 4.00/5.

- AME790, *Ph.D. Direct Research*, 3 unit, Fall 2022 (Manqi Li).
- AME790, *Ph.D. Direct Research*, 4 unit, Fall 2022 (Yeowon Yoon).
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2022 (Han Xu).
- AME504/ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Fall 2022. **Instr. Eval.:** 4.08/5.
- AME790, *Ph.D. Direct Research*, 3 unit, Spring 2022 (Manqi Li).
- AME790, *Ph.D. Direct Research*, 3 unit, Spring 2022 (Yeowon Yoon).
- ISE790, *Ph.D. Direct Research*, 2 unit, Fall 2021 (Han Xu).
- ENGR596, *M.S. Direct Research*, 1 unit, Fall 2021 (Songwei Li).
- ISE590, *M.S. Direct Research*, 2 unit, Spring 2021 (Fangjie Qi).
- ENGR596, *M.S. Direct Research*, 1 unit, Spring 2021 (Frank Zhang).
- ISE510/AME510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Spring 2021. **Instr. Eval.:** 4.60/5.
- ISE511L/AME504, *Mechatronics Systems Engineering* (graduate), 3 unit, Spring 2021. **Instr. Eval.:** 4.22/5.
- ISE790, *Ph.D. Direct Research*, 5 unit, Spring 2020 (Yang Xu).
- AME590, *M.S. Direct Research*, 3 unit, Spring 2020 (Xiangyun Gao).
- ISE510/AME510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Spring 2020. **Instr. Eval.:** 4.33/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Spring 2020. **Instr. Eval.:** 4.0/5.
- ISE651, *Seminar in Industrial and Systems Engineering* (graduate), 1 unit, Spring 2020. **Instr. Eval.:** 4.57/5.
- ISE790, *Ph.D. Direct Research*, 6 unit, Fall 2019 (Yang Xu).
- ISE590, *M.S. Direct Research*, 2 unit, Fall 2019 (Yizhen Zhu).
- ISE511L/AME504, *Mechatronics Systems Engineering* (graduate), 3 unit, Fall 2019. **Instr. Eval.:** 3.89/5.
- ISE790, *Ph.D. Direct Research*, 2 unit, Spring 2019 (Jie Jin).
- ISE790, *Ph.D. Direct Research*, 1 unit, Spring 2019 (Han Xu).
- ISE590, *M.S. Direct Research*, 2 unit, Spring 2019 (Yujie Shan).
- ISE599, *Advanced Topics in 3D Printing* (graduate), 3 unit, Spring 2019. **Instr. Eval.:** 4.80/5.
- ISE510/AME510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Spring 2019. **Instr. Eval.:** 4.75/5.
- AME490, *B.S Direct Research*, 3 unit, Fall 2018 (Wenxuan Jia).

- ISE790, *Ph.D. Direct Research*, 4 unit, Fall 2018 (Jie Jin).
- ISE790, *Ph.D. Direct Research*, 1 unit, Fall 2018 (Yang Xu).
- ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Fall 2018. **Instr. Eval.:** 4.38/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2018. **Instr. Eval.:** 4.0/5.
- ISE790, *Ph.D. Direct Research*, 3 unit, Spring 2018 (Xiangjia Li).
- ISE790, *Ph.D. Direct Research*, 2 unit, Spring 2018 (Huachao Mao).
- ISE510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Spring 2018. **Instr. Eval.:** 4.83/5.
- ISE590, *M.S. Direct Research*, 1 unit, Fall 2017 (Luyang Liu).
- ISE590, *M.S. Direct Research*, 1 unit, Fall 2017 (Han Xu).
- ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Fall 2017. **Instr. Eval.:** 4.75/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2017. **Instr. Eval.:** 3.62/5.
- ISE790, *Ph.D. Direct Research*, 1 unit, Spring 2017 (Yang Xu).
- ISE590, *M.S. Direct Research*, 3 unit, Spring 2017 (Jonghan Lim).
- ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Fall 2016. **Instr. Eval.:** 4.0/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2016. **Instr. Eval.:** 4.08/5.
- ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Spring 2016. **Instr. Eval.:** 4.75/5.
- ISE790, *Ph.D. Direct Research*, 1 unit, Fall 2015 (Jie Jin).
- ISE590, *M.S. Direct Research*, 3 unit, Fall 2015 (Zhuofeng Zhang).
- ISE590, *M.S. Direct Research*, 1 unit, Fall 2015 (Vibha Manvi).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2015. **Instr. Eval.:** 3.24/5.
- ISE790, *Ph.D. Direct Research*, 1 unit, Summer 2015 (Huachao Mao).
- ISE590, *M.S. Direct Research*, 2 unit, Spring 2015 (Sibo Wang).
- ISE590, *M.S. Direct Research*, 1 unit, Spring 2015 (Pin-I Wu).
- ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Spring 2015. **Instr. Eval.:** 4.89/5.
- ISE510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Spring 2015. **Instr. Eval.:** 4.75/5.
- ISE490, *B.S. Direct Research*, 3 unit, Fall 2014 (Faraz Jalil).
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2014 (Kai Xu).
- ISE790, *Ph.D. Direct Research*, 2 unit, Fall 2014 (Pu Huang).
- ISE790, *Ph.D. Direct Research*, 2 unit, Fall 2014 (Xiangjia Li).

- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2014 (Xuan Song).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2014. **Instr. Eval.:** 3.13/5.
- ISE790, *Ph.D. Direct Research*, 3 unit, Spring 2014 (Kai Xu).
- ISE790, *Ph.D. Direct Research*, 2 unit, Spring 2014 (Pu Huang).
- ISE590, *M.S. Direct Research*, 1 unit, Spring 2014 (Xiang Gao).
- ISE599, *Advanced Topics in 3D Printing* (graduate), 3 unit, Fall 2013 (new graduate-level course). **Instr. Eval.:** 4.67/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2013. **Instr. Eval.:** 3.78/5.
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2013 (Yongqiang Li).
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2013 (Kai Xu).
- ISE511L, *Mechatronics Systems Engineering* (graduate), 3 unit, Spring 2013. **Instr. Eval.:** 4.0/5.
- ISE790, *Ph.D. Direct Research*, 2 unit, Spring 2013 (Pu Huang).
- ISE510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Fall 2012. **Instr. Eval.:** 5/5.
- ISE790, *Ph.D. Direct Research*, 6 unit, Fall 2012 (Yongqiang Li).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Spring 2012. **Instr. Eval.:** 3.79/5.
- ISE651, *PhD Seminar in Industrial Engineering* (graduate), 1 unit, Spring 2012. **Instr. Eval.:** 4.80/5.
- ISE790, *Ph.D. Direct Research*, 3 unit, Spring 2012 (Xuan Song).
- ISE790, *Ph.D. Direct Research*, 3 unit, Spring 2012 (Yongqiang Li).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2011. **Instr. Eval.:** 3.86/5.
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2011 (Yayue Pan).
- ISE790, *PhD Direct Research*, 3 unit, Fall 2011 (Kai Xu).
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2011 (Yongqiang Li).
- ISE599, *Point-Sampled Geometry for Product Design and Manufacturing* (graduate), 3 unit, Spring 2011 (new graduate-level course. Co-taught with Prof. Charlie Wang from CUHK). **Instr. Eval.:** 4.67/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Spring 2011. **Instr. Eval.:** 3.50/5.
- ISE590, *M.S. Direct Research*, 1 unit, Spring 2011 (Malav Patwa).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2010. **Instr. Eval.:** 3.28/5.
- ISE790, *Ph.D. Direct Research*, 2 unit, Fall 2010 (Yayue Pan).
- ISE596, *M.S. Direct Research*, 1 unit, Fall 2010 (Pooja Chawla).

- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Spring 2010, **Instr. Eval.:** 4.20/5.
- ISE590, *M.S. Direct Research*, 3 unit, Spring 2010 (Jinho Jung).
- ISE590, *M.S. Direct Research*, 1 unit, Spring 2010 (Jingyuan Lao).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2009, **Instr. Eval.:** 2.78/5.
- ISE510, *Advanced Computational Design and Manufacturing* (graduate), 3 unit, Fall 2009 (new graduate-level course offering), **Instr. Eval.:** 4.80/5.
- ISE590, *M.S. Direct Research*, 3 unit, Fall 2009 (Jinho Jung).
- ISE590, *M.S. Direct Research*, 1 unit, Fall 2009 (Jingyuan Lao).
- ISE511, *Computer-aided Manufacturing* (graduate), 3 unit, Spring 2009, **Instr. Eval.:** 4.46/5.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2008, **Instr. Eval.:** 4.10/5.
- ISE790, *Ph.D. Direct Research*, 3 unit, Fall 2008 (Chi Zhou).
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2007, **Instr. Eval.:** 3.52/5.
- ISE650, *PhD Seminar in Industrial Engineering* (graduate), 1 unit, Fall 2007, **Instr. Eval.:** 4.33/5.
- ENGR499, *From Humans to Robots* (undergraduate), 3 unit, Fall 2007 (guest lecture).
- ISE790, *Ph.D. Direct Research*, 1 unit, Summer 2007 (Shanglong Wang).
- ISE650, *PhD Seminar in Industrial Engineering* (graduate), 1 unit, Spring 2007.
- ISE232L, *Manufacturing Processes* (undergraduate), 3 unit, Fall 2006, **Instr. Eval.:** 4.00/5.
- ISE590, *M.S. Direct Research*, 3 unit, Fall 2006 (Kasidit Subsomboon).
- ISE599, *Geometric Modeling and Computation for Digital Fabrication* (graduate), 3 unit, Spring 2006 (*developed* a graduate-level course offering), **Instr. Eval.:** 4.50/5.

RESEARCH SUPERVISION

In Progress:

Ph.D. students:

Joshua Vandervelde

Jian Ni

Yeowon Yoon

Manqi Li

Yichen Cui

M.S. students:

Charm Nicholas

Qizhou Li

Chiawei Lin

Shuai Chen

B.S. students:

Brinda Acharya

Michael Simineri

Charlie Welland

Completed:

(A total of 6 Ph.D. students and 3 post-doctors trained in my lab have landed faculty positions in North American Universities, and a total of 1 Ph.D. student and 1 post-doctor trained in my lab have landed faculty positions in Asian Universities.)

Post-doc researchers:

Han Xu: 7/2023 – 6/2025, landed an Assistant Professor in the Department of Industrial, Manufacturing and Systems Engineering at the **Texas Tech University**, Lubbock, Texas.

Yang Xu: 9/2021 – 12/2022, landed an Assistant Professor in the Department of Industrial and Manufacturing Systems at the **University of Hong Kong**, Hong Kong.

Yizhou Jiang: 01/2021 – 07/2022, landed an Assistant Professor in the Department of Aerospace Engineering at **Embry-Riddle Aeronautical University**, Daytona Beach, FL.

Bin Yao: 09/2020 – 04/2022, landed a Senior Process Engineer at **Applied Materials Inc.,** Sunnyvale, CA.

Laiming Jiang: 12/2019 – 10/2021, landed an Assistant Professor in the College of Materials Science and Engineering at **Sichuan University**, Chengdu, Sichuan, China.

Xiangjia Li: 07/2019 – 1/2020, landed an Assistant Professor in the Department of Mechanical Engineering at **Arizona State University – Tempe**, AZ.

Yang Yang: 03/2016 – 12/2019, landed an Assistant Professor in the Department of Mechanical Engineering at **San Diego State University**, San Diego, CA.

Debbie Leung: 08/2016 – 08/2018, landed a Software Engineer in Angel Technologies, San Francisco, CA.

Tom Kwok: 09/2014 – 08/2016, landed an Assistant Professor in the Department of Mechanical and Industrial Engineering at **Concordia University**, Montreal, Quebec, Canada – ***tenured***.

Ph.D. students:

Han Xu: Motion-assisted Vat Photopolymerization: An Approach to High-resolution Additive Manufacturing, Graduated in Summer 2023 (landed a Post-Doctoral position at USC, Los Angeles, CA, and later an Assistant Professor in the Department of Industrial, Manufacturing and Systems Engineering at the **Texas Tech University**, Lubbock, Texas.

Yang Xu: Hybrid Vat Photopolymerization Processes for Viscous Photocurable and Non-photocurable Materials, Graduated in Summer 2021 (landed a Post-Doctoral position at USC, Los Angeles, CA, and later an Assistant Professor in the Department of Industrial and Manufacturing Systems at the **University of Hong Kong**, Hong Kong).

Jie Jin: Hybrid Vat Photopolymerization: Method and Systems, Graduated in Summer 2020 (landed a Software Engineer in ShadeCraft Robotics Inc., Pasadena, CA).

Huachao Mao: Scalable Polymerization Additive Manufacturing: Principle and Optimization, Graduated in Summer 2019 (landed an Assistant Professor in Polytechnic Institute (Engineering Technology) at **Purdue University - West Lafayette**).

Xiangjia Li: Multi-scale Additive Manufacturing of Biomimetic Functional Materials and Structures, Graduated in Summer 2019 (landed an Assistant Professor in the Department of Mechanical Engineering at **Arizona State University - Tempe**).

Dongping Deng: 4D Printing of Self-folding Structures Using Polystyrene Film, Graduated in Fall 2016 (landed a Software Engineer in Google Inc., CA).

Xuan Song: Slurry based Stereolithography: A Solid Freeform Fabrication Method of Ceramics and Composites, Graduated in Summer 2016 (landed an Assistant Professor in Department of Mechanical and Industrial Engineering at the **University of Iowa – Iowa City**).

Kai Xu: Deformation Control for Mask Image Projection based Stereolithography Process, Graduated in Spring 2016 (co-founded ZSFab Inc., Cambridge, MA).

Yayue Pan: Energy Control and Material Deposition Methods for Fast Fabrication with High Surface Quality in Additive Manufacturing Using Photo-polymerization, Graduated in Summer 2014 (landed an Assistant Professor in Department of Mechanical and Industrial Engineering at the **University at Illinois at Chicago** – ***tenured***).

Yongqiang Li: Deformable Geometry Design with Controlled Mechanical Property based on 3D Printing, Graduated in Summer 2014 (landed a Software Engineer in Microsoft Inc., Seattle, WA).

Chi Zhou: Optimized Mask Image Projection for Large-area based Additive Manufacturing Process, Graduated in Fall 2011 (landed an Assistant Professor in Department of Industrial and Systems Engineering at the **University at Buffalo – State University of New York** – ***tenured***).

M.S. students: Over 120 master students worked in our lab in the past 18 years.

B.S. students: Over 40 undergraduate students worked in our lab in the past 18 years.

Undergraduate/High School Summer Intern:

Bhargavi Deshpande (from Franklin W. Olin College of Engineering): Cancer Cell Isolation Using Maskless Lithography, Finished in Summer 2024.

Daniel Ruiz (from University of California - Berkeley): Cancer Cell Isolation Using Maskless Lithography, Finished in Summer 2023.

Steven Li (from University High School - Irvine): Magnetics Assisted Stereolithography, Finished in Summer 2018.

Nicholas Fu (from Oxford Academy High School): Custom-made Teeth Clean Device, Finished in Summer 2015.

Kaline Tong (from Troy High School): Energy Modeling and Control of Micro-Stereolithography, Finished in Summer 2014.

Zaid Badwan (from National Autonomous University of Mexico): PZT Part Fabrication based on an Additive Manufacturing Process, Finished in Summer 2014.

Andrew Davidson (from Brigham Young University): Process Monitoring for Layer Manufacturing Processes, Finished in Summer 2013.

Pu Huang (from Chinese University of Hong Kong): Computation Techniques for Layer Manufacturing Processes, Finished in Summer 2011.

Eun Cheol Yu (from Korean Aerospace University): A Study of Low-cost Rapid Tooling Processes, Finished in Summer 2010.

Brian Lam (from Illinois Institute of Technology): Curing Properties of UV LEDs, Finished in Summer 2008.

Visiting Scholars:

Chengqian Zhang (from Zhejiang University, China): Oct. 2019 – Oct. 2020.

Haidong Wu (from Guangdong University of Technology, China): Oct. 2019 – Oct. 2020.

Ye Yang (from Shanghai Normal University, China): Sept. 2019 – Sept. 2020.

Kuan-Ming Li (from National Taiwan University, Taiwan): September 2019 – February 2020.

Mujun Li (from University of Science and Technology of China): Dec. 2018 – Dec. 2019.

Dan Liu (from Guizhou University, China): August 2018 – August 2019.

Fuyuan Luo (from Nanjing University of Aeronautics and Astronautics, China): April 2016 – April 2017.

Zhengcai Zhao (from Nanjing University of Aeronautics and Astronautics, China): Sept. 2015 – March 2016.

Liwen Lei (from Wuhan University of Technology, China): May 2014 – April 2015.

Zuyao Yu (from Huazhong Univ. of Science and Technology, China): Dec. 2012 – Aug. 2013.

Pekka Lehtinen (from Aalto University, Finland): September 2013 – November 2013.

Ruisong Jiang (from Northwestern Polytechnical University): Nov. 2012 – Nov. 2013.

