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(54) AUTO TIP CALIBRATION IN AN EXTRUSION APPARATUS

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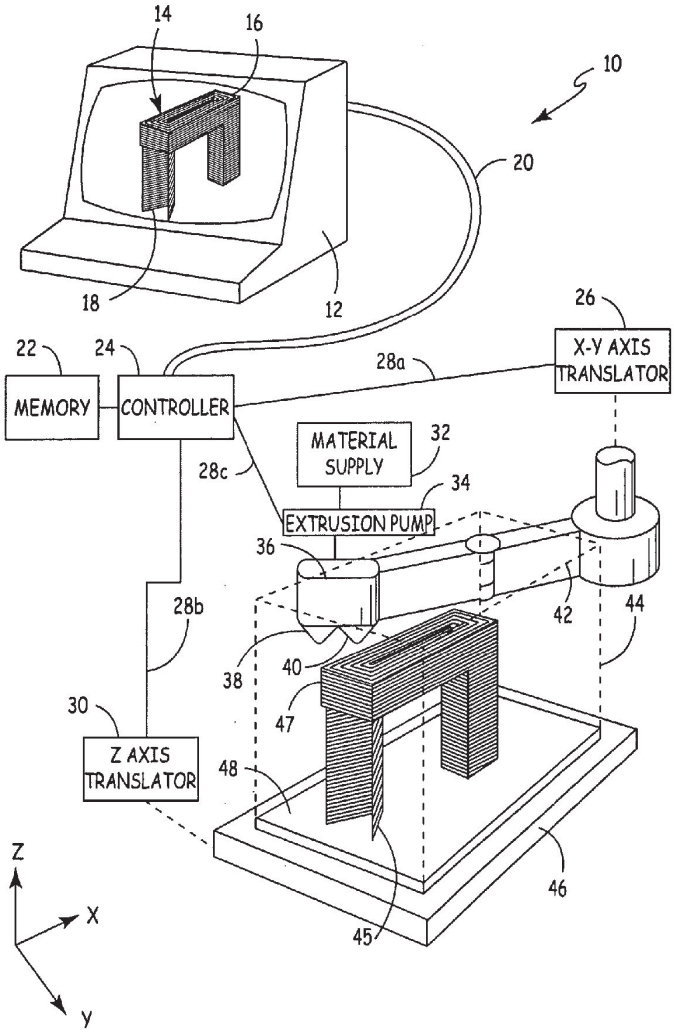
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(57) **ABSTRACT**

The present invention is a method for performing a calibration routine of a deposition device in a three-dimensional modeling machine that deposits a material to build up three-dimensional objects as directed by a controller on a substrate mounted on a platform. The method comprises generating a material build profile, which represents a three-dimensional structure at defined locations. A relative position of the material build profile is then determined. An expected build profile is identified and then compared to the determined relative position of the material build profile to identify any difference which represents an offset. The modeling system then positions the deposition device based upon the offset.



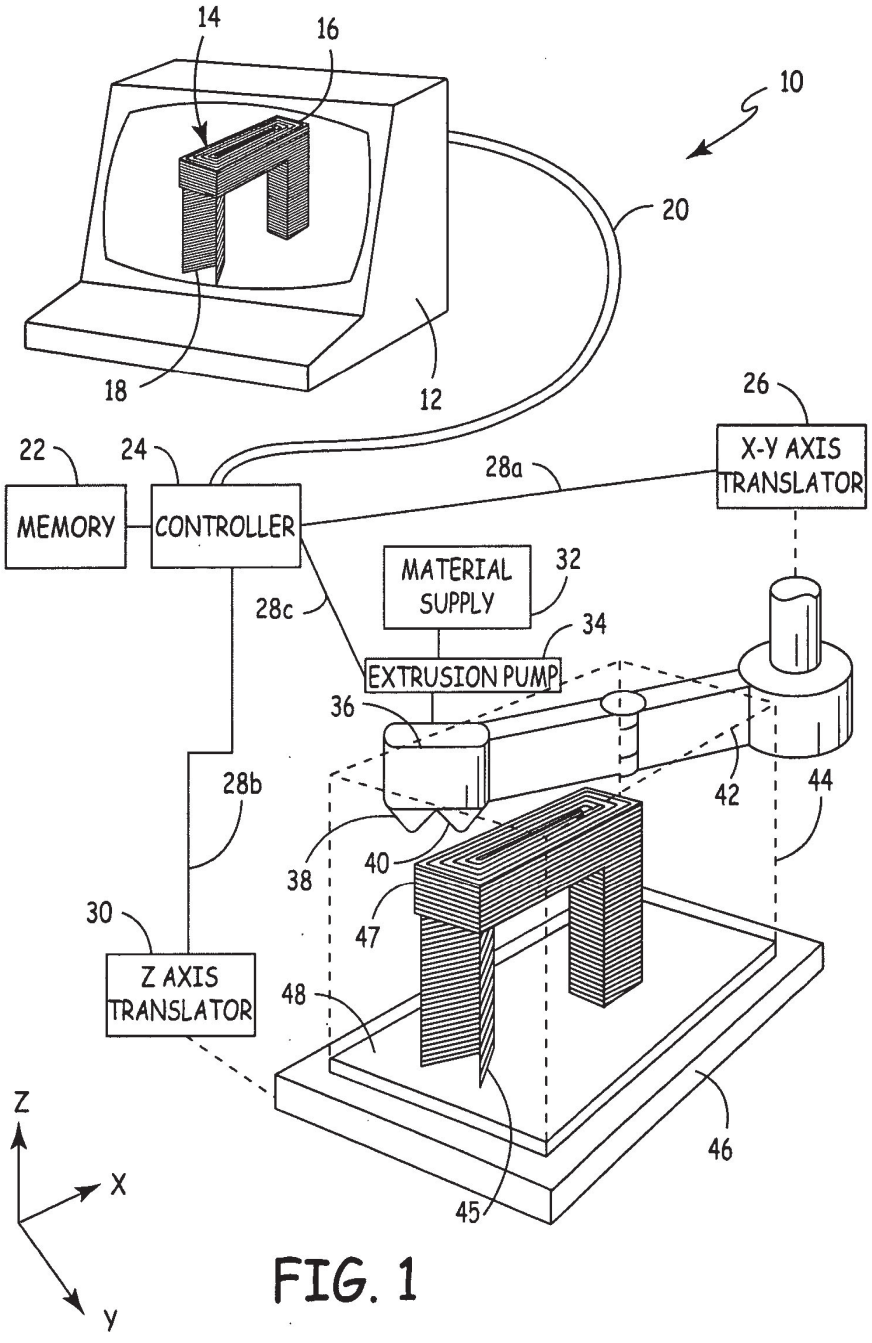

14
16
10
20
18
12
26
22
24
28a
X-Y AXIS TRANSLATOR
MEMORY
CONTROLLER
MATERIAL SUPPLY
32
28c
34
EXTRUSION PUMP
36
28b
42
44
38
40
47
30
Z AXIS TRANSLATOR
48
46
45
Z
X
y

FIG. 1

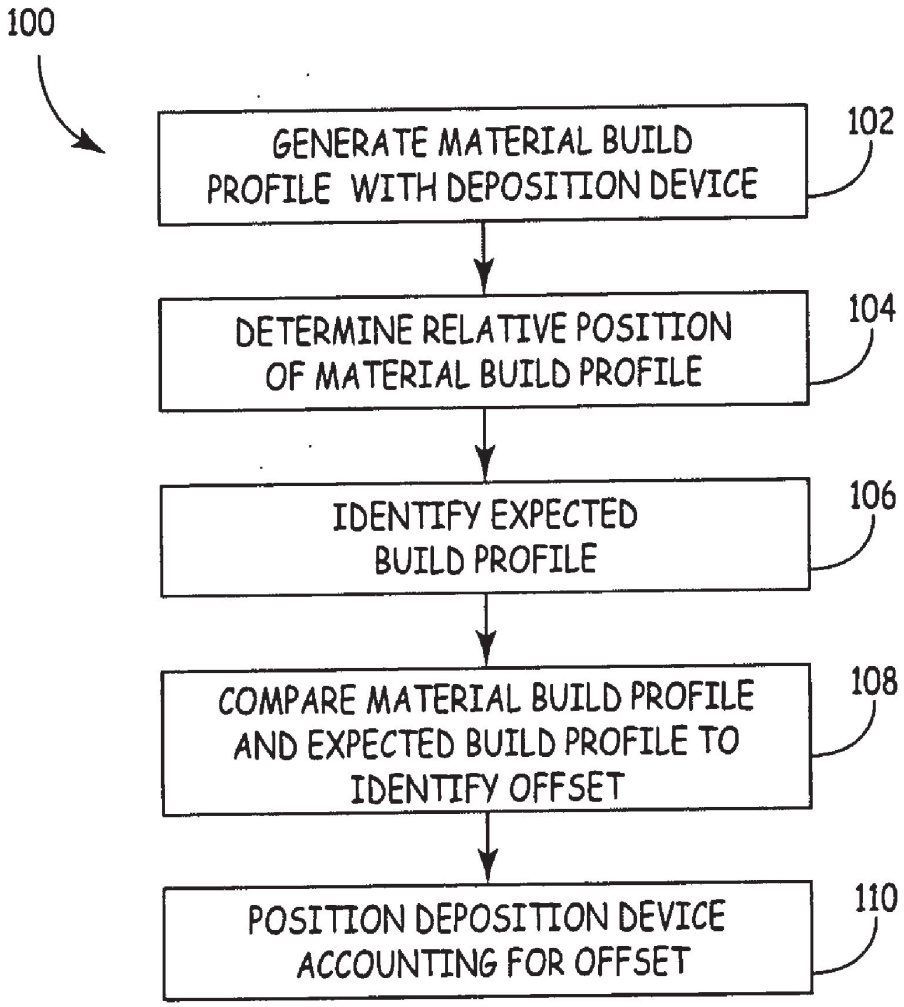

100
GENERATE MATERIAL BUILD PROFILE WITH DEPOSITION DEVICE
102
DETERMINE RELATIVE POSITION OF MATERIAL BUILD PROFILE
104
IDENTIFY EXPECTED BUILD PROFILE
106
COMPARE MATERIAL BUILD PROFILE AND EXPECTED BUILD PROFILE TO IDENTIFY OFFSET
108
POSITION DEPOSITION DEVICE ACCOUNTING FOR OFFSET
110

