

Survey paper

Web-based rapid prototyping and manufacturing systems: A review

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ABSTRACT

Rapid prototyping and manufacturing (RP&M) technique has shown a high potential to reduce the cycle and cost of product development, and has been considered as one of crucial enabling tools in digital manufacturing to effectively aid rapid product development. Manufacturing industry is evolving toward digitalization, network and globalization. The Internet, incorporating computers and multimedia, has provided tremendous potential for remote integration and collaboration in business and manufacturing applications. RP&M technique using the Internet can further enhance the design and manufacturing productivity, speed, and economy, as well as share the RP machines. Web-based RP&M systems have been developed and employed to implement remote service and manufacturing for rapid prototyping, enhance the availability of RP&M facilities and improve the capability of rapid product development for a large number of small and medium sized enterprises. This paper provides a comprehensive review of recent research on Web-based RP&M systems. Various architectures proposed for Web-based RP&M systems are presented. Furthermore, some key issues and enabling tools to implement the remote RP&M systems, which involve (1) RP&M process selection, (2) RP price quotation, (3) STL Viewer, (4) RP data pre-processing, (5) job planning and scheduling, (6) remote control and monitoring for RP machines, (7) security management, (8) applying new technologies and concepts to the systems, are described in detail. Finally, this review gives an outlook on possible future development and research direction for Web-based RP&M systems.

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1. Introduction

Due to the pressure of international competition and market globalization in the 21st century, there continues to be strong

driving forces in industry to compete effectively by reducing time-to-market and cost while assuring high quality product and service. Quick response to business opportunity has been considered as one of the important factors to ensure company competitiveness. Rapid prototyping and manufacturing (RP&M) technique has shown a high potential to reduce the cycle and cost of product development, and has been considered as one of critical

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enabling tools in digital manufacturing to effectively aid rapid product development. RP&M mainly involves rapid prototyping (RP) and rapid tooling (RT). RP is a new forming process which fabricates physical parts layer by layer under computer control directly from 3D CAD models in a very short time. In contrast to traditional machining methods, the majority of rapid prototyping systems tend to fabricate parts based on additive manufacturing process, rather than subtraction or removal of material. Therefore, this type of fabrication is unconstrained by the limitations attributed to conventional machining approaches [1–3]. The application of RP technique as a compelling tool can provide benefits throughout the process of developing new products. Specifically, there are serious benefits that RP can bring in the areas of market research, sales support, promotional material, and the ever-important product launch. Physical RP can also become a powerful communication tool to ensure that everyone involved in the development process fully understands and appreciates the product being developed. Hence, it can help to reduce substantially the inevitable risks in the route from product concept to commercial success, and help shorten time-to-market, improve quality and reduce cost. In general, the application of RP to the product development process has shown a 60% decrease in lead-time over traditional methods [4]. From the emergence of the first RP system in 1988, RP technology has been introduced successfully in the industries of automobiles, aerospace, electronics, toy and so on. The RP methods commercially available include StereoLithography (SL), Selective Laser Sintering (SLS), Fused Deposition Manufacturing (FDM), Laminated Object Manufacturing (LOM), Ballistic Particle Manufacturing (BMP), and Three-Dimensional Printing (3D printing) [1,3,5]. RP is newly evolving toward rapid tooling (RT). RT is a technique that transforms the RP patterns into functional parts, especially metal or plastic parts. It offers a fast and low cost method to produce moulds and functional parts. Furthermore, the integration of both RP and RT in development strategy promotes the implementation of concurrent engineering in companies. Numerous processes have been developed for producing molds from RP systems. The RT methods can generally be divided into direct and indirect tooling categories, and also soft (firm) and hard tooling subgroups. Indirect RT requires some kinds of master patterns, which can be made by conventional methods (e.g. High-speed Machining, HSM), or more commonly by an RP process such as SL or SLS. Direct RT, as the name suggests, involves manufacturing a tool cavity directly on the RP system, hence eliminating the intermediate step of generating a pattern [6]. Soft tooling can be obtained via replication from a positive pattern or master. Soft tooling is associated with low costs; used for low-volume production and uses materials that have low hardness levels such as silicones, epoxies, low melting point alloys, etc. RTV silicone rubber moulds, epoxy moulds, metal spraying moulds, etc., are some of these typical soft molds. Hard tooling is associated with higher volume of production, and the use of materials of greater hardness. Keltool process, Quickcast process, and the ExpressTool process are some of these hard toolings. Electrical discharge machining (EDM) seems to be an interesting area in which rapid tooling finds a potential application. Some methods of making EDM electrodes based on RP technique have developed such as abrading process, copper electroforming and net shape casting, etc. [1,2,4].