Xuejin Zhao (from Shandong University, China): December 2010 – August 2012.

Jouni Partanen (from Aalto University, Finland): June 2012 – July 2012.

Charlie Wang (from Chinese University of Hong Kong): December 2010 – August 2011.

Jouni Partanen (from Aalto University, Finland): June 2011 – July 2011.

Weiqing Guo (from Zhejiang University of Technology, China): March 2010 – April 2011.

DISSERTATION COMMITTEE

Dissertation Defense

- Renbo Su, Ph.D. Dissertation: *Data-driven Optimization of Multi-material Complex Structures: Design & Manufacturing*, Mechanical and Aerospace Engineering, The University of Manchester, Manchester, UK, December 2024 (External Examiners).
- Yizhe Sun, Ph.D. Dissertation: *Design and Fabrication of Ultrasound Transducers: from Single Element to High Frequency 2D Array*, Biomedical Engineering, USC, February 2024.
- Tak Yu Lau, Ph.D. Dissertation: *Process Planning of Scalar Field-based Multi-axis Fused Deposition Modeling*, Mechanical Engineering, Hong Kong University of Science and Technology, Hong Kong, January 2024 (External Examiners).
- Po-Lun Feng, Ph.D. Dissertation: *Metallization of Polymers and Polymer Matrix Composites by Cold Spray*, Materials Science, USC, December 2023.
- Rezwan A. Rasul, Ph.D. Dissertation: *In-SRAM Matrix-vector Multiplication Accerlerator for Neural Network Inference*, Electrical and Computer Engineering, USC, November 2023.
- Juzheng Liu, Ph.D. Dissertation: *Towards Hight-performance Low-cost AMS Designs: Time-domain Conversion and ML-based Design Automation*, Electrical and Computer Engineering, USC, October 2023.
- Han Xu, Ph.D. Dissertation: *Motion-assisted Vat Photopolymerization: An Approach for High-resolution Additive Manufacturing*, Industrial and Systems Engineering, USC, April 2023 (Chair).
- Qinglei Ji, Ph.D. Dissertation: *Learning-based Control for 4D Printing and Soft Robotics*, Production Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, November 2022 (Opponent).
- Christina Schmidleithner, Ph.D. Dissertation: *3D Printed Microdevices for Advanced Tissue Culture*, Health Technology, Technical University of Denmark (DTU), June 2022 (Assessment Committee Member).
- Haochen Kang, Ph.D. Dissertation: *2D Ultrasonic Transducer Array's Design and Fabrication with 3D Printed Interposer and Applications*, Biomedical Engineering, USC, May 2022.
- Yuanxiang Wang, Ph.D. Dissertation: *Fabrication-aware Machine Learning for Accuracy Control in Additive Manufacturing*, Industrial and Systems Engineering, USC, May 2022.
- Kun-Hao Yu, Ph.D. Dissertation: *Mechanics and Additive Manufacturing of Bio-inspired Polymers*, Civil and Environmental Engineering, USC, May 2022.
- Rishi Malhan, Ph.D. Dissertation: *Robot Placement and Trajectory Generation Under Motion Constraints*, Aerospace and Mechanical Engineering, USC, April 2022.
- Nathan Decker, Ph.D. Dissertation: *Machine Learning-driven Deformation Prediction and Compensation for Additive Manufacturing*, Industrial and Systems Engineering, USC, March 2022.
- Prahar M. Bhatt, Ph.D. Dissertation: *Process Planning for Robotic Additive Manufacturing*, Aerospace and Mechanical Engineering, USC, November 2021.

- Danyong Zhao, Ph.D. Dissertation: *Acquisition of Human Tissue Elasticity Properties Using Pressure Sensors*, Computer Science, USC, October 2021.
- Yang Xu, Ph.D. Dissertation: *Hybrid Vat Photopolymerization Processes for Viscous Photocurable and Non-photocurable Materials*, Industrial and Systems Engineering, USC, July 2021 (Chair).
- Ke Xu, Ph.D. Dissertation: *Neuromorphic Mechanical Computation for Decentralized Control of Soft Fluidic Robots*, Aerospace and Mechanical Engineering, USC, June 2021.
- An Xin, Ph.D. Dissertation: *Harness Microorganisms to Design Resilient Engineering Materials*, Civil and Environmental Engineering, USC, May 2021.
- Jie Jin, Ph.D. Dissertation: *Hybrid Vat Photopolymerization: Methods and Systems*, Industrial and Systems Engineering, USC, July 2020 (Chair).
- Ariel Calderon, Ph.D. Dissertation: *Novel Soft and Micro Transducers for Creating Biologically-inspired Robots*, Aerospace and Mechanical Engineering, USC, May 2020.
- Xiufeng Yang, Ph.D. Dissertation: *Development of Biologically-inspired Sub-germ Insect-scale Autonomous Robots*, Aerospace and Mechanical Engineering, USC, January 2020.
- Xiangjia Li, Ph.D. Dissertation: *Multi-scale Additive Manufacturing of Biomimetic Functional Materials and Structures*, Industrial and Systems Engineering, USC, June 2019 (Chair).
- Huachao Mao, Ph.D. Dissertation: *Scalable Polymerization Additive Manufacturing: Principle and Optimization*, Industrial and Systems Engineering, USC, June 2019 (Chair).
- Yuanrui Li, Ph.D. Dissertation: *Metasurfaces in 3D Applications: Multiscale Stereolithography and Inverse Design for Structural Light*, Electrical and Computer Engineering, USC, May 2019.
- Xiang Gao, Ph.D. Dissertation: *Selective Separation Shaping (SSS) – Large Scale Fabrication Potential*, Industrial and Systems Engineering, USC, January 2019.
- Hadis Nouri, Ph.D. Dissertation: *3D printing of Polymer Parts Using Selective Separation Shaping (SSS)*, Industrial and Systems Engineering, USC, July 2018.
- Ali Kazemian, Ph.D. Dissertation: *Mixture Characterization and Real-time Extrusion Quality Monitoring for Construction-scale 3D Printing (Contour Crafting)*, Civil Engineering, USC, July 2018.
- He Luan, Ph.D. Dissertation: *Statistical Modeling and Machine Learning for Shape Accuracy Control in Advanced Manufacturing*, Industrial and Systems Engineering, USC, May 2018.
- Chu-Yi Wang, Ph.D. Dissertation: *Managing Functional Coupling Sequences to Reduce Complexity and Increase Modularity in Conceptual Design*, Aerospace and Mechanical Engineering, USC, April 2018.
- Yanqing Duanmu, Ph.D. Dissertation: *Some Scale-up Methodologies for Advanced Manufacturing*, Industrial and Systems Engineering, USC, May 2017.
- Hongyi Xu, Ph.D. Dissertation: *Interactive Material and Damping Design*, Computer Science, USC, April 2017.
- Dongping Deng, Ph.D. Dissertation: *4D Printing of Self-folding Structures Using Polystyrene Film*, Industrial and Systems Engineering, USC, December 2016 (Chair).

- Xiao Yuan, Ph.D. Dissertation: *Contour Crafting Construction with Sulfur Concrete*, Industrial and Systems Engineering, USC, June 2016.
- Amir Mansouri, Ph.D. Dissertation: *Analyses of Strength of Layered Structures Fabricated by Contour Crafting*, Industrial and Systems Engineering, USC, June 2016.
- Xuan Song, Ph.D. Dissertation: *Slurry based Stereolithography: A Solid Freeform Fabrication Method of Ceramics and Composites*, Industrial and Systems Engineering, USC, June 2016 (Chair).
- Payman Torabi, Ph.D. Dissertation: *Enhancing the Surface Quality and Dimensional Accuracy of SIS-Metal Parts with Applications to High-Temperature Alloys*, Industrial and Systems Engineering, USC, June 2016.
- Matthew R. Petros, Ph.D. Dissertation: *The Extension of Selective Inhibition Sintering (SIS) to High-Temperature Alloys*, Industrial and Systems Engineering, USC, May 2016.
- Jing Zhang, Ph.D. Dissertation: *Selective Separation Shaping – An Additive Manufacturing Method for Metals and Ceramics*, Industrial and Systems Engineering, USC, May 2016.
- Kai Xu, Ph.D. Dissertation: *Deformation Control for Mask Image Projection based Stereolithography Process*, Industrial and Systems Engineering, USC, January 2016 (Chair).
- Krisna C. Bhargava, Ph.D. Dissertation: *A Modular Microscale Laboratory*, Chemical Engineering and Materials Science, USC, December 2015.
- Yayue Pan, Ph.D. Dissertation: *Energy Control and Material Deposition Methods for Fast Fabrication with High Surface Quality in Additive Manufacturing Using Photo-polymerization*, Industrial and Systems Engineering, USC, May 2014 (Chair).
- Yongqiang Li, Ph.D. Dissertation: *Deformable Geometry Design with Controlled Mechanical Property based on 3D Printing*, Industrial and Systems Engineering, USC, May 2014 (Chair).
- Ruimin Chen, Ph.D. Dissertation: *High-frequency Ultrasonic Transducers for Photoacoustic Applications*, Biomedical Engineering, USC, December 2013.
- Li Wang, Ph.D. Dissertation: *Modeling and Analysis of Nanostructure Growth Process Kinetics and Variations for Scalable Nanomanufacturing*, Industrial and Systems Engineering, USC, October 2013.
- Lijuan Xu, Ph.D. Dissertation: *Nanostructure Interaction Modeling and Estimation for Scalable Nanomanufacturing*, Industrial and Systems Engineering, USC, October 2013.
- Tony Di Carlo, Ph.D. Dissertation: *Experimental and Numerical Techniques to Characterize Structural Properties of Fresh Concrete Relevant to Contour Crafting*, Industrial and Systems Engineering, USC, September 2012.
- Mahdi Yoozbashizadeh, Ph.D. Dissertation: *Metallic Parts Fabrication with the Selective Inhibition Sintering (SIS) based on Microscopic Inhibition*, Industrial and Systems Engineering, USC, August 2012.
- Winston Wen Chiang, Ph.D. Dissertation: *A Meta-interaction Model for Designing Cellular Self-Organizing Systems*, Aerospace and Mechanical Engineering, USC, April 2012.