FIG. 2

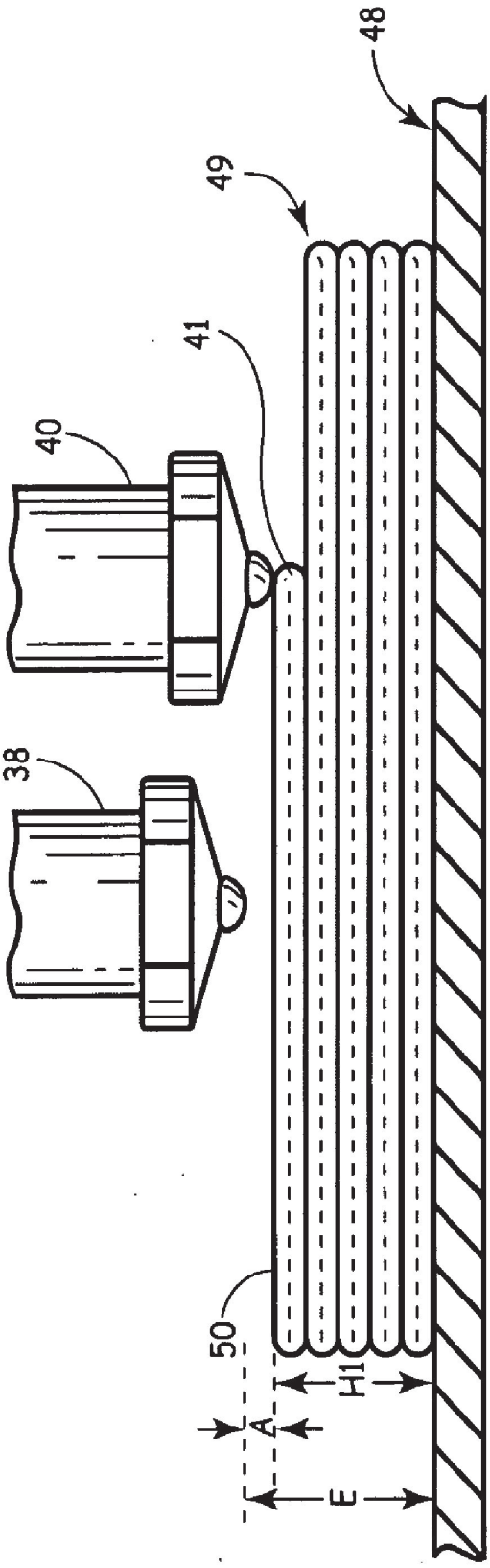


FIG. 3

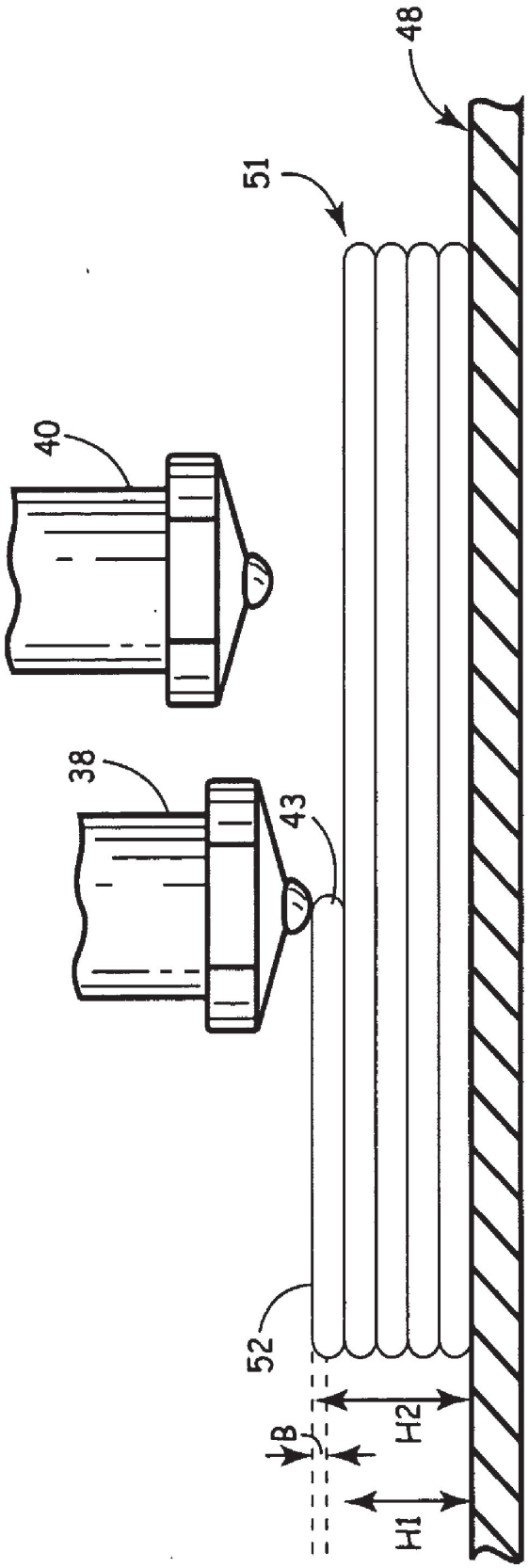


FIG. 4

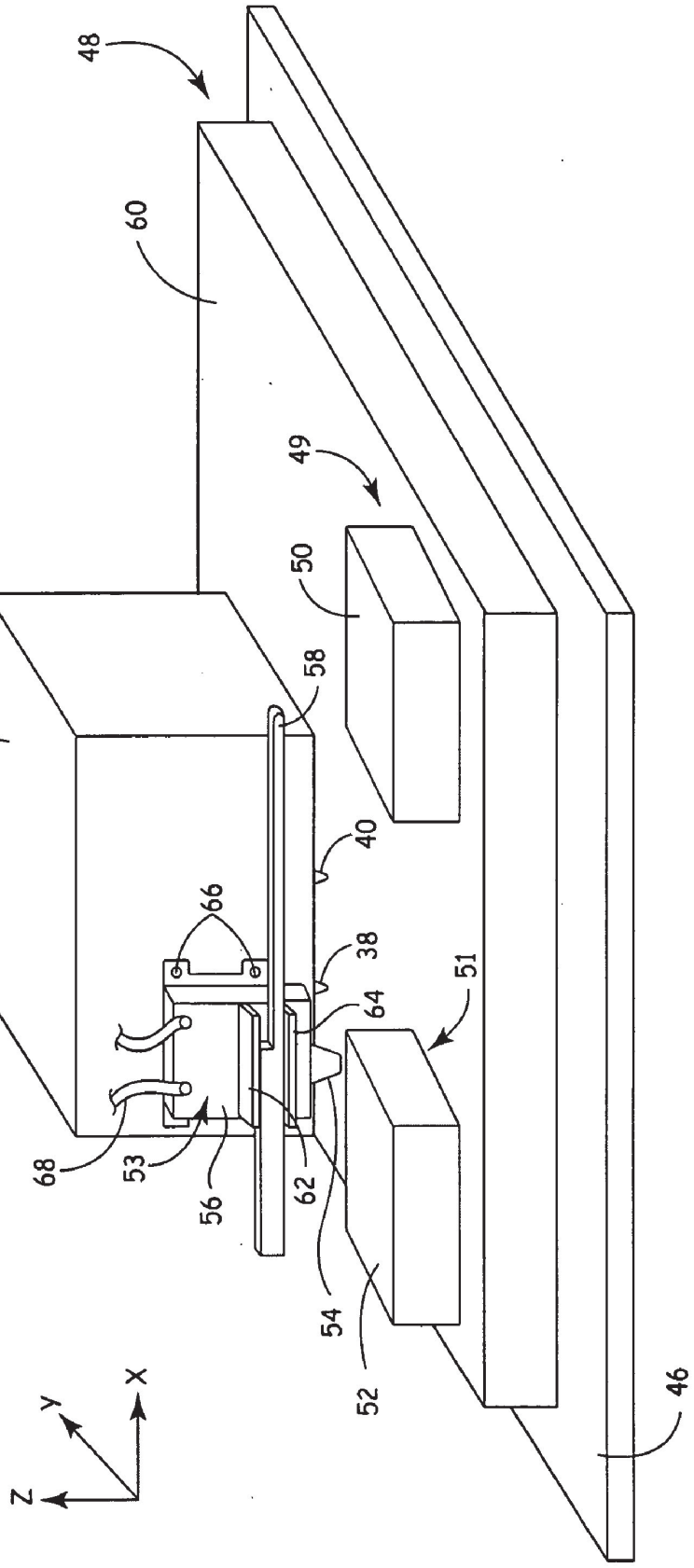


FIG. 5

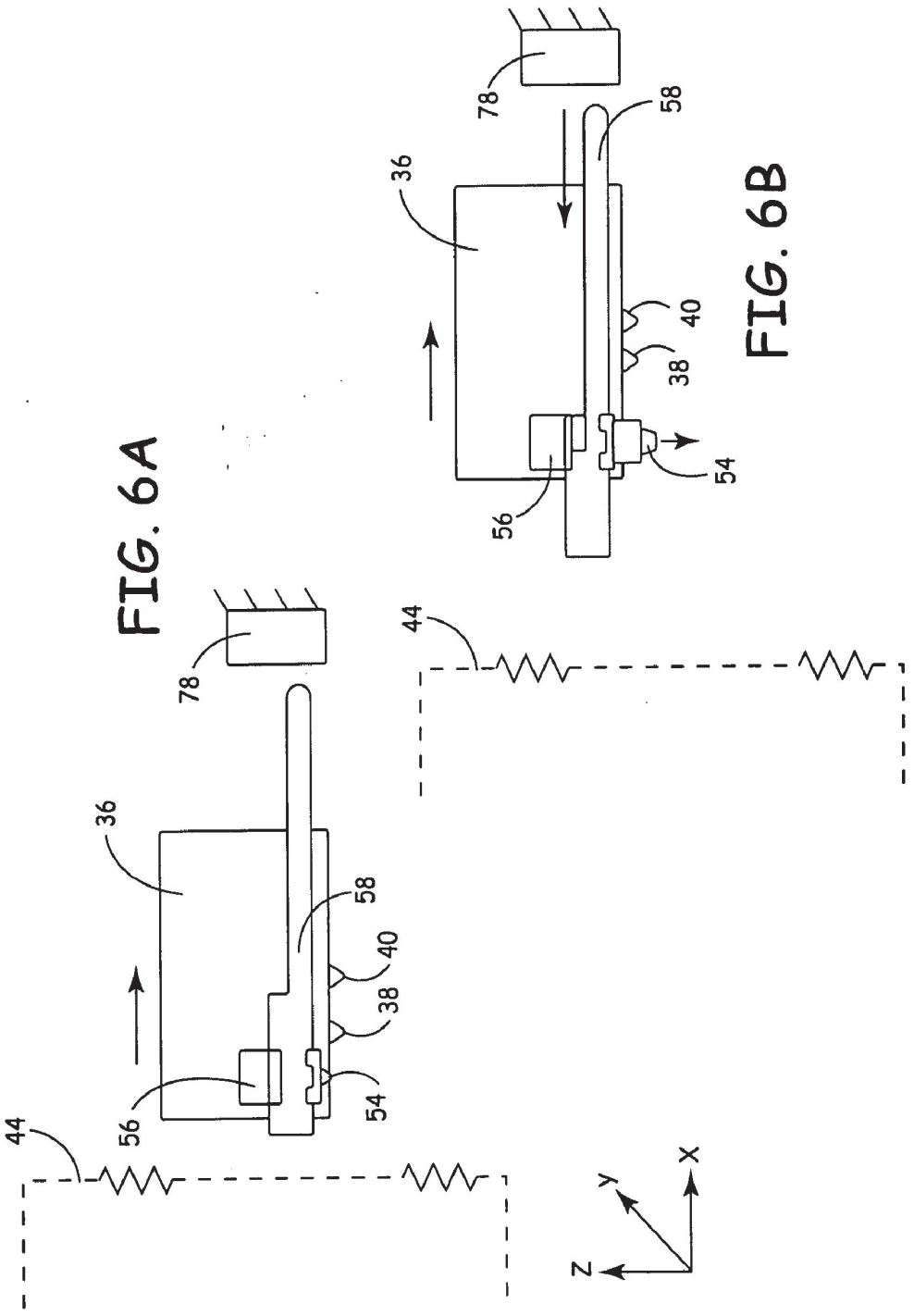


FIG. 6A

FIG. 6B

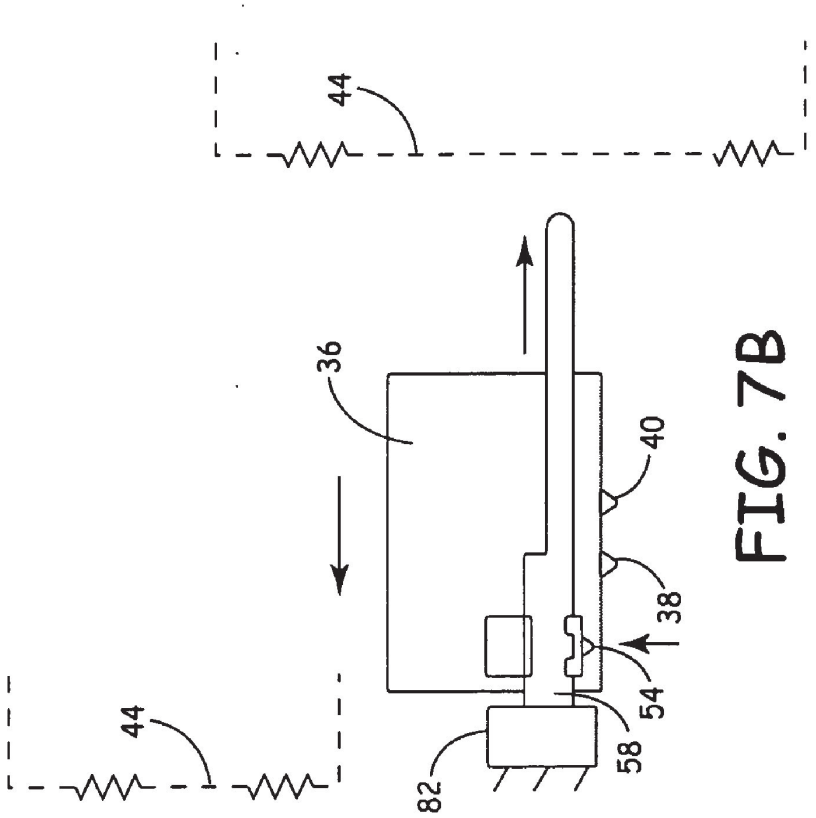


FIG. 7B

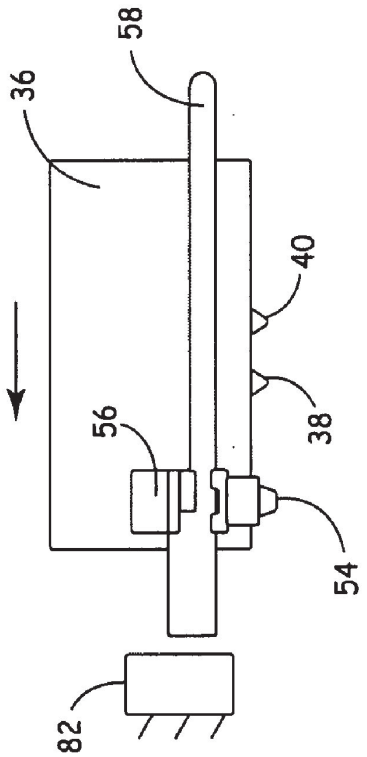
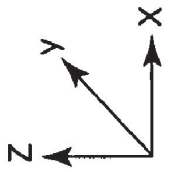