- Hojong Choi, Ph.D. Dissertation: *Development of Front-End Circuits for High-Frequency Ultrasonic System*, Electric Engineering, USC, November 2011.
- Chi Zhou, Ph.D. Dissertation: *Optimized Mask Image Projection for Large-Area based Additive Manufacturing Process*, Industrial and Systems Engineering, USC, August 2011 (Chair).
- Hamid R. Chabok, Ph.D. Dissertation: *Development of High-Frequency 1-3 Composite Annular Array Ultrasound Transducers*, Industrial and Systems Engineering, USC, March 2011.
- Majid Yahyaei, Ph.D. Dissertation: *Modeling Enterprise Operations and Organizations for Productivity Improvement*, Aerospace and Mechanical Engineering, USC, Dec. 2009.
- Dawei Wu, Ph.D. Dissertation: *Development of High-Frequency (~100MHZ) PZT Thick-Film Ultrasound Transducers and Arrays*, Biomedical Engineering, USC, July 2009.
- Khashayar Behdinan, Ph.D. Dissertation: *Methodology for Design of a Vibration Operated Valve for Abrasive Viscous Fluids*, Industrial and Systems Engineering, USC, March 2009.
- Jasper Jing Zhang, Ph.D. Dissertation: *Contour Crafting Process Planning and Optimization*, Industrial and Systems Engineering, USC, Feb. 2009.
- George E. Zouein, Ph.D. Dissertation: *A Biologically Inspired DNA-based Cellular Approach to Developing Complex Adaptive Systems*, Aerospace and Mechanical Engineering, USC, January 2009.

Proposal Defense

- Shengqiang Chen, Ph.D. Dissertation: *Computational Foundation for Realizing Human-supervised Robot Teams Operating on Challenging Terrains*, Aerospace and Mechanical Engineering, USC, June 2025.
- Yushun Zeng, Ph.D. Dissertation: *Advanced Ultrasound Transducers: From Design and Fabrication to Biomedical Applications*, Biomedical Engineering, USC, May 2025.
- Rishabh Shukla, Ph.D. Dissertation: *Robot Trajectory Generation for Complex Tool Manipulation Tasks*, Aerospace and Mechanical Engineering, USC, May 2025.
- Jiahao Wen, Ph.D. Dissertation: *Optimal r-Adaptive In-Timestep Remeshing for Elastodynamics*, Computer Science, USC, April 2025.
- Manqi Li, Ph.D. Dissertation: *Interface Control in Vat Photopolymerization: In-site Transfer and Assembly*, Aerospace and Mechanical Engineering, USC, April 2025.
- Christopher Henson, Ph.D. Dissertation: *Smart 3D Printing Systems for Real-time Quality Analysis*, Industrial and Systems Engineering, USC, January 2025.
- Xinrui Wang, Ph.D. Dissertation: *A Machine Learning based Approach to Work Process Knowledge Capture and Transfer*, Aerospace and Mechanical Engineering, USC, September 2024.
- Adnan Rayes, Ph.D. Dissertation: *Advanced Elastography in Biomedical Applications: Assessing Mechanics from Cells to Tissue*, Biomedical Engineering, USC, July 2024.
- Yeowon Yoon, Ph.D. Dissertation: *Embedding Functional Materials within Structures via Hybrid Vat Photopolymerization*, Aerospace and Mechanical Engineering, USC, April 2024.

- Weizhi Lin, Ph.D. Dissertation: *Domain-informed Learning of Surface Manifold Data and Its Applications in 3D Printing*, Industrial and Systems Engineering, USC, January 2024.
- Jiahao Wen, Ph.D. Dissertation: *Kirchhoff-Love Shells with Arbitrary Hyperelastic Materials*, Computer Science, USC, November 2023.
- Yizhe Sun, Ph.D. Dissertation: *Design and Fabrication of Ultrasonic Transducers: From Single Element to High Frequency 2D Array*, Biomedical Engineering, USC, February 2023.
- Kyung Hoon Lee, Ph.D. Dissertation: *Modulating Dynamics with Innovative Metastructures*, Civil and Environmental Engineering, USC, October 2022.
- Han Xu, Ph.D. Dissertation: *Mask Shifting in Projection-based Vat Photopolymerization for Sub-pixel Resolution and Layerless Fabrication*, Industrial and Systems Engineering, USC, March 2022.
- Yuanxiang Wang, Ph.D. Dissertation: *Shape Deformation Prediction Through a Convolution Learning Framework for Additive Manufacturing*, Industrial and Systems Engineering, USC, May 2021.
- Nathan Decker, Ph.D. Dissertation: *Data-driven Deformation Characterization, Prediction, and Compensation for Additive Manufacturing*, Industrial and Systems Engineering, USC, May 2021.
- Haochen Kang, Ph.D. Dissertation: *2D Ultrasonic Transducer Array's Fabrication with 3D Printed Interposer and Its Application in Elastography*, Biomedical Engineering, USC, May 2021.
- Rishi Malhan, Ph.D. Dissertation: *Robot Placement and Trajectory Generation Under Motion Constraints*, Aerospace and Mechanical Engineering, USC, April 2021.
- Prahar M. Bhatt, Ph.D. Dissertation: *Process Planning for Robotic Additive Manufacturing*, Aerospace and Mechanical Engineering, USC, December 2020.
- Yang Xu, Ph.D. Dissertation: *A Multi-material Vat Photopolymerization Process for Viscous and Non-photocurable Materials*, Industrial and Systems Engineering, USC, August 2020.
- Kun-Hao Yu, Ph.D. Dissertation: *Mechanics and Additive Manufacturing of Self-healing Polymers*, Civil and Environmental Engineering, USC, March 2020.
- Michael Kruger, Ph.D. Dissertation: *The Challenges and Potential Benefits of Electric Propulsion for Aircraft*, Aerospace and Mechanical Engineering, USC, March 2020.
- An Xin, Ph.D. Dissertation: *Bacteria Assisted Remodeling of Engineering Materials*, Civil and Environmental Engineering, USC, February 2020.
- Bohan Wang, Ph.D. Dissertation: *Anatomically based Hand Modeling*, Computer Science, USC, November 2019.
- Shantanu Thakar, Ph.D. Dissertation: *Planning and Learning for Mobile Manipulation*, Aerospace and Mechanical Engineering, USC, August 2019.
- Ariel Calderon, Ph.D. Dissertation: *Design and Synthesis of Hybrid Soft-Micro Transducers for Bio-inspired Robots*, Aerospace and Mechanical Engineering, USC, June 2019.
- Jie Jin, Ph.D. Dissertation: *Hybrid 3D Printing for Stereolithography*, Industrial and Systems Engineering, USC, May 2019.

- Danyong Zhao, Ph.D. Dissertation: *Acquisition of Human Tissue Elasticity Properties Using Pressure Sensors*, Computer Science, USC, May 2019.
- Jiachuan Chen, Ph.D. Dissertation: *The Warehouse Traveling Salesman Problem*, Industrial and Systems Engineering, USC, January 2019.
- Yuanrui Li, Ph.D. Dissertation: *Multiscale Stereolithography and Nonlinear Metamaterial Over Multiple Wavelength Ranges*, Electrical Engineering, USC, June 2018.
- Ariyan M. Kabir, Ph.D. Dissertation: *Trajectory Planning and Self-directed Learning for High Degrees of Freedom Robotic Systems*, Aerospace and Mechanical Engineering, USC, June 2018.
- Huachao Mao, Ph.D. Dissertation: *Energy Control and Process Planning for Multiscale Stereolithography*, Industrial and Systems Engineering, USC, May 2018.
- Xiangjia Li, Ph.D. Dissertation: *Multi-scale Additive Manufacturing of Biomimetic Functional Materials and Structures*, Industrial and Systems Engineering, USC, May 2018.
- Xiang Gao, Ph.D. Dissertation: *Selective Separation Shaping (SSS) – Large Scale Fabrication Potentials*, Industrial and Systems Engineering, USC, Feb. 2018.
- Yiming Li, Ph.D. Dissertation: *Artist-controlled Physically based Animation*, Computer Science, USC, May 2017.
- Hadis Nouri, Ph.D. Dissertation: *Selective Separation Shaping of Polymeric Parts*, Industrial and Systems Engineering, USC, May 2017.
- He Luan, Ph.D. Dissertation: *Prescriptive Shape Deformation Modeling and Monitoring for Additive Manufacturing*, Industrial and Systems Engineering, USC, May 2017.
- Edwin Ordoukhanian, Ph.D. Dissertation: *A Methodology for Introducing and Evaluating Resilience Mechanisms in System-of-Systems: Application to Multi-UAV SoS*, Astronautical Engineering, USC, January 2017.
- Zeyu Chen, Ph.D. Dissertation: *Additive Manufacturing of Composites for Biomedical Application*, Biomedical Engineering, USC, November 2016.
- Hongyi Xu, Ph.D. Dissertation: *Interactive Material and Damping Design*, Computer Science, USC, November 2016.
- Chu-Yi Wang, Ph.D. Dissertation: *Managing Functional Coupling Sequences to Reduce Design Complexity During Concept Improvements*, Aerospace and Mechanical Engineering, USC, August 2016.
- Yuan Jin, Ph.D. Dissertation: *Accuracy Control of Three-Dimensional Shape Deformation in Additive Manufacturing*, Chemical Engineering, USC, December 2015.
- Xiao Yuan, Ph.D. Dissertation: *Contour Crafting Construction with Sulfur Concrete*, ISE, USC, September 2015.
- Dongping Deng, Ph.D. Dissertation: *Freeform 3D Shell Structure Fabrication Using 3D Printed Constraint-based Self-foldable Structures*, ISE, USC, September 2015.
- Amir Mansouri, Ph.D. Dissertation: *Analysis of Strength of Layered Structures Fabricated by Contour Crafting*, ISE, USC, May 2015.

- Matthew Petros, Ph.D. Dissertation: *Enhancing the Mechanical Properties of SIS-Metal Parts*, ISE, USC, May 2015.
- Xuan Song, Ph.D. Dissertation: *Composite Fabrication Using Mask-image Projection based Stereolithography*, ISE, USC, April 2015.
- Payman Torabi, Ph.D. Dissertation: *Enhancing the Surface Quality and Dimensional Accuracy of SIS-Metal Parts*, ISE, USC, April 2015.
- Kai Xu, Ph.D. Dissertation: *Deformation Control for Mask Image Projection Based Stereolithography Process*, ISE, USC, January 2015.
- Jing Zhang, Ph.D. Dissertation: *Study of Principles of Selective Separation Sintering (SSS)*, ISE, USC, January 2015.
- Yongqiang Li, Ph.D. Dissertation: *Desired Flexible Skin Design For 3D Printing*, ISE, USC, December 2013.
- Yayue Pan, Ph.D. Dissertation: *Energy Control and Material Deposition methods for Multi-scale Additive Manufacturing Using Photo-polymerization*, ISE, USC, August 2013.
- Ruimin Chen, Ph.D. Dissertation: *High-frequency Ultrasonic Transducers for Photoacoustic Applications*, BME, USC, December 2012.
- Hojong Choi, Ph.D. Dissertation: *Development of Front-End Integrated Preamplifier for High-Frequency Ultrasonic Transducer*, EE, USC, October 2010.
- Hamid R. Chabok, Ph.D. Dissertation: *Development of High-Frequency 1-3 Composite Annular Array Ultrasound Transducers*, ISE, USC, May 2010.
- Chi Zhou, Ph.D. Dissertation: *Optimized Mask Image Projection for Large-Area based Additive Manufacturing Process*, ISE, USC, September 2010.
- Tony Di Carlo, Ph.D. Dissertation: *Modeling and Optimization of a Cementitious Material System for Automated Construction of Sustainable and Affordable Homes*, ISE, USC, August 2010.
- Mahdi Yoozbashizadeh, Ph.D. Dissertation: *Metallic Parts Fabrication with the Selective Inhibition Sintering (SIS) based on Microscopic Inhibition*, ISE, USC, January 2010.
- Hamid R. Chabok, Ph.D. Dissertation: *Development of High-Frequency 1-3 Composite Annular Array Ultrasound Transducers*, ISE, USC, November 2009.
- Kathryn R. Rieger, Ph.D. Dissertation: *A Performance-based Bayesian Model to Identify Use-Error Risk Levels in Medical Devices*, ISE, USC, May 2009.
- Majid Yahyaei, Ph.D. Dissertation: *Process Management Technology (PMT): Modeling Enterprise Operations and Organizations*, AME, USC, Dec. 2008.
- Khashayar Behdinan, Ph.D. Dissertation: *Analysis of a Piezoelectric Operated Valve for Abrasive Viscous Fluids*, ISE, USC, Jan. 2008.
- Jasper Jing Zhang, Ph.D. Dissertation: *Contour Crafting Process Planning and Optimization*, ISE, USC, Dec. 2007.

- Haifeng Ji, Ph.D. Dissertation: *Extraction of Preferences from Early Stage Engineering Design Team Discussion*, ISE, USC, May 2007.
- Gregory Placencia, Ph.D. Dissertation: *A Finite Element Model of Haptic Tactile Response*, ISE, USC, Dec. 2006.

MS THESIS COMMITTEE:

- Sunyoung Jung, M.S. Thesis: *Improving Implantable Neural Probe Stiffness for Enhanced Brain Penetration*, Biomedical Engineering, USC, October 2024.
- Bo-Wei Wu, M.S. Thesis: *The Effect of Lattice Structure and Porosity of Thermal Conductivity of Additively-manufactured Porous Materials*, Aerospace and Mechanical Engineering, USC, May 2023.
- Yushun Zeng, M.S. Thesis: *Fabrication of Ultrasound Transducer and 3D-printing Ultrasonic Device*, Biomedical Engineering, USC, March 2021.
- John Pham, M.S. Thesis: *Monitoring of Typodont Root Movement via Crown Superimposition of Single CBCT and Consecutive iTero Scans*, Orthodontics program, School of Dentistry, USC, January 2014.
- Kabir Kanodia, M.S. Thesis: *Real-time Flow Control of Viscous Fluids Using 3D Image Processing*, Industrial and Systems Engineering, USC, August 2008.

SERVICE

ADMINISTRATIVE EXPERIENCE

I have served as the ***Director*** of the Daniel J. Epstein Institute of Viterbi School of Engineering at USC for three years (7/2018~06/2021). The director was appointed by the Dean of Engineering School and is responsible for managing the day-to-day activities of the Institute and sets the strategic direction for the Institute. (Refer to: https://ise.usc.edu/research/epstein-institute/administration/)

PROFESSIONAL AFFILIATIONS

Fellow of American Society of Mechanical Engineers (ASME), since 2018

Senior Member of National Academy of Inventors (NAI), since 2022

Senior member of Society of Manufacturing Engineers (SME), since 2006

Member of American Association for Advancement of Society (AAAS), since 2022

Member of Institute of Industrial Engineers (IIE), 2006 - 2021

Member of American Society of Engineering Education (ASEE), 2011 - 2016

Member of Solid Modeling Association (SMA), since 2006

Member of Chinese American Faculty Association (CAFA)

PROFESSIONAL ACTIVITIES

ASME CIE Division

Senate, Computer-aided Product and Process Development (CAPPD) Committee, 2010-2013.

Chair, Computer-aided Product and Process Development (CAPPD) Committee, 2008.

Vice Chair, Computer-aided Product Development (CAPD) Committee, 2007.

Secretary, Computer-aided Product Development (CAPD) Committee, 2006.

SME North American Manufacturing Research Institute

Member, Scientific Committee, 2012-2016.