FIG. 7A



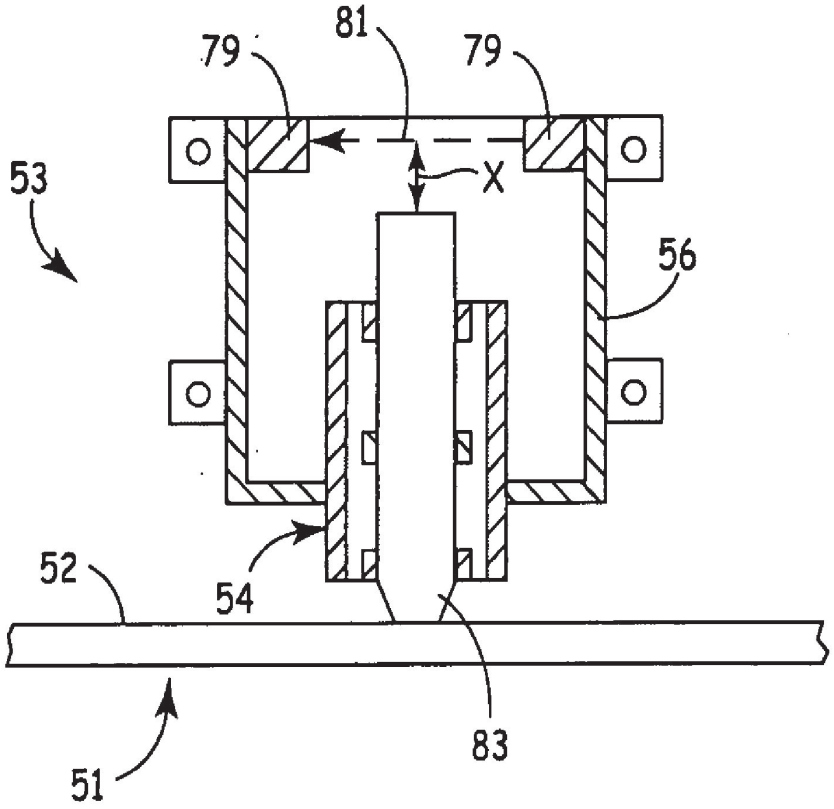


FIG. 8A

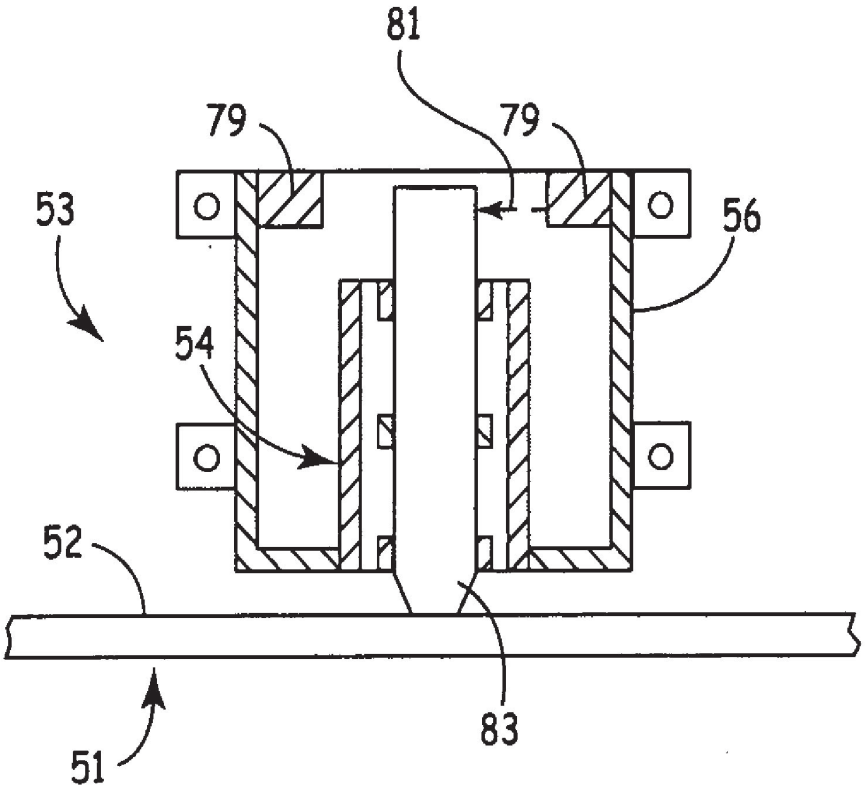


FIG. 8B

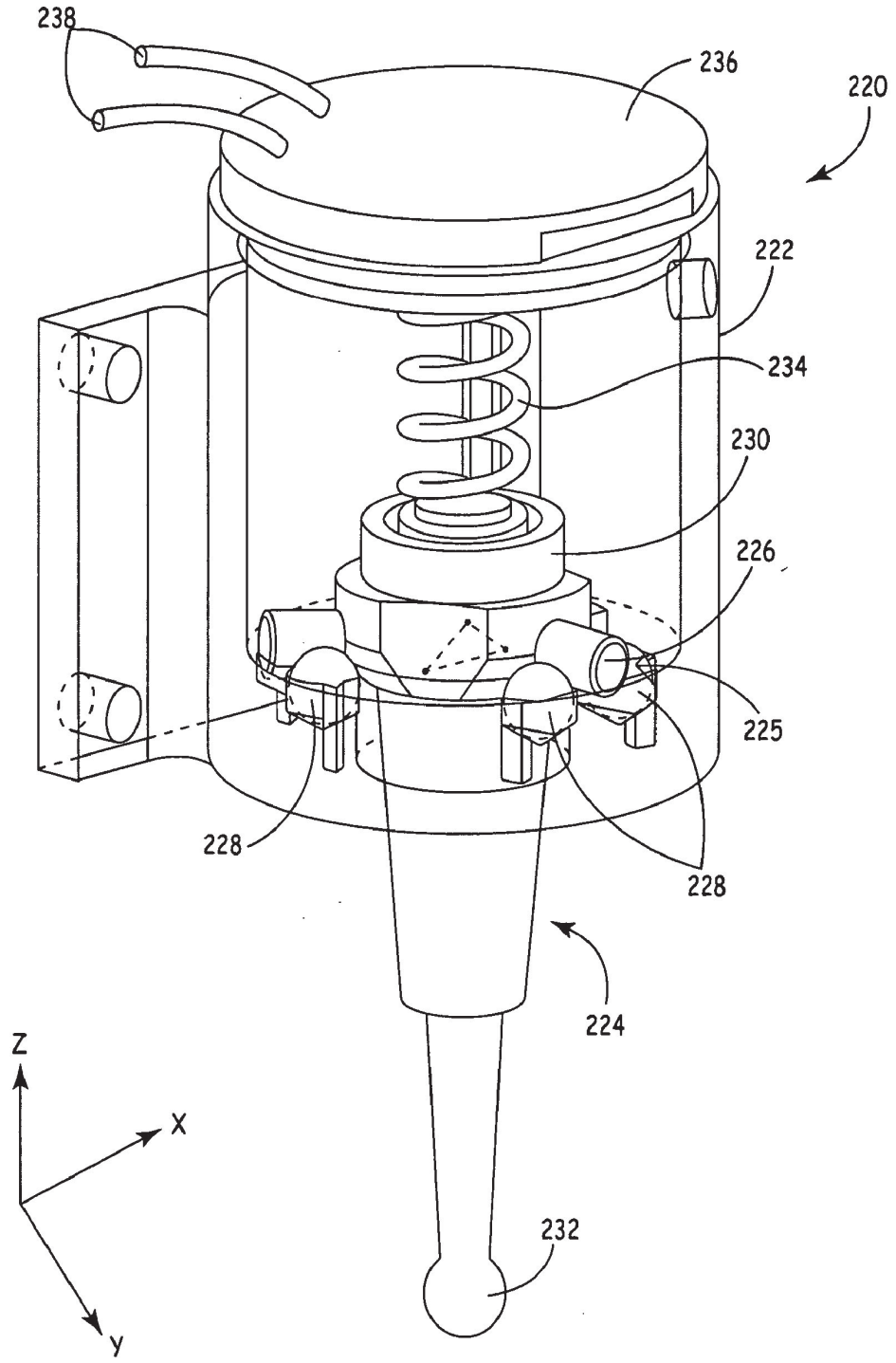


FIG. 9

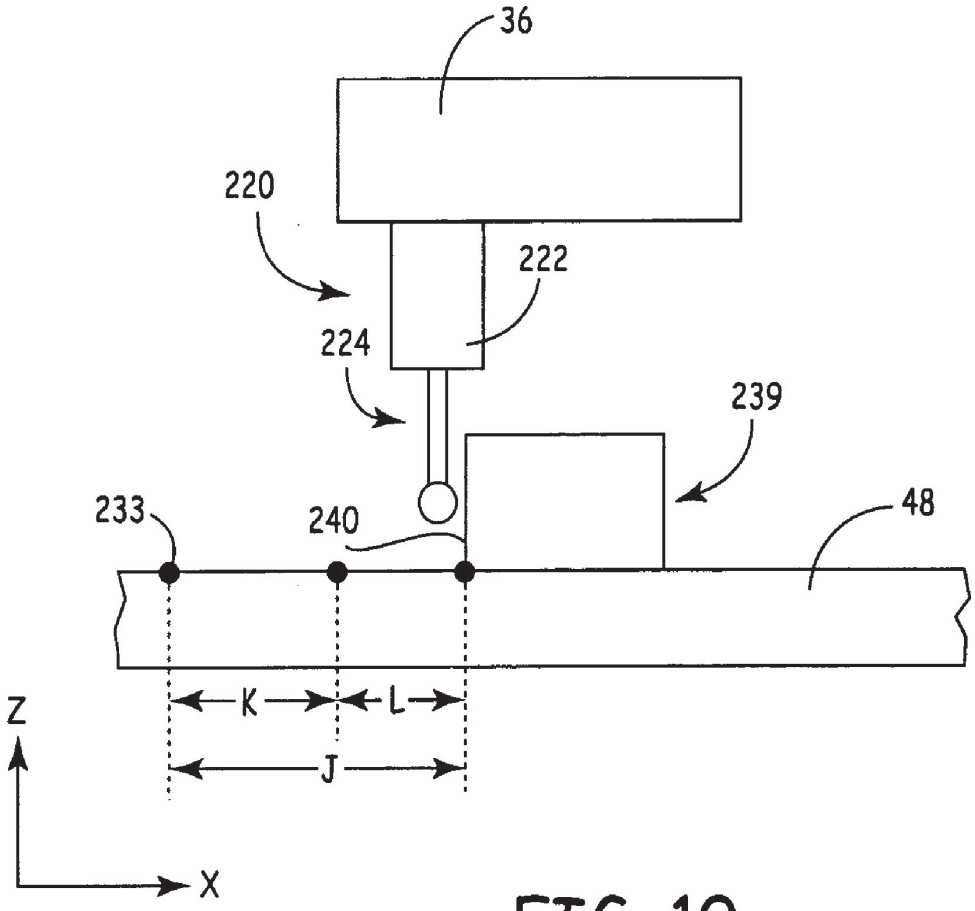


FIG. 10

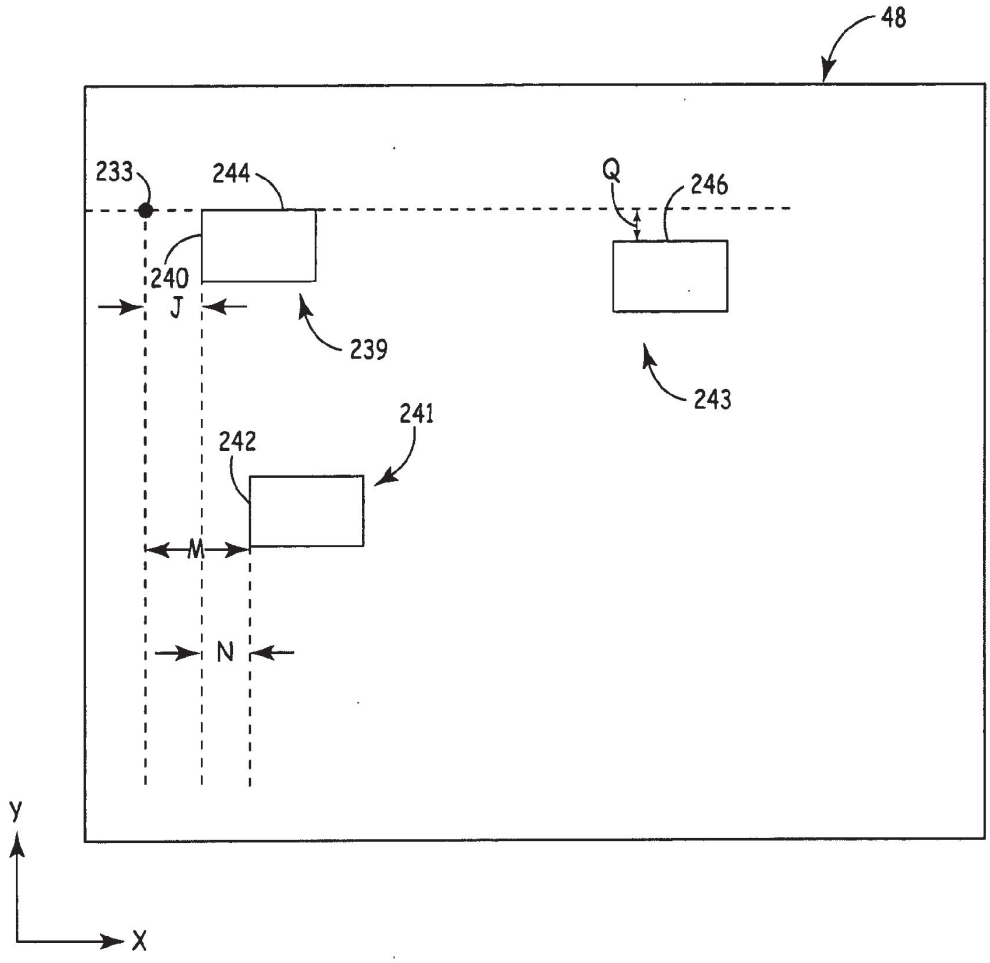


FIG. 11

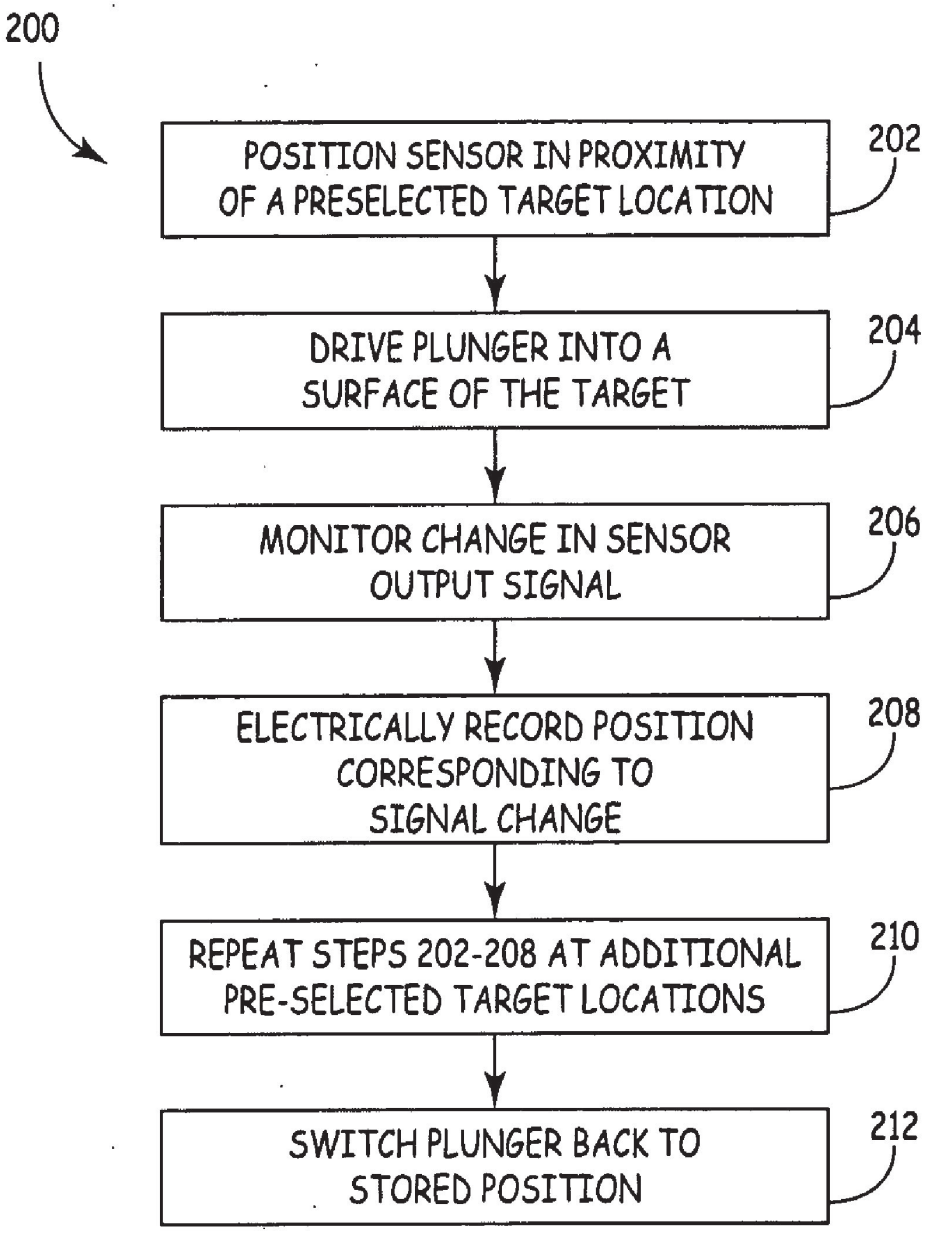

200
POSITION SENSOR IN PROXIMITY OF A PRESELECTED TARGET LOCATION
202
DRIVE PLUNGER INTO A SURFACE OF THE TARGET
204
MONITOR CHANGE IN SENSOR OUTPUT SIGNAL
206
ELECTRICALLY RECORD POSITION CORRESPONDING TO SIGNAL CHANGE
208
REPEAT STEPS 202-208 AT ADDITIONAL PRE-SELECTED TARGET LOCATIONS
210
SWITCH PLUNGER BACK TO STORED POSITION
212

FIG. 12

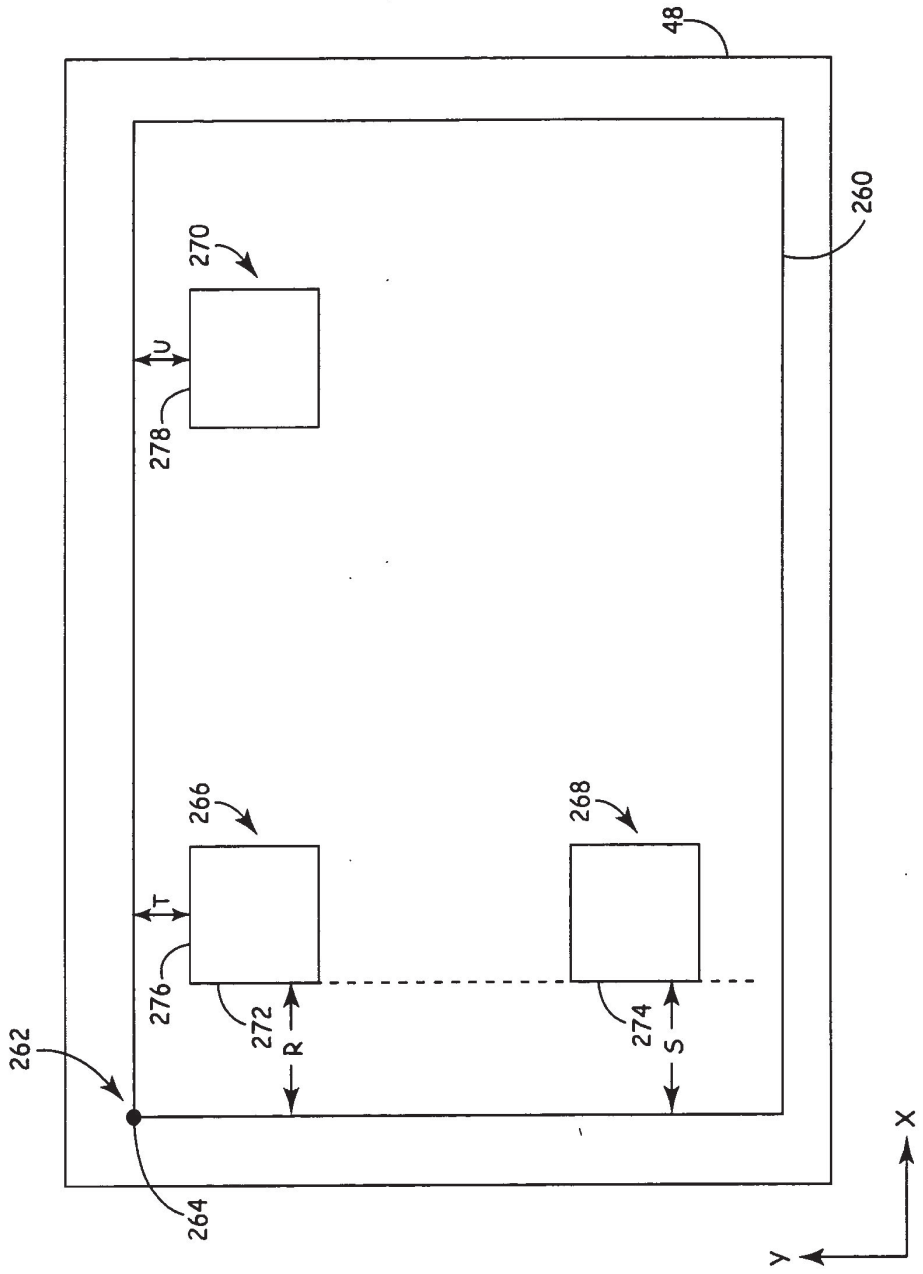


FIG. 13A

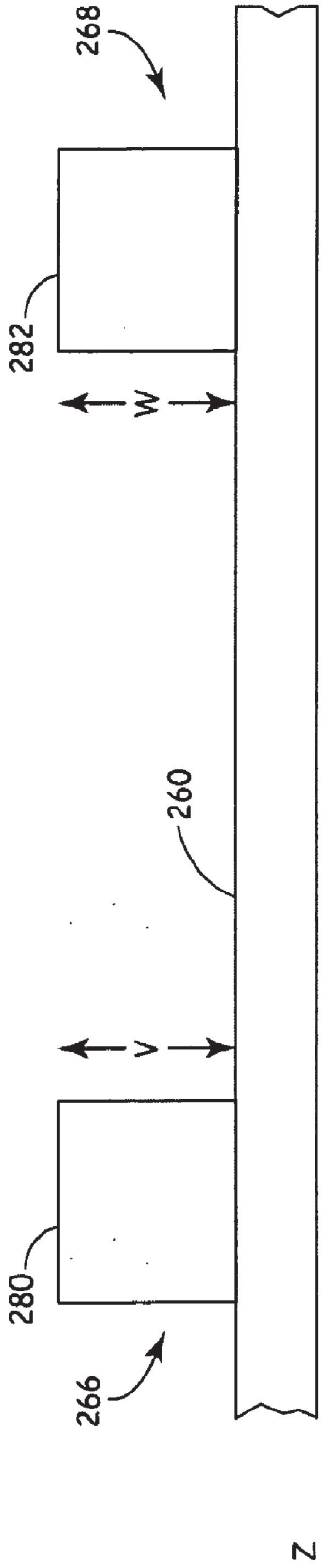


FIG. 13B

AUTO TIP CALIBRATION IN AN EXTRUSION APPARATUS

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] None.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to the fabrication of three-dimensional objects using additive process modeling techniques. More particularly, the invention relates to a method for calibrating extrusion tips in a three-dimensional modeling machine.

[0003] Additive process modeling machines make three-dimensional models by building up a modeling medium, usually in planar layers, based upon design data provided from a computer aided design (CAD) system. A mathematical description of a physical part to be created is usually split into planar layers, and those layers are individually shaped and applied to produce the final part. Three-dimensional models are used for functions including aesthetic judgments, proofing the mathematical CAD model, forming hard tooling, studying interference and space allocation, and testing functionality. The dominant application of layered manufacturing in recent years has been for rapid prototyping.

[0004] Examples of apparatus and methods for making three-dimensional models by depositing solidifiable modeling material are described in Crump U.S. Pat. No. 5,121,329, Batchelder, et al. U.S. Pat. No. 5,303,141, Crump U.S. Pat. No. 5,340,433, Batchelder, et al. U.S. Pat. No. 5,402,351, Crump et al. U.S. Pat. No. 5,503,785, Abrams et al. U.S. Pat. No. 5,587,913, Danforth, et al. U.S. Pat. No. 5,738,817, Batchelder, et al. U.S. Pat. No. 5,764,521 and Comb et al. U.S. Pat. No. 5,939,008, all of which are assigned to Stratasys, Inc., the assignee of the present invention. An extrusion head extrudes solidifiable material in a fluent strand (also termed a "bead" or "road") from an extrusion tip onto a base. An extrusion head may have several extrusion tips in order to extrude different materials. For example, an extrusion head may have a first extrusion tip that extrudes modeling material to build up a three-dimensional model, and a second extrusion tip that extrudes support material to provide temporary support during a model build cycle. A base comprises a modeling substrate which is removably affixed to a modeling platform. The extruded material is deposited by the extrusion tip layer-by-layer in areas defined from the CAD model, as the extrusion head and the base are moved relative to each other by mechanical means in three dimensions. It is important to maintain a proper distance between the extrusion tip and the base while the model is being built to ensure proper construction of the model. If the extrusion tip is too far away from the base, then the build material may be misplaced or deformed. Conversely, if the extrusion tip is too close to the base, then it may contact the model and cause damage to the model and possibly the extrusion tip or head itself. Furthermore, it is important to tightly control the distance between extrusion tips in a multiple tip system to ensure material layers are properly placed on the substrate or on top of one another.

[0005] Once finished, the model is removed from the substrate. A solidifiable material which adheres to the previous layer with an adequate bond upon solidification is used as the modeling material. Thermoplastic materials have been found particularly suitable for these deposition modeling techniques. Other additive process manufacturing techniques include depositing UV curable polymers as in Masters U.S. Pat. No. 5,46,569; jetting of droplets of material as in Helinski U.S. Pat. No. 5,50,515; extruding a settable plastic in vertical strips as in Valavaara U.S. Pat. No. 4,749,347; laser welding deposition as in Pratt U. S. Pat. No. 5,038,014; stacking and adhering planar elements as in DiMatteo U.S. Pat. No. 3,932,923; and applying shaped layers of paper as in Hull U.S. Pat. No. 5,82,559.

[0006] Several different types of rapid prototyping machines are commercially available. This commercial availability makes three-dimensional modeling very convenient for consumers because they can create three-dimensional models right at their own facility. However, the machines also require servicing from time to time such as when an extrusion tip may become unusable or unreliable due to a back-up or solidification of modeling material inside the tip. When the flow of modeling material through the extrusion tip is obstructed installation of a new tip is typically necessary. Consumer-replaceable components within the rapid prototyping field have become more available including replacement extrusion tips. While consumer-replaceable extrusion tips have made machine repairs more convenient, it also requires calibration of the tip once it has been replaced or re-installed. The calibration routine includes calibrating a Z-axis tip-to-substrate offset to ensure that the system knows the spatial relationship between the extrusion tip and the substrate prior to building a model. Furthermore, the calibration routine may include calibrating an X-axis and Y-axis tip-to-origin offset to ensure that the system knows the spatial relationship between the extrusion tip and an origin on the substrate. If multiple tips exist, the calibration routine also includes a Z-axis tip-to-tip offset, an X-axis tip-to-tip offset, and a Y-axis tip-to-tip offset. Without calibration, the position of the extrusion tips relative to the base and relative to each other may be incorrect, which may result in the inability of the modeling system to build accurate, error-free models.

[0007] Traditionally, calibration routines consisted of a manual or "eyeball" method performed by a trained consumer or technician. Previously, identifying any Z-axis tip-to-tip offset typically involved extruding layers of material and then manually measuring the thickness of the extruded material with a caliper. Similarly, identifying any X-axis or Y-axis tip-to-tip offset typically involved manually measuring the position of the extruded material along the X-Y axis. The tip-to-substrate offset is typically determined by etching a series of consecutive numbers into the substrate at increasing distances between the extrusion tip and the base and "eyeballing" the highest visible number etched into the substrate. The tip-to-origin offset was typically calibrated during assembly or as part of an extrusion head gantry position calibration. Unfortunately, calibration routines involving manual or "eyeball" methods can be unreliable and time-consuming. Additionally, because proper manual calibration requires operator judgment, it can be difficult for inexperienced users to identify the correct calibrated offsets.

[0008] Incorrect calibration of extrusion tips can result in the failure to form or build the three-dimensional model.

Therefore, there exists a need for an automatic extrusion tip calibration routine that does not require operator intervention or judgment.

SUMMARY OF THE INVENTION

[0009] The present invention is a method for performing a calibration routine in a three-dimensional modeling machine that builds-up three-dimensional objects as directed by a controller that deposits modeling material from a deposition device onto a substrate mounted on a platform. The method comprises generating a material build profile, which represents a three-dimensional structure at a defined location. A relative position of the material build profile is then determined. An expected build profile is identified and then compared to the determined relative position of the material build profile to identify any difference therebetween from which an offset is determined. The modeling system then positions the deposition device based upon the offset.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** is a schematic of a representative generic three-dimensional layered modeling system.