NSF Roadmap for Additive Manufacturing Workshop

Invited participant, NSF, CMMI Division, March 2009.

JOURNAL SERVICE

Associate Editor, Dec. 2022 – Current, ASME Journal of Manufacturing Science and Engineering (JMSE).

Guest Editor, ASME Journal of Manufacturing Science and Engineering, Special Issue of MSEC 2022, 2022.

Editorial Board Member, January 2022 – December 2024, International Journal of Extreme Manufacturing.

Editorial Board Member, July 2019 – Current, Manufacturing Letters.

Editorial Board Member, February 2019 – Current, Journal of Intelligent Manufacturing.

Editorial Board Member, January 2019 – Current, Bio-Design and Manufacturing.

Editorial Board Member, March 2016 – Current, Virtual and Physical Prototyping Journal.

Associate Editor, Nov. 2016 – Nov. 2022, ASME Journal of Computing and Information Science in Engineering (JCISE).

Associate Editor, Aug. 2018 – July 2021, IISE Transaction – Design and Manufacturing Focus Issue.

Editorial Board Member, April 2015 – Current, International Journal of Rapid Manufacturing.

Editorial Board Member, Dec. 2014 – Current, Computer-aided Design.

Guest Editor, Computer-aided Design, Special Issue on "Geometric and Physical Modeling for Additive Manufacturing," 2014.

Editorial Board Member, 2012-current, International Journal of Precision Engineering and Manufacturing.

CONFERENCE SERVICE

Chair, Research Professionals in Academia, Industry & National Laboratories: An Early Career Forum, 2023 ASME Manufacturing Science and Engineering Conferences (MSEC) and SME North American Manufacturing Research Conference (NAMRC), June 14, New Brunswick, New Jersey.

Program Chair, 2022 ASME Manufacturing Science and Engineering Conferences (MSEC), June 27-July 1, West Lafayette, Indiana.

Symposium co-Chair, 2022 MSEC Doctoral Symposium, June 27-July 1, West Lafayette, Indiana.

Track co-Chair, 2022 MSEC Poster Track, June 27-July 1, West Lafayette, Indiana.

Symposium organizer, Symposium of Machine Learning and Generative Design for Additive Manufacturing, Mechanistic Machine Learning and Digital Twins for Computational Science, Engineering and Technology (MMLDT-CSET) Conference, San Diego, California, Sept. 26-29, 2021.

Symposium Chair, 2021 MSEC Doctoral Symposium, June 22-25, Virtual conference hosted by the University of Cincinnati.

Track Chair, 2021 MSEC Poster Track, June 22-25, Virtual conference hosted by the University of Cincinnati.

Program co-Chair, 2021 ASME Manufacturing Science and Engineering Conferences (MSEC), June 22-25, Virtual conference hosted by the University of Cincinnati.

Program Committee Member, 2019 Symposium on Solid and Physical Modeling (SPM 2019), Vancouver, Canada, June 17-19, 2019.

Program co-Chair, 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE), August 18-21, Anaheim, California.

Member of Program Committee, 2018 International Symposium on Flexible Automation (ISFA), Kanazawa, Japan, July 15-19, 2018.

Conference Chair, 2017 International Manufacturing Research Conference (NAMRC/MSEC/ICM&P), Los Angeles, California, June 4-8, 2017.

Member of Program Committee, 2016 International Symposium on Flexible Automation (ISFA), Cleveland, Ohio, August 1-3, 2016.

Program Committee Member, 2016 Symposium on Solid and Physical Modeling (SPM 2016), Berlin, Germany, June 20-24, 2016.

Program Committee Member, 2015 SIAM/GD – SPM Conference on Geometric and Physical Modeling, Salt Lake City, Utah, October 12-14, 2015.

Conference Program Chair, 2014 International Conference on Innovative Design and Manufacturing (ICIDM), Montreal, QC, Canada, August 13-15, 2014.

Member of Program Committee, 2014 International Symposium on Flexible Automation (ISFA), Hyogo, Japan, July 14-16, 2014.

Tutorial Speaker, Computer-aided Design Tools for Additive Manufacturing, Tenth International Symposium on Tools and Methods of Competitive Engineering (TMCE), Budapest, Hungary, May 19, 2014.

Symposium Organizer, Integrated Product and Process Development Processes, 18th ASME Design for Manufacturing and the Life Cycle Conference, Portland, Oregon, August 2013.

Seminar Speaker, Advanced Manufacturing Seminars, 2013 Pacific Design and Manufacturing Show, Anaheim, California, February 13, 2013.

Member of Organization Committee, 2012 International Conferences on Innovative Design and Manufacturing (ICIDM), Taipei, Taiwan, Dec. 12-14, 2012.

Member of Program Committee, 2012 Symposium on Solid and Physical Modeling (SPM), Dijon, France, Oct. 29-31, 2012.

Member of Program Committee, 2012 International Symposium on Flexible Automation (ISFA), St. Louis, MO, June 19-20, 2012.

Conference Program Chairman, International Conference on Manufacturing Automation (ICMA) Hong Kong, China, December 2010.

Symposium Organizer, Sampling-based Geometric Modeling and Computing (CIE-14), 30th ASME Computers and Information in Engineering Conference, Montreal, Quebec, Canada, August 2010.

Symposium Co-Organizer, Computer-aided Product and Process Development Symposium, 30th ASME Computers and Information in Engineering Conference, Montreal, Quebec, Canada, August 2010.

Symposium Co-Organizer, Computer-aided Product and Process Development Symposium, 29th ASME Computers and Information in Engineering Conference, San Diego, CA, August 2009.

Symposium Co-Organizer, Computer-aided Product Development Symposium, 28th ASME Computers and Information in Engineering Conference, Brooklyn, NY, August 2008.

Symposium Co-Organizer, Computer-aided Product Development Symposium, 27th ASME Computers and Information in Engineering Conference, Las Vegas, Nevada, August 2007.

CONFERENCE SESSION ORGANIZED

Session Chair, Session Modeling, Symposium on Solid and Physical Modeling, Vancouver, Canada, June 18, 2019.

Session Chair, Session CIE-8-3: Materials Modeling and Process Quality, ASME 2018 Computers and Information in Engineering Conference (CIE), Quebec City, Canada, August 28, 2018.

Session Chair, Session OS1-1: Additive Manufacturing Sensing and Control I, International Symposium on Flexible Automation, Kanazawa, Japan, July 16, 2018.

Session Chair, Track 3 Additive Manufacturing – Mechanical Resistance, 46th North American Manufacturing Research Conference (NAMRC), College Station, Texas, June 20, 2018.

Session Chair, Session M-06, Symposium M – Additive Manufacturing for Fabrication of Advanced Materials/Devices, 9th International Conference on Materials for Advanced Technologies (ICMAT), Singapore, June 21, 2017.

Session Chair, Session 10: Additive Manufacturing (II), 2017 World Congress on Micro and Nano Manufacturing, Kaohsiung, Taiwan, March 29, 2017.

Session Chair, Session Process Development VII: Monitoring and Controls II, 28th International Solid Freeform Fabrication (SFF) Symposium, Austin, Texas, August 10, 2016.

Session Chair, Session T2: Flexible Automation in Manufacturing Systems II, International Symposium on Flexible Automation, Cleveland, Ohio, August 2, 2016.

Session Chair, Session MS13: Geometric Modeling and Processing in Additive Manufacturing, SIAM Conference on Geometric and Physical Modeling (GD/SPM15), Salt Lake City, UT, October 14,

2015.

Session Co-Chair, Session 2-7: Electrohydrodynamic Jet Printing, MSEC 2015 ASME International Manufacturing Science and Engineering Conference (MSEC), Charlotte, NC, June 11, 2015.

Session Chair, Session 2: Design for Additive Manufacturing, 43rd North American Manufacturing Research Conference (NAMRC), Charlotte, North Carolina, June 9, 2015.

Session Chair, Session *Process Modeling*, 2014 International Conference on Innovative Design and Manufacturing (ICIDM), Montreal, QC, Canada, August 15, 2014.

Session Chair, Session Modeling III – Thermal Effects, 25th Solid Freeform Fabrication Symposium, Austin, Texas, August 6, 2013.

Review Co-Coordinator, Design for Additive Manufacturing, ASME 2014 Design for Manufacturing and the Life Cycle Conference, Buffalo, NY, August 17-20, 2014.

Session Chair, Session Academic Workshop on Cloud Manufacturing and Cyber-physical Products, 10th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2014), Budapest, Hungary, May 20, 2014.

Session Chair, Session 26B4: Additive Manufacturing, International Conference on MicroManufacturing (ICOMM) 2014, Singapore, March 26, 2014.