[0011] FIG. **2** is a process flow diagram illustrating the steps executed in performing a calibration routine according to the present invention.

[0012] FIG. **3** is a side view of a support material extrusion tip of an extrusion-based layered modeling system of the present invention extruding a support pad of material.

[0013] FIG. **4** is a side view of a model material extrusion tip of the extrusion-based layered modeling system of the present invention extruding a model pad of material.

[0014] FIG. **5** is a perspective view of a preferred embodiment of a sensor assembly of the present invention with a plunger in the lowered position, mounted to an extrusion head of the extrusion-based layered modeling system and positioned over the model pad and the support pad.

[0015] FIGS. **6**A and **6**B depict the lowering of the plunger to a sensing position.

[0016] FIGS. **7**A and **7**B depict the raising of the plunger to a stored position.

[0017] FIG. **8**A is a cross-sectional view of the sensor assembly of FIG. **5**, with the plunger in contact with the model pad.

[0018] FIG. **8**B is a cross-sectional view of the sensor assembly of FIG. **5**, with the plunger occluding an optical sensor.

[0019] FIG. **9** is a perspective view of an alternative embodiment of the sensor assembly of the present invention.

[0020] FIG. **10** is a side view of the sensor assembly of FIG. **9** sensing a side surface of the model pad and the support pad.

[0021] FIG. **11** is a top view of the model pad and the support pad on a substrate.

[0022] FIG. **12** is a process flow diagram illustrating the steps executed in sensing a surface of an object by the modeling system.

[0023] FIG. **13**A is a top view of an alternative embodiment of a prefabricated fixture.

[0024] FIG. **13**B is a side view of the prefabricated fixture.

DETAILED DESCRIPTION

[0025] FIG. **1** shows a generic representation of a three-dimensional modeling system **10**, of a type known in the art with which the present invention may be used. More specifically, the three-dimensional modeling system **10** illustrated in FIG. **1** is an extrusion-based layered modeling system. A computer aided design (CAD) program resident in processor **12** generates a file describing the geometry of part **14** to be created. A slicing program (shown as resident in processor **12**, but which may alternatively be resident in a separate processor) algorithmically subdivides the file into modeling material volume elements **16** corresponding to shapes that can be extruded from a model material extrusion tip **38**. Additional support material volume elements **18** are added as necessary to provide a mechanical support **45** to a model **47** of the part **14** during its construction.

[0026] Modeling system **10** utilizes a pair of dispensers **38** and **40**, to dispense the different materials used to construct model **47** and support **45**. In this embodiment, each dispenser includes its own discharge tip, such that modeling system **10** includes model material extrusion tip **38** which extrudes modeling material, and support material extrusion tip **40**, which extrudes support material. Modeling material is dispensed by tip **38** to build the object or model **47** based on the modeling material volume elements **16**, while support material is dispensed by tip **40** to form the underlying support **45** based on the support material volume elements **18**. The support structure **45** is later removed after sufficient solidification of the modeling material that created the model **47**.

[0027] Upon receiving three-dimensional shape data from processor **12** over line **20**, controller **24** controls the extrusion of modeling material and support material in an XYZ-coordinate reference frame. Beads of modeling material and support material are extruded layer-by-layer in a build path that is a pattern defined by the modeling material volume elements **16** and support material volume elements **18**. Controller **24** determines and maintains in associated memory **22** data representative of movements required to build the model **47** according to the build path for each layer. Based on this data, controller **24** sends control signals to X-Y axis translator **26**, Z-axis translator **30**, and extrusion pump **34** over output signal lines **28***a*, **28***b* and **28***c*, respectively, to create the particular layer according to the build path. X-Y axis translator **26** is an electromechanical device that moves robotic arm **42** according to the build path for the particular layer. Extrusion pump **34** synchronously provides modeling material and support material from material supply **32** to extrusion head **36** and ultimately deposited by model material extrusion tip **38** and support material extrusion tip **40**, respectively.

[0028] The model **47** and support **45** are built on top of substrate **48**. Substrate **48** is removably mounted on modeling platform **46** and is located in modeling envelope **44**. Modeling platform **46** moves in a Z-direction under the control of Z-axis translator **30**. The Z-axis as shown is oriented radially away from the earth's surface. In other implementations, however, it can be towards the ground or

at some other chosen angle. Z-axis translator **30** incrementally lowers modeling platform **46** following deposition of a layer of modeling material or support material, to build up model **47** and support structure **45** layer-by-layer on substrate **48**. After model **47** is created, it along with any corresponding support elements **45** are removed from modeling system **10** and from substrate **48**.

[**0029**] Modeling system **10** builds precise and accurate models **47** by controlling the height and position of each layer that is built. Typically, modeling system **10** controls the rate that material is deposited from the deposition device to create each layer with a constant height. In this exemplary embodiment, the position of the tip depositing the material is important to ensure material is deposited and layers are built according to the build path in the proper locations. If the actual positions of the tips are not the same as the positions expected by controller **24**, the layers of material will not be accurately extruded in the proper X-Y-Z positions.

[**0030**] The tip position is also very important in controlling the height of each build layer in the Z-direction. The bottom of the extrusion tip typically includes an "iron" that physically contacts and flattens out the bead of material making up the build path for that layer as it is deposited. If the tip extruding material is positioned too high above the surface that the material is being deposited upon, then the iron will not flatten out as much of the bead of material as expected resulting in the bead and layer height being greater than desired and not constant. Conversely, if the tip extruding material is too low, then the iron will flatten out too much of the bead of material resulting in a bead and layer height that is less than desired as well as potentially clogging the extrusion tip. Inconsistent bead heights within a build layer results in inconsistent layer heights which are propagated throughout the build cycle as the model **47** is being created. This results in errors and structural deficiencies in the model **47**. It is important to the construction of accurate models **47** that the thickness and position of each layer be closely controlled.

[**0031**] Based upon the above discussion, it is apparent that in order to build accurate models, it is necessary to tightly control the X-Y position and the Z-axis height of a material bead. The present invention employs an automatic tip calibration capable of calibrating an extrusion tip in the X, Y, and Z directions in order to build precise and accurate models. For purposes of example and clarity of the invention, the following discussion will focus first on the calibration of one or more extrusion tips in the Z-direction, and then on the calibration in the X and Y directions.

[**0032**] Considering the Z-direction, the position of the tip extruding the material in relation to the surface upon which the material will be deposited must be controlled and maintained at a desired level in order to control the build layer thickness. This is accomplished by precise positioning of the extrusion tip with respect to the substrate **48** upon which the extrusion tip will initially deposit material. Once the extrusion tip is properly positioned in relation to the substrate **48**, then precise control of movement of the platform **46**, and hence the substrate **48**, by the Z-axis translator **30** as well as the head **36** by the X-Y axis translator **26** is required. Upon completion of depositing one layer of the model **47** and support **45**, the Z-axis translator **30** will lower the platform **46** a distance equal to the height of the next layer of material. This controlled movement will ensure that the extrusion tip remains positioned properly with respect to the surface upon which it will deposit material. The distance between the extrusion tip and the substrate **48** must therefore be determined along with any necessary offset to adjust the position of the platform **46** to attain the desired distance between the substrate **48** and the extrusion tip. The difference between the Z-axis position of the extrusion tip and the substrate represents a Z-axis tip-to-substrate offset for that particular extrusion tip.

[**0033**] Modeling system **10** may include multiple extrusion tips as illustrated in FIG. **1**. Typically, modeling system **10** includes only one extrusion position and toggles the multiple extrusion tips between a higher stored, or non-extruding position, and the lower extrusion position as explained in U.S. Pat. No. 5,503,785. As with a single tip, each of the multiple tips also must be positioned an equal distance from the surface upon which they will deposit their respective materials when they are in the extrusion position. However, until properly calibrated, the relative Z-axis positions of the tips may vary when each of the different tips are in the extrusion position. This difference should be accounted for and the position of the platform **46** adjusted to position each of the multiple tips an equal distance from the surface upon which they will deposit their respective material. The difference between the Z-axis position of the tips represents a Z-axis tip-to-tip offset value. The tip-to-tip offset value represents the adjustment necessary to the position or height of the platform **46** in order to position the tips the same distance away from the surface upon which they will deposit material.

[**0034**] The present invention relies upon the ability of the modeling system **10** to create constant height bead layers and to properly position the platform **46** to calibrate the position of the extrusion tips in relation to a reference point, such as the substrate, and any other extrusion tips. FIG. **2** is a flowchart of a tip calibration method **100** according to the present invention. For purposes of example, the calibration method **100** will now be described with reference to a Z-axis tip calibration. However, it should be understood that an X-axis and a Y-axis tip calibration may also be performed by application of calibration method **100**, as will be described in more detail later.

[**0035**] The method **100** begins by generating a material build profile in step **102**. The material build profile may either be generated by the modeling system **10** with the particular extrusion tip that is being calibrated or by placing a prefabricated structure on the platform **46**. In this example, the material build profile is a structure having a defined shape and size created from the material deposited by the extrusion tip. The defined shape and size of the material build profile results in defined lengths, widths, and heights for the structure that is built at a defined and precise location.

[**0036**] Once the material build profile is created, its relative position which may represent a dimension or a specific location is determined in step **104**. The relative position of the material build profile in this example is determined by measuring the height of the structure relative to a reference point, such as the substrate **48**, at specific defined locations.

[**0037**] An expected build profile is identified in step **106**. The expected build profile represents the dimension or

location that should be obtained for the relative position of the material build profile if the tip is properly calibrated. In this example, the expected build profile may be identified by relying on the ability of the modeling system **10** to generate layers of material with a constant height.

[**0038**] The expected build profile for a Z-axis tip-to-substrate calibration may be either provided as an input to or calculated by the controller **24**. For instance, an expected build profile (such as a height) may be inputted to the controller **24** from either the processor **12** or memory **22**. The controller **24** may also calculate the expected build profile by multiplying the constant height value for each layer generated by the modeling system **10** by the number of layers that would be required to create the material build profile according to its defined shape and size.

[**0039**] Alternatively, the expected build profile for a tip-to-tip calibration may be identified by determining the relative position of a second structure. The second structure may be either prefabricated or created by a second deposition device or, in this case, a second extrusion tip. In the case of a tip-to-tip calibration, the expected build profile could be identified by measuring a relative position, such as a height, of the second structure having the same defined shape and size and created according to the same build path as the original material build profile, but at a different defined location. The second structure would also be created by the other extrusion tip that is the subject of the tip-to-tip calibration.

[**0040**] After the expected build profile is identified, then the material build profile is compared to the expected build profile in step **108** to identify any offset that may exist. The offset may be identified as either the difference between or determined from the material build profile and the expected build profile when those values are compared. For instance, if the extrusion tip is too low or close to the substrate **48** when the initial layer is deposited, the extrusion tip will iron the material being deposited such that the height of the material build profile will be less than the constant height value of the layer of material when the modeling system **10** is operating and calibrated properly. The offset represents the adjustment necessary to properly position the extrusion tip that created the material build profile with respect to the substrate **48** carried by the platform **46**. This adjustment of the extrusion tip position taking into account the offset is performed in step **110**. In this instance where the extrusion tip is too low or close to the substrate **48**, the modeling system **10** would lower the platform **46** an amount equal to or derived from the offset to properly position the extrusion tip with respect to the substrate **48**. The modeling system **10** would also record or store the offset value in memory **22** to properly position the extrusion tip on subsequent builds.

[**0041**] FIG. **3** is a side view illustrating the support material extrusion tip **40** depositing, in this example, support material **41** on top of substrate **48**. Support material **41** is shown with a broken line through its center to distinguish the support material **41** from the build material **43** in FIG. **4**. The modeling system **10** deposits support material **41** with support material extrusion tip **40** according to a defined build path to generate the material build profile of step **102** in method **100**. The material build profile illustrated in FIG. **3** is referred to as a pad **49**. The pad **49** is in a geometric shape of a rectangle as shown in FIG. **5**. As shown in FIG. **3**, the support material extrusion tip **40** is depositing a top or final layer **50** of support material **41** to construct the pad **49**.

[**0042**] Upon completing the construction of pad **49**, or the material build profile, the relative position of the pad **49**, or step **104**, is determined in the X, Y, or Z axis to calibrate along that respective axis. In this example, the Z-axis is being calibrated and so the height of the pad **49**, which represents the material build profile, is determined to be a height H**1**.

[**0043**] The height of the expected build profile is identified next in step **106**. The expected build profile is identified as height E in FIG. **3**. In this instance, height E is determined by calculating the product of the constant layer height value that the modeling system **10** deposits material and the number of layers required to build the pad **49**, which in this case is five layers. The constant layer height value of the modeling system **10** equals the theoretical height of each layer according to the slicing program.

[**0044**] As illustrated in FIG. **3**, in this example the height H I is less than the height E by the distance A. This indicates that the support extrusion tip **40** is too low or close to the substrate **48** and as a result, the support material extrusion tip **40** plowed through the support material **41** while creating the pad **49** and lowered or reduced the height of the build layers comprising the pad **49**. The distance A is used to determine or derive the offset necessary to properly position the tip **40** with respect to the substrate **48**, or the Z-axis tip-to-substrate offset for the tip **40**. Once the tip **40** has been properly positioned with respect to the substrate **48** by accounting for the offset corresponding to the distance A, tip **40** has been calibrated with respect to substrate **48**, or the Z-axis tip-to-substrate calibration has been completed. In this embodiment, the calibration routine **100** determines the Z-axis tip-to-substrate offset within a tolerance of about 0.0005 inches.

[**0045**] Upon completing the Z-axis tip-to-substrate calibration, the modeling system **10** is able to build accurate models **47** or supports **45** with the tip **40**. If the modeling system **10** includes only one extrusion tip, then the Z-axis calibration of the extrusion tip is completed. However, if the modeling system **10** includes more than one extrusion tip, then the remaining extrusion tips also require calibration.

[**0046**] When the modeling system **10** includes multiple extrusion tips, it will typically toggle the extrusion tip that will deposit the desired material for that build path into the extrusion position from its stored or non-extruding position. The extrusion position is generally lower than the stored or non-extruding position. This difference in tip position between the extruding position and stored or non-extrusion position is illustrated by comparing the relative positions of tips **38** and **40** in FIGS. **3** and **4**. In FIG. **3**, tip **40** has been toggled by controller **24** into the extrusion position which is lower than the stored or non-extrusion position oftip **38**. Conversely, in FIG. **4**, controller **24** has toggled tip **38** into the extrusion position which is lower than the stored or non-extruding position of the tip **40**. By positioning the tip which is not depositing material in a higher stored position, the modeling system **10** ensures there is adequate clearance to deposit material out of the other tip and avoid the non-depositing tip from contacting or plowing into the deposited material.

[**0047**] In a multiple tip modeling system **10**, the tip that will deposit material first is generally used to perform the

Z-axis tip-to-substrate calibration. This will ensure that the initial layer of deposited material will begin correctly. Typically, the modeling system **10** will deposit a base of support material **41** atop substrate **48** and then build model **47** on top of the base. Creating a base of support material **41** will facilitate separation of the model **47** from the substrate **48** without damage to the model **47**. While each tip in a multiple tip modeling system **10** could be calibrated to the substrate, it is also preferable to calibrate one tip to another with a Z-axis tip-to-tip calibration.

[**0048**] FIG. **4** illustrates the method **100** of the present invention for a Z-axis tip-to-tip calibration. As shown in FIG. **4**, material extrusion tip **38** has been toggled into the extrusion position to deposit build material **43** while support extrusion tip **40** has been toggled to a stored or non-extruding position. Material extrusion tip **38** deposits build material **43** in the defined shape and size at a precise location to generate the material build profile of step **102**. Again, in this example, the modeling system **10** generates a pad **51** similar to the pad **49**, except that pad **51** is constructed with build material **43** rather than support material **41** like the pad **49**. As shown in FIG. **4**, the tip **38** is depositing a last layer or top layer **52** of build material **43** to create pad **51**, or the material build profile for this calibration.

[**0049**] Once the construction of the pad **51** is completed, then the relative position of the pad **51** is determined in step **104**. Again, in this example, the height of pad **51** is determined and is equal to a height H**2** as shown in FIG. **4**. The expected build profile is identified next in step **106**. Since this is a Z-axis tip-to-tip calibration, the expected build profile is identified by determining the relative position of a second structure of similar shape and size generated by the other tip, which in this case is tip **40**. As illustrated in FIG. **5**, the pads **49** and **51** were built with the same defined size and shape according to the same build path other than being created at different locations on the substrate **48**.

[**0050**] In this example, the expected build profile is identified by determining the height, or relative position, of the pad **49**. Here, the height, or relative position, of the pad **49** was already determined in the Z-axis tip-to-tip substrate calibration. The expected build profile for the tip-to-tip calibration is therefore identified as the height H**1**, which has already been determined. As demonstrated in this example, step **106** or the identification of the expected build profile can be determined or calculated at some earlier time other than after step **104** as set forth in the method **100** without departing from the spirit or scope of the invention.

[**0051**] As illustrated in FIG. **4**, the height H**2** of the material build profile when compared to the height H**1** of the expected build profile is greater by a distance B. The distance B represents the relative difference in the position of tip **38** compared to the tip **40** when each are placed into the extrusion position of the modeling system **10**. Given that the height H**2** is greater than the height H**1**, tip **38** is higher or farther away from the surface upon which it will deposit material than tip **40** when each are in the extrusion position. As a result, the distance B represents the offset between tips **38** and **40** or the Z-axis tip-to-tip offset.

[**0052**] The modeling system **10** will then adjust the position of the platform **46** to account for the offset B when the controller **24** toggles between tips **38** and **40**. In this example, the modeling system **10** would move the platform and hence the surface upon which the extrusion tip **38** would deposit material up or closer to the extrusion tip **38** by an amount determined or derived from distance B. The offset determined or derived from the distance B is then stored in memory **22** for later reference and use to create subsequent models. In an embodiment of the invention, the calibration routine **100** determines the Z-axis tip-to-tip offset with a tolerance of about 0.0005 inches.

[**0053**] The calibration routine **100** is ran by the controller **24** automatically, without requiring assistance by the operator. The calibration routine **100** could be programmed to automatically calibrate its extrusion tips during initialization or start up, or upon sensing or determining that an extrusion tip or substrate was replaced either with or without operator input. The calibration routine **100** could also be used to initially calibrate the system, adjust existing offsets to calibrate the system or confirm calibration of the modeling system **10**.

[**0054**] FIG. **5** is a perspective view of a sensor assembly **53** of the present invention, mounted to extrusion head **36** of the modeling system **10**. Sensor assembly **53** is a sensor assembly capable of sensing surfaces to determine the positions of those surfaces and hence to determine the dimensions of the material build profile or expected build profile such as the pads **49** and **51** in steps **104** and **106** of method **100**. It should be understood that the teaching of this invention is not limited for use only with an extrusion-based layered manufacturing system of the type shown and described in FIG. **1**. That is, the invention may also be used in any "additive" or "subtractive" three-dimensional modeling system.

[**0055**] Portions of the modeling system **10** are shown in FIG. **5** to highlight the sensor assembly **53**. Those portions of the modeling system **10** include the extrusion head **36** which is positioned over the substrate **48**, that is supported by the platform **46**. Extrusion head **36** moves in an X-Y plane and platform **46** moves along a Z-axis, as described above with respect to FIG. **1**. Extrusion head **36** terminates in model material extrusion tip **38** and support material extrusion tip **40**.

[**0056**] Sensor assembly **53** includes a plunger **54**, a housing **56**, and an actuator **58**. Sensor assembly **53** is mounted to a backside of the extrusion head **36** by a set of four connectors **66**. The actuator **58**, which is generally in the shape of a bar, is bounded between an upper guide **62** and a lower guide **64** of housing **56**. Actuator **58** slides horizontally from side-to-side between the upper guide **62** and the lower guide **64** in response to an application of a horizontal force. The side-to-side motion of actuator **58** alternately lowers and raises plunger **54**. In its raised position, plunger **54** is located above both model material extrusion tip **38** and support material extrusion tip **40** in the Z-direction. Conversely, in its lowered, sensing position as shown in FIG. **5**, plunger **54** is located below both model material extrusion tip **38** and support material extrusion tip **40** in the Z-direction.

[**0057**] To determine the relative positions, or in this case the height of the pads **51** or **49**, the plunger **54** is lowered into its sensing position and the extrusion head **36** positions itself over the model pad **51**, such that the X,Y coordinates of the plunger **54** are within the X,Y coordinates that define the top surface **52** of the model pad **51**. After plunger **54** is

positioned at a preselected X,Y coordinate above model pad **51**, platform **46** moves along the Z-axis at a steady rate in a direction toward plunger **54** until it pushes the top surface **52** of the model pad **51** into the plunger **54**. At that point, sensor assembly **53** sends a detection signal to controller **24** via a signal line **68**. Controller **24** records the Z-axis position of the platform **46** corresponding to the instant in time at which the signal change was detected. By recording the Z-axis position of the platform **46** at which the signal change is detected, the controller **24** is able to determine the Z-axis position of platform **46** at which point the top surface **52** of the model pad **51** contacted the plunger **54**. This same process may be repeated at other preselected X,Y coordinates lying within the boundary defining the top surface **52** of the model pad **51** in order to obtain a plurality of Z-axis positions that can be averaged to identify a more accurate Z-axis value corresponding to the top surface **52**.

[**0058**] The extrusion head **36** will also position itself over support pad **49** such that the X,Y coordinates of plunger **54** are within the X,Y coordinates that define the top surface **50** of the support pad **49**. Controller **24** will then determine one or more Z-axis positions of the platform **46** corresponding to the points at which the top surface **50** of the support pad **49** contacts the plunger **54** in the same manner as described above with respect to the model pad **51**.

[**0059**] Extrusion head **36** also positions itself over the substrate **48** such that the X,Y coordinates of the plunger **54** are within the X,Y coordinates that define the top surface **60** of the substrate **48**. Then, controller **24** will determine one or more Z-axis positions of the substrate **48** corresponding to the points at which the top surface **60** of the substrate **48** contacts the plunger **54** in the same manner as described above with respect to the model pad **51** and the support pad **49**. Once the Z-axis position of substrate **48** is identified, it can be used as a baseline, reference, or origin from which to determine the height of the pads **49** and **51** by the relative difference in the Z-axis positions of the tops **50** and **52** of the pads **49** and **51**, respectively, and the substrate **48**. However, the Z-axis positions of the substrate **48** are preferably determined prior to building any structures on the substrate **48**. Otherwise, care must be taken regarding the X,Y position used to sense the top surface **60** of the substrate **48** to ensure there is sufficient clearance of any structure for the sensor assembly **53** carried by the extrusion head **36**.

[**0060**] The method used by modeling system **10** to automatically move plunger **54** into its lowered, sensing position is depicted in FIGS. **6**A and **6**B, which represent a close-up view of extrusion head **36** from FIG. **5**. To lower the plunger **54**, the X-Y axis translator **26** moves the extrusion head **36** in the X-plane so as to drive the actuator **58** against a first stationary block **78** located outside of the modeling envelope **44**. In the embodiment shown in FIG. **6**B, the force of the block **78** against the actuator **58** pushes the actuator **58** to its leftward position and lowers the plunger **54** into its sensing position.

[**0061**] The method used to move the plunger **54** into its raised, stored position after the sensor assembly **53** has finished sensing Z-axis positions corresponding to the model pad **51**, the support pad **49**, and the substrate **48** is depicted in FIGS. **7**A and **7**B. To raise the plunger **54**, the X-Y axis translator **26** moves the extrusion head **36** in the X-plane so as to drive the actuator **58** against a second stationary block **82** located outside of the modeling envelope **44** in a direction opposite that of the stationary block **78**. In the embodiment shown in FIG. **7**B, the force of the block **82** against the actuator **58** pushes the actuator **58** to its rightward position, thereby raising the plunger **54** to its stored position.

[**0062**] FIGS. **8**A and **8**B show details of an embodiment of the plunger **54** attached to the sensor assembly **53** as it senses the top surface **52** of the model pad **51**. In FIG. **8**A, the platform **46** has moved in a Z-axis direction toward the sensor assembly **53** such that the model pad **51** and the plunger **54** have just made contact. As shown in FIG. **8**A, a sensor **79** emits-a beam of light **81** across the inside of sensor assembly **53**. The top of plunger **54** is situated a predetermined distance X below the beam of light **81**. In an embodiment of the sensor assembly **53**, the predetermined distance X is about 0.1875 inches.

[**0063**] In FIG. **8**B, platform **46** has moved in the Z-axis direction closer toward the sensor assembly **53**, such that the force of the model pad **51** on the plunger **54** has moved the plunger **54** upward by the predetermined distance X into the beam of light **81**. As a result, there is a change in the signal provided by the sensor **79**, and controller **24** records the Z-axis position of the platform **46** corresponding to the instant in time at which the signal change was detected. Sensor assembly **53** senses the top surface **50** of the support pad **49** and the top surface **60** of the substrate **48** in a similar manner.

[**0064**] As depicted in FIGS. **8**A and **8**B, the plunger **54** terminates in a flat downward-facing tip **83**. Tip **83** should have a contact area large enough that the force of contact of the tip **83** against the substrate **48**, the model pad **51**, or the support pad **49** does not exceed an elastic yield limit of the substrate, modeling material, or support material. As shown in FIGS. **8**A and **8**B, the sensor **79** is an optical sensor. Suitable optical sensors are available from OPTEK Technologies, for example, model OPB380T51. The electrical output signal from sensor **79** changes state when the light beam of sensor **79** is occluded by plunger **54**.

[**0065**] Although the foregoing discussion has been directed toward tip calibration in the Z-direction, tip calibration in the X-direction and Y-direction may also be performed by application of the present invention. For example, sensor assembly **53** may be rotated so that plunger **54** senses in the X-direction and the Y-direction. In that case, sensor assembly **53** is raised and lowered as described with respect to FIGS. **6**A, **6**B, **7**A, and **7**B. However, instead of driving plunger **54** into pad **49** or **51** by moving platform **46**, modeling system **10** would drive plunger **54** into a side of one of the pads **49** or **51**. For example, modeling system **10** would move extrusion head **36** in the X-plane until plunger **54** contacts a side of the pad that is substantially parallel with the Y-axis, thereby pushing plunger **54** into sensor assembly **53** until it moves the predetermined distance X as shown in FIG. **8**B. The same routine applies for sensing a side of the pad that is parallel with the X-axis, although extrusion head **36** will instead move in the Y-plane.

[**0066**] Calibrating extrusion tip offsets in the X and Y directions in addition to the Z-direction is necessary to construct accurate, error-free models. If the precise location of and relation between extrusion tips is not tightly controlled, the tips will extrude beads of material that are misplaced, thereby causing inaccuracies in the model. In

order to control the position of extruded layers of material, the position of the tip extruding the material in relation to the surface upon which the material will be deposited must be controlled and maintained. In particular, controller **24** will direct X-Y axis translator **26** to position tip **38** or **40** at specific X,Y locations above substrate **48** corresponding to a defined build path. Thus, it is important for controller **24** to know the precise position and relation between the tips. Calibrating the tip positions along the X and Y axes ensures that layers of material are extruded in a precise, known position.

[**0067**] Similar to the Z-axis tip calibration described above, the X-Y axis tip calibration may also have two components. The first component of the X-Y axis tip calibration is an X-axis tip-to-origin offset and a Y-axis tip-to-origin offset. The tip-to-origin offsets represent a deviation between an actual tip position and an expected tip position relative to a predetermined origin, which is generally located on the substrate. If an offset exists, the controller **24** will move the relative position of the extrusion tip based upon the offset value to position the tip in relation to the substrate **48** at the location expected by modeling system **10**. Thus, calibrating the tip-to-origin offset ensures that the actual X and Y position of the extrusion tip is consistent with the position expected by modeling system **10**.