Session Chair, Session 2-1-3 Additive Manufacturing Process Development I, International Mechanical Engineering Congress & Exposition (IMECE) 2013, San Diego, CA, Nov. 17, 2013.

Session Chair, Session Process Development II, 24th Solid Freeform Fabrication Symposium, Austin, Texas, August 13, 2013.

Session Chair, Session 20 Additive Manufacturing, International Conference on MicroManufacturing (ICOMM) 2013, Victoria, Canada, March 27, 2013.

Session Chair, Session *CAD/CAM-2*, 2012 International Symposium on Flexible Automation, St. Louis, MO, June 19, 2012.

Session Co-Chair, Session *Application of Additive Manufacturing*, 2012 International Symposium on Flexible Automation, St. Louis, MO, June 18, 2012.

Track Co-Organizer, Computer-aided Design and Manufacturing, 2012 International Symposium on Flexible Automation, St. Louis, MO, June 18-20, 2012.

Session Chair, Session 10: Rapid Prototyping, 40th North American Manufacturing Research Conference (NAMRC), Notre Dame, Indiana, June 1, 2012.

Session Co-Chair, Session 1-2-2 *Layered Manufacturing*, ASME International Manufacturing Science and Engineering Conference, Notre Dame, Indiana, June 5, 2012.

Review Co-Coordinator and Special Session Organizer, Geometry in Design, 37th ASME Computers and Information in Engineering Conference, Washington DC, USA (2011).

Review Co-Coordinator, Direct Digital Manufacturing, 37th ASME Design Automation Conference, Washington DC, USA (2011).

Session Chair, Session 1-6: Additive and Polymer manufacturing, 39th North American Manufacturing Research Conference (NAMRC), Corvallis, Oregon, June 15, 2011.

Session Chair, Session 4B Computer-aided Manufacturing I, International Conference on

Manufacturing Automation (ICMA) 2010, Hong Kong, China (2010).

Session Chair, Session 5B Computer-aided Manufacturing II, International Conference on Manufacturing Automation (ICMA) 2010, Hong Kong, China (2010).

Review Coordinator and Special Session Organizer, Direct Digital Manufacturing (Topic), 36th ASME Design Automation Conference, Montreal, Quebec, Canada (2010).

Session Chair, Session CIE-9-3 *Geometric Modeling, Analysis and Optimization*, 30th ASME Computers and Information in Engineering Conference, Montreal, Quebec, Canada (2010).

Session Chair, Session CIE-14-1 *Sampling based Geometric Modeling and Computing*, 30th ASME Computers and Information in Engineering Conference, Montreal, Quebec, Canada (2010).

Session Co-Chair, Session DAC-15-1 *Direct Digital Manufacturing*, 36th ASME Design Automation Conference, Montreal, Quebec, Canada (2010).

Review Co-Coordinator, Direct Digital Manufacturing (Topic), 35th ASME Design Automation Conference, San Diego, CA (2009).

Session Chair, Session CIE-10-3 *Computers and Knowledge Management*, 29th ASME Computers and Information in Engineering Conference, San Diego, CA (2009).

Session Co-Chair, Session DAC-18-1 *Direct Digital Manufacturing*, 35th ASME Design Automation Conference, San Diego, CA (2009).

Review Co-Coordinator, Direct Digital Manufacturing (Topic), 34th ASME Design Automation Conference, Brooklyn, NY (2008).

Session Chair, Session CIE-3-2 *Features and Solid Modeling*, 28th ASME Computers and Information in Engineering Conference, Brooklyn, NY (2008).

Session Co-Chair, Session DAC-13-1 *Direct Digital Manufacturing*, 34th ASME Design Automation Conference, Brooklyn, NY (2008).

Session Co-Chair, Session CIE-12-1 *Optimal Product Design*, 28th ASME Computers and Information in Engineering Conference, Brooklyn, NY (2008).

Session Co-Chair, Session CIE-3-5 *Object Visualization and Manipulation*, 27th ASME Computers and Information in Engineering Conference, Las Vegas, Nevada (2007).

Session Co-Chair, Session CIE-4-2 *Geometric Analysis in Simulation-based Design*, 26th ASME Computers and Information in Engineering Conference, Philadelphia, PA (2006).

Session Co-chair, Session CIE-3-10 *Solid Modeling Applications*, 25th ASME Computers and Information in Engineering Conference, Long Beach, California (2005).

GRANT PROPOSAL REVIEW

Panel Reviewer, National Science Foundation (NSF), IIP Division, 2024.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2024.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2023.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2021.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2020.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2019.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2018.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2017.

Panel Reviewer, National Science Foundation (NSF), IIP Division, 2015.

External Reviewer, Natural Science and Engineering Research Council of Canada, 2015.

Panel Reviewer, National Science Foundation (NSF), EEC Division, 2013.

Panel Reviewer, National Science Foundation (NSF), IIP Division, 2013.

Panel Reviewer, National Science Foundation (NSF), IIP Division, 2012.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2012.

Panel Reviewer, Zumberge Faculty Research & Innovation Fund, 2012.

Panel Reviewer, Zumberge Faculty Research & Innovation Fund, 2011.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2010.

Panel Reviewer, Zumberge Faculty Research & Innovation Fund, 2010.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2009.

Panel Reviewer, Zumberge Faculty Research & Innovation Fund, 2009.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2008.

Panel Reviewer, National Science Foundation (NSF), CMMI Division, 2007.

PAPER REVIEW

Journal and Conference Proceedings Reviewer

Additive Manufacturing
Advanced Materials
Advanced Functional Materials
AI in Engineering Design, Analysis and Manufacturing
ASME - Journal of Computing and Information Science in Engineering
ASME - Journal of Mechanical Design
ASME - Journal of Manufacturing Science and Engineering
ASME - Journal of Micro and Nano-Manufacturing
ASME - Journal of Mechanisms and Robotics
Bioinspiration & Biomimetics
Computer-aided Design
Computer-aided Design and Application
Computer in Industry
Engineering
Frontiers of Mechanical Engineering
IIE Transactions

IEEE – Transactions on Industrial Informatics
IEEE – Transactions on Automation Science and Engineering
IEEE – Transactions on Ultrasonics, Ferroelectrics, and Frequency Control
IEEE – Transactions on Visualization and Computed Graphics
Integrated Computer-aided Engineering
International Journal of Advanced Manufacturing Technology
International Journal of Precision Engineering and Manufacturing
International Journal of Computer Integrated Manufacturing
International Journal of Computer Aided Engineering and Technology
Journal of Additive Manufacturing
Journal of Mechanical Engineering Science
Journal of Materials Processing Technology
Journal of Reinforced Plastics and Composites
Materials Science and Engineering
Matter
Nature Communications
Science Advances
SME - Journal of Manufacturing Systems
SME - Journal of Manufacturing Processes
Structural and Multidisciplinary Optimization
Rapid Prototyping Journal
Virtual and Physical Prototyping

Conference Proceedings Reviewer

CAD Conference and Exhibition
Solid Freeform Fabrication Symposium
SME NAMRC Conference
ASME - DETC Conferences
ASME - IMECE Conference
International Conference on MicroManufacturing
Euro-Graphics
ACM SIGGraph
International Symposia on Tools and Methods of Competitive Engineering
Symposium on Solid and Physical Modeling

CONFERENCE POSTER REVIEW

Graduate Student Poster Competition Reviewer, 30th ASME Computers and Information in Engineering Conference, Montreal, Quebec, Canada (2010).

Graduate Student Poster Competition Reviewer, 29th ASME Computers and Information in Engineering Conference, San Diego, California (2009).

INSTITUTIONAL SERVICES

University of Southern California – Department of Aerospace and Mechanical Engineering:

Chair – Ph.D. Admission Committee, 2023 -2024.
Member – Energy and Manufacturing Faculty Search Committee, 2022-2023.
Member – Ph.D. Admission Committee, 2022 - 2023.
Member – Design and Manufacturing Faculty Search Committee, 2021.