[**0068**] The second component of the X-Y axis tip calibration applies only in modeling systems that utilize multiple tips, such as modeling system **10** shown in FIG. **1**. Once again, in a modeling system that includes multiple extrusion tips, it will typically toggle the extrusion tips between an extrusion position and a stored, non-extruding position. As in the Z-direction, modeling systems with multiple extrusion tips also require calibration and a determination of any necessary offset between the tips when each tip is in the extruding position for the X-direction as well as the Y-direction. As a result, the X and Y tip offsets reposition the extrusion tips as necessary to ensure they extrude material at the specific X, Y locations called for by the build path. Calibrating an X-axis tip-to-tip offset and a Y-axis tip-to-tip offset is necessary to extrude layers of material in expected locations and to build accurate, error-free models. The tip-to-tip offset for the X and Y directions can be performed relative to a first tip that is calibrated with a tip-to-origin calibration as was discussed in relation to the Z direction with FIG. **4**. Alternatively, each tip of a multiple tip modeling system could be calibrated individually with a tip-to-origin calibration.

[**0069**] A multi-axis sensor assembly **220** shown in FIG. **9** may be alternatively used instead of the sensor assembly **53** to determine the extrusion tip offsets in the X and Y directions, as well as in the Z-direction. Multi-axis sensor assembly **220** includes a housing **222**, a plunger **224**, and a sensor **225**. Plunger **224** includes an upper end **230** located within housing **222**, and a tip **232** hanging below housing **222**. The sensor **225** includes a plurality of rod members **226** and a plurality of electrical contacts **228**. Rod members **226**, which are coupled to plunger **224**, are positionable between electrical contacts **228** as shown in FIG. **9**. Multi-axis sensor assembly **220** further includes spring **234**, which is coupled on one end to top **236** of housing **222**, and on another end to upper end **230** of plunger **224**. Spring **234** allows plunger **224** to move upward along the Z-axis, and provides a means for returning plunger **224** to its lowered position with rod members **226** in contact with electrical contacts **228**. In addition to sensing surfaces in the Z-direction, multi-axis sensor assembly **220** has the capability of sensing surfaces in the X and Y directions by applying a force to an outer surface of tip **232**. In the preferred embodiment, multi-axis sensor assembly **220** generally consists of three rod members **226** and three pairs of electrical contacts **228**, as shown in FIG. **9**.

[**0070**] When every rod member **226** in the plurality of rod members **226** of the multi-axis sensor assembly **220** is in contact with its respective pair of electrical contacts **228**, an electrical circuit is completed. However, as soon as one or more rod members **226** break their connection with the pair of electrical contacts **228**, a signal is sent over signal lines **238** to controller **24**. For instance, when plunger **224** is pushed against a surface in the Z direction, it moves upward into housing **222**, thereby breaking the connection between rod members **226** and electrical contacts **228**. Similarly, when plunger **224** is pushed against a surface in the X or Y direction, it tilts with respect to housing **222**, thereby causing one or more rod members **226** to break the connection with its respective pair of electrical contacts **228**. The multi-axis sensor assembly **220** may therefore be used to sense not only a top surface of a material pad, but also the sides of the material pad as well.

[**0071**] Multi-axis sensor assembly **220** may be coupled to extrusion head **36** and actuated into position as previously described with regard to sensor assembly **53** illustrated in FIGS. **6**A, **6**B, **7**A, and **7**B. Alternatively, multi-axis sensor assembly **220** may be temporarily attached to extrusion head **36** during the calibration routine, and removed once the calibration is complete.

[**0072**] FIG. **10** illustrates the method **100** of the present invention for an X-axis tip-to-origin calibration. As shown in FIG. **10**, material extrusion tip **38** has deposited build material **43** in a defined shape and size to generate the material build profile of step **102**. In particular, the material build profile is shown as model pad **239**. The pad **239** is positioned to the right of a predetermined X-Y axis origin **233** on substrate **48**. Origin **233** serves as a reference point from which to measure relative positions of pad **239** in order to perform a tip-to-origin calibration.

[**0073**] The calibration routine continues at step **104** where the relative position of pad **239** is determined. In this example, side **240** of pad **239** lies parallel to the Y-axis and its relative position to origin **233** along the X-axis is determined by sensing side **240** of pad **239** with multi-axis sensor assembly **220**. The relative position of side **240** is determined to be a distance J relative to origin **233** along the X-axis. The expected build profile is identified next in step **106**. In an X-axis tip-to-origin calibration, the expected build profile can be provided to or determined by the controller **24** as the expected X-axis position of side **240**. The expected X-axis position of side **240** has been identified in FIG. **10** as a distance K from origin **233**. As illustrated in FIG. **10**, the expected position of side **240** of pad **239** was closer to the origin **233** represented by the distance K than the actual material build profile of side **240** represented by the distance J. In other words, the actual position of the tip **38** along the X-axis is further from the origin **233** than expected by controller **24**. The offset in step **108** of the method is then determined by the difference between the

distances J and K which is identified as distance L in FIG. **10**. The distance L is used to determine or derive the offset necessary to properly position model extrusion tip **38** with respect to origin **233**, or the X-axis tip-to-origin offset for the tip **38**. Once the tip **38** has been properly positioned with respect to the origin **233** instep **110** by accounting for the offset corresponding to the distance L, tip **38** has been calibrated in the X-direction with respect to origin **233**, or the X-axis tip-to-origin calibration has been completed. In this embodiment, the calibration routine **100** determines the X-axis tip-to-origin offset within a tolerance of about 0.001 inches.

[**0074**] This same calibration routine may be applied to calibrate the Y-axis tip-to-origin offset of model extrusion tip **38** relative to origin **233** by comparing an expected Y-axis position of a second side of pad **239** that is perpendicular to side **240** or that lies parallel to the X-axis with an actual position of the second side. Additionally, in a multiple tip system such as modeling system **10**, calibration method **100** may be applied in a similar manner to calibrate the X-axis and Y-axis positions of support extrusion tip **40** relative to origin **233** on substrate **48**. Thus, an X-axis and Y-axis tip-to-origin offset calibration for a modeling system utilizing any number of tips is within the intended scope of this invention. In a multiple tip modeling system, such as modeling system **10**, a tip-to-tip offset for the X-axis and Y-axis may also be performed to properly position additional tips rather than performing a tip-to-origin calibration for each of the additional tips.

[**0075**] FIG. **11** illustrates the method **100** of the present invention for an X-axis tip-to-tip offset. As shown in FIG. **11**, the same pad **239** comprising build material **435** from FIG. **10** remains on substrate **48**. In step **102** of the calibration method **100**, the modeling system **10** generates a pad **241** similar to the pad **239**, except that pad **241** is constructed with support material **41** by extrusion tip **40**, rather than build material **43** by extrusion tip **38**. When directing the building of pad **241**, controller **24** varies the Y-axis position of extrusion head **36** but maintains the same X-axis position to create side **24010** of pad **239** and side **242** of pad **241** along the same X-axis coordinate relative to origin **233** on substrate **48**. The origin **233** again serves as a reference point from which to measure the relative positions of the material pads in order to perform the tip-to-tip calibration.

[**0076**] The calibration routine continues at step **104** where the relative position **15** of pad **241** with respect to the origin **233** is determined. In this example, the side **242** of pad **241** relative to origin **233** is determined by sensing side **242** of pad **241** with multi-axis sensor assembly **220**. As illustrated in FIG. **11**, side **242** is a distance M away from the origin **233** along the X-axis.

[**0077**] The expected build profile is identified next in step **106**. Since this is an **20** X-axis tip-to-tip calibration, the expected build profile is identified by determining the relative position of a second structure preferably created along the same X-axis position as side **242** but generated by the other tip, which in this case is tip **38**. In this example, the pad **239** created by tip **38** and the pad **241** created by the tip **40** were attempted to be built by the controller **24** along the same X-axis position relative to origin **233**. **25** Since the pad **239** has already been created and its relative position determined in the X-axis tip-to-origin calibration, the relative position J of the expected build profile from the origin **233** called for in step **106** has already been identified. Distance J of the pad **239** serves as the expected position in step **106** because the modeling system **10** attempted to build the side **242** of the pad **241** along the same X-axis position as the side **240** of the pad **239**. As illustrated in FIG. **11**, distance M of the material build profile when compared to the distance J of the expected build profile is further away from origin **233** in the X-direction by a distance N. The distance N represents the relative difference in the X-axis position of tip **38** compared to the tip **40** when each are placed into the extrusion position of the modeling system **10**. Given that distance M is greater than distance J, tip **40** is further away from origin **233** than tip **38** in the X-direction when in the extrusion position. As a result, the offset between tips **38** and **40** along the X-axis is determined by or derived from the distance N.

[**0078**] The modeling system **10** will then adjust the position of the extrusion head **36** to account for the X-axis tip-to-tip offset when the controller **24** toggles between tips **38** and **40**. In this example, the modeling system **10** would move the tip **40** closer to origin **233** by an amount determined or derived from the distance N. In an embodiment of the invention, the calibration routine **100** determines the X-axis tip-to-tip offset with a tolerance of about 0.001 inches.

[**0079**] FIG. **11** also illustrates the method **100** of the present invention for a Y-axis tip-to-tip offset. In this example, the modeling system **10** generates a pad **243** similar to the pad **239**, except that pad **243** is constructed by tip **40** with support material **41** rather than tip **38** with build material **43**. The modeling system **10** preferably builds pad **243** by varying the X-axis position of extrusion head **36** but holds the Y-axis position constant in an attempt to create a Y-side **244** of the pad **239** and a side **246** of the pad **243** along the same Y-axis coordinate relative to origin **233**. As shown in FIG. **11**, side **244** of pad **239** is located along or at the same Y-axis position as origin **233**.

[**0080**] Similar to the discussion above with regard to the X-axis tip-to-tip offset, the Y-axis tip-to-tip calibration routine continues at step **104** where the relative position of side **246** of pad **243**, which represents the material build profile, is determined. In this example, the relative position of side **246** of pad **243** relative to origin **233** is determined by sensing the side **246** of pad **243** with the multi-axis sensor assembly **220**. The distance Q represents the relative distance between the side **246** and the origin **233**. The expected build profile is identified next in step **106**. Since this is a Y-axis tip-to-tip calibration, the expected build profile is once again identified by determining the relative position of a second structure preferably attempted to be created along the same Y-axis position as side **246** but generated by the other tip, which in this case is tip **38**.

[**0081**] The specific derivation for the Y-axis tip-to-origin offset of pad **239** and specifically side **244** was not discussed in detail above due to its similarity to the X-axis tip-to-origin offset. For purposes of example, and as indicated in FIG. **11**, side **244** is located along the same Y-axis position as the origin **233**. As a result, the expected build profile relative position called for in step **106** is represented by side **244** that is located along the same Y-axis position as the origin **233**. As illustrated in FIG. **11**, distance Q then also represents the

difference between the material build profile and the expected build profile for the Y-axis and thus the offset for the tip-to-tip calibration along the Y-axis. The distance Q represents the relative difference in the Y-axis position of tip **38** compared to the tip **40** when each are placed into the extrusion position of the modeling system **10**. Given that distance Q is further away from the expected build profile, or the Y-axis position of the origin **233** in this example, tip **40** is further away from origin **233** than tip **38** in the Y-direction when in the extrusion position. As a result, the distance Q represents the Y-axis tip-to-tip offset between tips **38** and **40**.

[**0082**] The modeling system **10** will adjust the position of the extrusion head **36** to account for the Y-axis tip-to-tip offset when the controller **24** toggles between tips **38** and **40**. In this example, the modeling system **10** would move the tip **40** closer to the origin **233** by an amount determined or derived from the distance Q. In an embodiment of the invention, the calibration routine **100** determines the Y-axis tip-to-tip offset with a tolerance of about 0.001 inches.

[**0083**] While the X-Y axis origin **233** was shown near model material pad **239**, origin **233** could have been placed anywhere on substrate **48**, including a starting build path coordinate of one of the pads of material or the edges of the substrate **48** itself without departing from the spirit or scope of this invention. The origin **233** was shown in the upper left corner of substrate **48** in FIG. **11** solely for purposes of example.

[**0084**] Referring now to the process flow diagram of FIG. **12**, there is described a preferred method of sensing a surface (top or side) of an object that can be used in determining the relative position of the material build profile, or identifying the expected build profile by determining the X, Y, and Z-axis locations of the substrate **48** and the pads **49** and **51** as called for in steps **104-106** of the calibration routine **100**. Determining the X, Y, and Z-axis locations of steps **104-106** begins by lowering the plunger **224** (or alternatively, plunger **54**) into its lowered or sensing position in step **202**, as previously described with reference to plunger **54** in FIGS. **6**A and **6**B. The sensor **225** (or sensor **79**) is then positioned in proximity of the target, such as the model pad **51**, at a first pre-selected location to locate a surface of the model pad **51** in step **204**. For a square or rectangular model pad, a preferred location is towards one of the four corners of the surface. Step **204** drives the tip **232** (or tip **83**) of the plunger **224** (or plunger **54**) into the surface of the model pad **51**. Next, in step **206** the output of the sensor **225** (or sensor **79**) is monitored to detect movement of the plunger **224** (or plunger **54**). The controller **24** monitors the signal line **238** (or signal line **68**) for a change in its state or condition. A change in the state or condition of the signal signifies that the plunger **224** has broken the electrical connection between rod members **226** and electrical contacts **228** (or alternatively, that plunger **54** has moved the predetermined distance X into the beam of light **81**). In step **208**, controller **24** electrically records in memory **22** the position corresponding to the time at which the output signal of the signal line **238** (or signal line **68**) changed.

[**0085**] Step **210** repeats steps **202** through **208** at a plurality of additional pre-selected locations for the target. In one embodiment, where the material build profile is pad **51** that has a square or rectangular shape, steps **202** through **208** are repeated in the vicinity of each of the corners of the square or rectangle as well as at the mid-point of the surface of the model page **51**, to obtain a total of five recorded surface positions corresponding to five different coordinates.

[**0086**] To improve accuracy, additional measurements may be taken at the same or different locations on the surface of the model pad **51**. In one embodiment, two measurements are taken at each of the five different coordinates, for a total of ten recorded positions. Upon completing the desired measurements or sensing, the plunger **224** (or plunger **54**) is returned to its stored position in step **212**. While the method of steps **202-212** is described with respect to the pad **51**, the dimensions of the pad **49** or the substrate **48** or any other material build profile or expected build profile could also be determined.

[**0087**] After all of the relative positions are sensed and recorded for the determination of a particular dimension or location, controller **24** calculates an average of all positions corresponding to the sensing of the surface that were recorded during the performance of the method **200** described above. Controller **24** then uses those calculated averages in order to determine the relative position of the material build profile or expected build profile. Controller **24** may use the following algorithm to determine the average position that corresponds to the location that the target is sensed:

[**0088**] (1) Calculate the average position of the target touchdown points (target average) by adding all of the positions recorded in step **208** of FIG. **12** and dividing by the total number of recorded points, in this example there are ten points.

[**0089**] (2) Then, compare each of the recorded positions to the average value. If the recorded position with the maximum error from the calculated average is outside of an acceptable range about the average, then throw away that position and recalculate the average.

[**0090**] (3) If a recorded position was discarded, repeat the compare step with the remaining positions.

[**0091**] (4) Repeat the compare and discard steps until either of the following two conditions occur:

[**0092**] The maximum error of the remaining positions is within the acceptable range; or

[**0093**] The number of positions to be averaged falls below an acceptable level, or in this example below seven points.

[**0094**] The acceptable range about the average value amount that is used to compare the positions is about 0.001 inches for the X, Y, and Z-axis tip-to-tip calibrations, about 0.001 inches for the X-axis and Y-axis tip-to-origin calibrations, and about 0.012 inches for the Z-axis tip-to-substrate calibrations. Depending upon the required accuracy of the modeling system, the acceptable range that is used for comparison may be larger or smaller. Furthermore, the acceptable range may be modified by the operator to adjust the accuracy of the calibration. It will be apparent to those skilled in the art that the above algorithm is but one example of an algorithm that may be used for determining the average position for the target based upon the recorded positions of the target using the method of the present invention.

[0095] In an embodiment of the invention, calibration of the extrusion tips **38** and **40** is achieved by initially sensing the top surface **60** of the substrate **48**. This establishes the baseline for future reference in identifying the relative heights of the material build profile and the expected build profile while performing a Z-axis calibration, which in this case, represent pads **49** and **51**. The layers of material which make up pads **49** and **51** are also preferably created or deposited by their respective extrusion tips **40** and **38** as part of the same build path, or prior to the controller **24** lowering the platform **46** for the next layer of material to be deposited. Once the pads **49** and **51** are created, the controller **24** can determine their respective dimensions by sensing their top and side surfaces with sensor assembly **220** or **53** at specific, defined locations. The controller **24** can then process the information to confirm the proper height and placement of the pads **49** and **51** at the specific defined coordinates and identify any offset required for the extrusion tips **38** and **40** with respect to the substrate **48** as well as the other extrusion tip **40** and **38**, respectively. As a result, the modeling system **10** automatically calibrates its extrusion tips **38** and **40** without requiring measuring or involvement by the operator.

[0096] Although the above discussion has focused on sensor assemblies **53** and **220**, these sensor assemblies represent only two possible embodiments of a sensor assembly that may be used in the calibration method of the present invention. Those skilled in the art will recognize that many other embodiments of a sensor assembly are possible which may be used interchangeably with sensor assemblies **53** or **220**. Particularly, sensor **79** may be interchanged with any sensing means that can detect and signal contact between plunger **54** and another surface, and need not be limited to an optical sensor. In other embodiments, sensor assemblies **53** or **220** may, for example, use a magnet proximity switch, a Hall sensor, a Wiegand wire, a reed switch, a capacitive sensor or an inductance sensor. Likewise, plunger **54** or **224** may be interchanged with any plunging means that can be driven a predetermined distance by force of contact with a surface such as a cam, pawl, cantilever, screw, or membrane, or other mechanical structure. Or, contact between the plunger **54** and the model pad **51**, the support pad **49**, or the substrate **48** can be sensed at their initial contact, in which case the plunging means need not move in response to contact with the various surfaces.

[0097] In addition, numerous other sensor technologies may be interchanged with sensor assemblies **53** and **220** without affecting the accuracy of the calibration including, but not limited to, an atomic force microscope (AFM), a thermal probe, or an air gage. Typically, an AFM monitors the resonant frequency of a vibrating mechanical stylus to sense contact with a surface. Thermal probes generally include a heated thermocouple that is monitored as it is moved toward a surface. When the thermocouple gets close to the surface, the temperature drops due to a lower thermal resistance of the surface as compared to the surrounding air, thereby indicating contact with the surface.

[0098] Air gages typically measure air flow or back pressure through a nozzle to sense the position of a surface and could also be used.

[0099] Although the calibration method I **00** of the present invention has been previously discussed in reference to determining a relative position of a pad of material generated by modeling system **10**, the calibration method **100** may also be used in conjunction with a prefabricated pad. The prefabricated pad or pads of material can be attached to a fixture at precise, known positions. The fixture is then placed on top of platform **46** or substrate **48** in step **102** of the calibration method **100**.

[0100] FIG. **13**A illustrates the method **100** of the present invention using a plurality of prefabricated pads on a fixture placed on top of substrate **48**. As shown in FIG. **13**A, fixture **260** is placed inside modeling envelope **44** on top of substrate **48** such that corner **262** of fixture **260** matches-up with origin **264** of modeling system **10**. Attached to fixture **260** is first calibration standard **266**, second calibration standard **268**, and third calibration standard **270**. The calibration standards are prefabricated pads of material that are precisely positioned at known distances from corner **262** of fixture **260**. Although calibration standards **266**,**268**, and **270** are shown as squares, they may be formed as numerous other shapes, such as rectangles or circles, without departing from the spirit and scope of the present invention.

[0101] As shown in FIG. **13**A, calibration method **100** maybe used to calibrate an X-axis tip-to-origin offset by measuring a known distance R between side **272** of first calibration standard **266** and origin **264**, and comparing the measured value with the known, expected value. The expected value of R is known because side **272** was positioned at a precise X-axis location relative to origin **264**. If the measured and expected values of R are exactly the same, then no X-axis tip-to-origin offset exists. However, if there is a difference between the measured and expected values of distance R, then there exists an X-axis tip-to-origin offset that must be taken into account as previously discussed. This offset is used to determine or derive the offset necessary to correct movement or position of the extrusion head with respect to origin **264**.

[0102] Additional calibration standards such as standards **268** and **270** may also be placed on fixture **260** to calibrate along the desired axis across the entire area of substrate **48**. For example, an X-axis tip offset for calibration standard **268** may be identified by measuring a known distance S between side **274** of second calibration standard **268** and origin **264**, and comparing the measured value with the expected value which is known based on the prefabricated layout and construction of the fixture **260**. If a difference exists, it may be used to determine or derive the offset necessary to correct the movement or position of the extrusion head within modeling envelope **44**.

[0103] As shown in FIG. **13**A, calibration method **100** may be used to calibrate a Y-axis tip-to-origin offset by measuring a known distance T between side **276** of first calibration standard **266** and origin **264**, and comparing the measured value with the known, expected value. Once again, the expected value of T is known because side **276** was positioned at a precise Y-axis location relative to origin **264**. If the measured and expected values of T are exactly the same, then no Y-axis tip-to-origin offset exists. However, if there is a difference between the measured and expected values of distance T, then there exists a Y-axis tip-to-origin offset that should be determined or derived to correct the movement or position of the extrusion head with respect to origin **264**.

[0104] Again, the calibration method **100** may be used to calibrate a Y-axis tip offset at another location within the

modeling envelope **44** or a different location with respect to the substrate **48**. For example, a Y-axis tip offset for calibration standard **270** may be identified by measuring a known distance U between side **278** of third calibration standard **270** and origin **264**, and comparing the measured value with the expected value which is known based on the prefabricated layout and construction of the fixture **260**. If a difference exists, it may be used to determine or derive the offset necessary to correct the movement or position of the extrusion head within modeling envelope **44**.

[**0105**] FIG. **13**B illustrates a Z-axis tip calibration according to the method **100** using first calibration standard **266** and second calibration standard **268**. As shown in FIG. **13**B, fixture **260** is placed inside modeling envelope **44** as described above in reference to FIG. **13**A. In addition to being positioned at precise, known locations on fixture **260**, calibration standards **266** and **268** were prefabricated such that their heights relative to fixture **260** are precisely known.

[**0106**] Calibration method **100** may be used to calibrate a Z-axis tip-to-reference point offset by measuring a known height V between top **280** of first calibration standard **266** and fixture **260**, and comparing the measured value with the known, expected value. In this instance, a top surface of fixture **260** may represent the reference point. The expected value of V is known because first calibration standard **266** was prefabricated with a precise, known height. If the measured and expected values of V are exactly the same, then no Z-axis tip-to-origin offset exists. However, if there is a difference between the measured and expected values of distance V, then there exists a Z-axis tip-to-origin offset that should be taken into account. This offset is used to determine or derive the offset necessary to correct the movement or positioning of the extrusion head with respect to an origin or a reference point, such as substrate **48**.

[**0107**] Again, the calibration method **100** may be used to calibrate a Z-axis tip offset at another location within the modeling envelope **44** at a different location with respect to the substrate **48**. For example, a Z-axis tip offset for calibration standard **268** may be identified by measuring a known height W and comparing the measured value with the expected value, which is known based on the prefabricated layout and construction of the fixture **260**. If a difference exists, it may be used to determine or derive the offset necessary to properly correct the movement of the extrusion tip within modeling envelope **44**.

[**0108**] Those skilled in the art will recognize that deviations from the particular order of steps or the structures of the embodiments shown and described herein may be implemented or used in practice of the present invention. For example, although the above discussion focused on a modeling system that utilizes two extrusion tips, a system that utilizes either more or less than two tips is also within the scope of this invention. Additionally, one skilled in the art would understand that in a modeling system having a dispensing head movable along the Z-axis, the plunger could be driven upward in the method of the present invention by lowering the dispensing head instead of raising the modeling platform. Additionally, the automatic calibration routine of the present invention may be used as part of a three-dimensional modeling system to calibrate a single axis without departing from the spirit and scope of the invention. Thus, although the present invention has been described with reference to preferred embodiments workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

1. A method for performing a calibration routine in a three-dimensional modeling machine that builds-up three-dimensional objects as directed by a controller by depositing modeling material with a deposition device onto a substrate mounted on a platform, the method comprising:

generating a material build profile, wherein the material build profile represents a three-dimensional structure at defined locations;

determining a relative position of the material build profile;

identifying an expected build profile;

comparing the relative position of the material build profile to an expected build profile to determine an offset; and

positioning the deposition device based upon the offset.

2. The method of claim 1, wherein the step of determining the relative position of the material build profile measures a height of the material build profile.

3. The method of claim 1, wherein the step of determining the relative position of the material build profile senses a side surface of the material build profile.

4. The method of claim 1, wherein the step of generating the material build profile places a prefabricated three-dimensional pad onto the substrate of the three-dimensional modeling machine.

5. The method of claim 1, wherein the step of generating the material build profile deposits material by the deposition device of the three-dimensional modeling machine onto the substrate.

6. The method of claim 1, wherein the step of identifying an expected build profile determines a relative position of a second three-dimensional structure created by a second deposition device of the three-dimensional modeling machine.

7. The method of claim 1, wherein the step of identifying an expected build profile determines an expected location of the material build profile in relation to an origin.

8. The method of claim 7, wherein the expected location of the material build profile represents a height of the material build profile above the substrate which is determined by multiplying a predetermined number of layers that are required to generate the material build profile by a desired height of each of the number of layers.

9. The method of claim 7, wherein the expected location of the material build profile represents an expected position of a side surface of the material build profile relative to the origin.

10. The method of claim 1, wherein the expected build profile is provided as an input to the three-dimensional modeling machine.

11. The method of claim 1, wherein the expected build profile is a known value from a prefabricated three-dimensional structure.

12. The method of claim 1, wherein the step of determining the relative position of the material build profile uses a sensor assembly to sense a surface of the material build profile at a specific location.

13. The method of claim 12, wherein the sensor assembly includes an optical sensor.

14. The method of claim 12, wherein the sensor assembly includes a multi-axis electrical sensor.

15. The method of claim 1, wherein the deposition device is an extrusion tip.

16. The method of claim 1, wherein the steps are performed automatically.

17. A method for performing a calibration routine in a machine that builds-up three-dimensional objects under the operation of a controller by depositing modeling material onto a substrate mounted on a platform, the method comprising:

building a first pad on the platform using a first deposition device;

sensing a top surface of the first pad at a first defined X,Y location;

sensing a top surface of the substrate mounted on the platform at a second defined X,Y location;

using a combination of the sensed positions to calculate an actual height of the first pad; and

determining the difference between the actual height of the first pad and an expected height of the first pad to determine an offset.

18. The method of claim 17, and further comprising the step of positioning the platform in relation to the first deposition device based upon the offset.

19. The method of claim 17, wherein the offset has a tolerance of about 0.0005 inches.

20. The method of claim 17, and further comprising:

building a second pad on the platform using a second deposition device;

sensing a top surface of the second pad at a third defined X,Y location; and

determining the difference between the top surfaces corresponding to the sensing of the first pad and the sensing of the second pad to determine a relative offset between the first and second deposition devices.

21. The method of claim 20, wherein the relative offset between the first and second deposition devices has a tolerance of about 0.0005 inches.

22. The method of claim 20, and further comprising the step of positioning the platform in relation to the first deposition device and the second deposition device based upon the relative offset between the first and second deposition devices.

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