University of Southern California – Department of Industrial & Systems Engineering:

Chair – Department Space Planning Committee, 2021.
Chair – Department Space Planning Committee, 2020.
Chair – Department Research Restart Committee, 2020.
Member – Ph.D. Admission Committee, 2020.
Member – Research Space Review Committee, 2019.
Member – Ph.D. Admission Committee, 2019.
Member – Department Chair Nomination Committee, 2018.
Member – Ph.D. Admission Committee, 2018.
Member – Faculty Merit Evaluation Committee, 2017.
Member – Ph.D. Admission Committee, 2016.
Member – Ph.D. Admission Committee, 2016.
Member – Ph.D. Admission Committee, 2015.
Chair – Research Space Review Committee, 2015.
Member – Faculty Merit Evaluation Committee, 2015.
Member – ISE UCAR Review Committee, 2014.
Chair – Course Review Committee (ITP482), 2013.
Member – Ph.D. Admission Committee, 2013.
Chair – Research Space Review Committee, 2013.
Member – Course Review Committee (ISE426), 2012.
Chair – Research Space Review Committee, 2011.
Member – Ph.D. Admission Committee, 2011.
Chair – Course Review Committee (ISE435), 2011.
Member – Course Review Committee (ISE482), 2010.
Member – Ph.D. Admission Committee, 2009.
Chair – Course Review Committee (ISE410), 2009.
Member – Faculty Merit Evaluation Committee, 2009.
Chair – Ph.D. Admission Committee, 2008.
Member – Ph.D. Admission Committee, 2006-07.
Member – Undergraduate Curriculum Development Committee, 2006-07.
Member – Ph.D. Program Development Committee, 2006-08.
Doctoral Screening Examiner, 2007-09.

University of Southern California – Viterbi School of Engineering:

Member – Engineering Faculty Council (EFC), 2023-2025.

Member – Advanced Manufacturing Faculty Search Committee, 2019.

Member – Advanced Manufacturing Faculty Search Committee, 2018.

Director – Daniel J. Epstein Institute, 2018-2020.

Member – Viterbi Student Design-Build Space Advisory Committee, 2015.

Member – Advanced Manufacturing Cross-departmental Search Committee, 2013.

Member – VSoE Space Metrics Committee, 2010.

Academic advisor – Undergraduate Fab Lab, USC, 2007 ~ current.

OTHER SERVICES

Panel Member – State-of-the-art, Challenges and Research Needs to Further Additive Manufacturing, MSEC 2015 ASME International Manufacturing Science and Engineering Conference, Charlotte, NC, June 10, 2015.

Presenter – 1st Huazhong University of Science & Technology (HUST) SoCal Forum, Newport Beach, CA, May 31, 2015.

Panel Member – Viterbi Spring 2015 Academic Career Mentoring Panel – *Career in Industry vs. Research Lab vs. Academia*, USC, April 15, 2015.

External Expert Reviewer – Evaluation of Candidates for the Faculty Position in Design of Mechatronic Machines, Aalto University, Espoo, Finland, January 2015.

Panel Member – 2nd HKUST-USC Forum on 3D Printing – Research and Practice, HKUST, Kowloon, Hong Kong, December 18, 2014.

Panel Member – 1st HKUST-USC Forum on 3D Printing – Research and Practice, HKUST, Kowloon, Hong Kong, January 18, 2014.

Panel Member – Med Innovation Challenge Rounds – 3D Printing: Reshaping the Future of Pediatric Medical Devices, Children's Hospital Los Angeles, Los Angeles, November 21, 2013.

Team advisor – VisionFab Technologies, Maseeh Entrepreneurship Prize Competition, Viterbi School of Engineering, USC, 2013.

Team advisor – ComfortCorrect, Maseeh Entrepreneurship Prize Competition, Viterbi School of Engineering, USC, 2013.

Panel Member – An Early Career Forum on Manufacturing Research Professions in Academia, Industry and National Laboratories, Notre Dame, Indiana, June 5, 2012.

Presenter – NSF CAREER Award Proposal Workshop, USC, May 16, 2012.

Mentor – WESTEC Guided Tours for High School Students, SME, March 24, 2010.

Mentor - Bright Minds Workgroup for High School Students, SME, May 2, 2007.

External Judge - Global Access Program Final Presentation, Anderson School of Management, University of California – Los Angeles, Dec. 2006.

APPENDIX B

DOCUMENTS CONSIDERED

Exhibit No.	Reference
1001	U.S. Patent No. 11,338,511 ("'511 Patent")
1002	Excerpts from the Prosecution History of the '511 Patent (the "Prosecution History"), including: • PPH Request (dated May 24, 2021) • PPH Request Decision (dated July 9, 2021) • Subsequent PPH Request and IDS (dated July 14, 2021) • Subsequent PPH Request Decision (dated July 16, 2021) • Non-Final Office Action (dated September 2, 2021) • Applicant-Initiated Interview Summary (from interview held on December 16, 2021) • Terminal Disclaimer and Approval of Terminal Disclaimer (dated December 20, 2021) • Response (dated December 20, 2021) • Notice of Allowance (dated January 28, 2022) • Rule 312 Amendment (dated February 28, 2022) • Additional IDS (dated March 8, 2022) • Issue Fee Payment (dated April 19, 2022) • Issue Notification (dated May 4, 2022)
1003	Yong Chen Declaration
1004	U.S. Patent No. 8,666,142, "System and Method for Manufacturing" ("Shkolnik")
1005	International Patent Application Publication WO 2017/154564 A1, "Three-Dimensional Shaping Device" ("Sekine") – translated to English and including declaration of Eric Vance (translator)
1006	U.S. Patent Application Publication No. 2017/0102679, "Sub-Pixel Grayscale Three-Dimensional Printing" ("Greene")
1007	Paul F. Jacobs, "Fundamentals of Stereolithography," *Proceedings of the 1992 International Solid Freeform Fabrication Symposium*, pages 196-211 ("Jacobs")

1008	C. Groth *et al.*, Three-Dimensional Printing Technology, VOLUME XLVIII NUMBER 8 © 2014 JCO, Inc. ("Groth")
1009	U.S. Patent 8,102,332 ("Intensity Scaling for Multi-Projector Displays")
1010	Song *et al.*, "A new edge blending paradigm for multi-projector tiled display wall," *2010 International Conference on Computer Application and System Modeling* (ICCASM 2010), Taiyuan, 2010, pp. V5-349-V5-352, doi: 10.1109/ICCASM.2010.5620133
1011	Brown and Lowe, "Automatic panoramic image stitching using invariant features," *International Journal of Computer Vision*, 74 (2007): 59-73
1012	U.S. Patent 6,456,339 B1 ("Super Resolution Display")
1013	U.S. Patent 7,079,157 B2 ("Matching the Edges of Multiple Overlapping Screen Images")
1014	Garcia-Dorado and Cooperstock, "Fully automatic multi-projector calibration with an uncalibrated camera," *CVPR 2011 WORKSHOPS*, Colorado Springs, CO, USA, 2011, pp. 29-36, doi: 10.1109/CVPRW.2011.5981726
1015	Harville *et al.*, "Practical Methods for Geometric and Photometric Correction of Tiled Projector," *2006 Conference on Computer Vision and Pattern Recognition Workshop (CVPRW '06)*, New York, NY, USA, 2006, pp. 5-5, doi: 10.1109/CVPRW.2006.161
1016	U.S. Patent 7,443,364 B2 ("Projection of Overlapping Sub-Frames onto a Surface")
1017	U.S. Patent 7,907,792 B2 ("Blend Maps for Rendering an Image Frame")
1018	U.S. Patent 7,292,207 B1 ("Computing Blending Functions for the Tiling of Overlapping Video Projectors")
1019	U.S Patent 8,427,391 B2 ("Configurable Imaging System")
1020	U.S. Patent 8,446,431 B2 ("DLP Edge Blending Artefact Reduction")
1021	U.S. Patent Application Publication No. 2013/0269882 A1 ("Tiled Display Rotational Assembly")
1022	U.S Patent Application Publication No. 2013/0278840 A1 ("System and Method for Image Aspect Preservation in Multiple Projector Alignment")
1023	U.S. Patent Application Publication No. 2013/0321475 A1 ("Zonal Illumination for High Dynamic Range Projection")
1024	U.S. Patent Application Publication No. 2016/0046075 A1 ("Three-Dimensional Printing with Supported Build Plates")

1025	Y. Chen *et al.*, "Digital Material Fabrication Using Mask-Image-Projection-Based Stereolithography," *Rapid Prototyping Journal*, Vol. 19(3), 2013
1026	Y. Chen *et al.*, "Hopping Light Vat Photopolymerization for Multiscale Fabrication," *Small*, Vol. 19(11), 2205784, 2023
1027	Y. Chen *et al.*, "Smooth Surface Fabrication Based on Controlled Meniscus and Cure Depth in Microstereolithography," *Journal of Micro- and Nano-Manufacturing*, Vol. 3, September 2015
1028	European Patent Application Publication No. EP 3,053,729 A1, "Method for exposing a photo polymerizable material for solidification of material layer by layer to build a 3D object" ("Jørgensen")
1029	Yi *et al.*, "Delta DLP 3-D Printing of Large Models," *IEEE Transactions on Automation Science and Engineering*, Vol. 15, No. 3 (DOI: 10.1109/TASE.2017.2751664) ("Yi")