Manufacturing industry is evolving toward digitalization, network and globalization. With the fast advance and extensive usage of the Internet technologies, they have been widely employed in developing manufacturing systems to associate various product development activities, such as marketing, design, process planning, production, customer service, etc., distributed at different locations into an integrated environment [7]. It has now been widely accepted that the future of manufacturing organiza-

tions will be information-oriented, knowledge driven and much of their daily operations will be automated around the global information network that connects everyone together [8]. The integration and collaboration among different partners of the product development team can largely improve the product quality, reduce the product development cost and lead-time, and extend the use capability of critical equipments. Therefore, it can better satisfy the requirements of different users, and provide better global competitiveness of products in the marketplace [7]. The Internet, incorporating computers and multimedia, has provided tremendous potential for remote integration and collaboration in business and manufacturing applications. RP&M technique using the Internet can further enhance the design and manufacturing productivity, speed, and economy, as well as share the RP machines. In addition, various RP machines are currently too expensive to be offered by a large number of small and medium size enterprises. Web-based RP&M systems, however, will let these small and medium size companies make prototypes remotely, without owning the expensive RP machines. RP can be made by designer from anywhere in the world [9]. All currently commercial RP processes can be obtained through RP&M providers (service bureaus). However, most service providers generally specialize in one of these processes, although some offer two or more methods. It is necessary to depend on numerous partners to carry out the remaining tasks that this service provider has no such manufacturing capabilities to accomplish in time. For RP service providers, Web-based RP&M systems can closely integrate various RP machines and enable the RP resources are shared on the Web to increase competitiveness. Therefore, integrated RP&M with Web-based manufacturing technologies, the Web-based RP&M system provides a production collaborative environment among users and RP&M providers to implement remote service and manufacturing for rapid prototyping, enhances the availability of RP&M facilities and can improve the capability of rapid product development for small and medium sized enterprises. Since the mid-1990s, the research and development of the Web-based RP&M systems have received much attention [4]. Substantial investments have been made to support the research and practice of Web-based RP&M systems from both the academic community and industrial bodies all over the world. A number of studies from both the academia and industrial bodies have been performed to explore the architecture, key issues and enabling tools for developing Web-based RP&M systems. The objective of this paper is to present a comprehensive review of recent advances in Web-based RP&M systems, and discuss the future research directions. That may provide a reference and direction for the development of Web-based RP&M systems. The rest of this paper is organized as follows. Section 2 presents various architectures of Web-based RP&M systems. Section 3 discusses the key issues and enabling tools in developing the Web-based RP&M systems. Finally, Section 4 summarizes this paper.

2. Various architectures for Web-based RP&M systems

A variety of frameworks for developing Web-based RP&M systems have been proposed. The Tele-Manufacturing Facility (TMF) is probably the first system that provides users with direct access to a rapid prototyping facility over the Internet. TMF allows users to easily submit jobs and have the system automatically maintain a queue. It can automatically check many flaws in STL files, and in many cases, fix them. A LOM machine was first connected with network, and then the STL file of a part to be built could be submitted to this machine by a line command [10–12]. Luo et al. [9,13–17] presented an E-manufacturing application framework of the Web-based RP system which mainly includes five components. (1) Open STL file and display it using Open GL

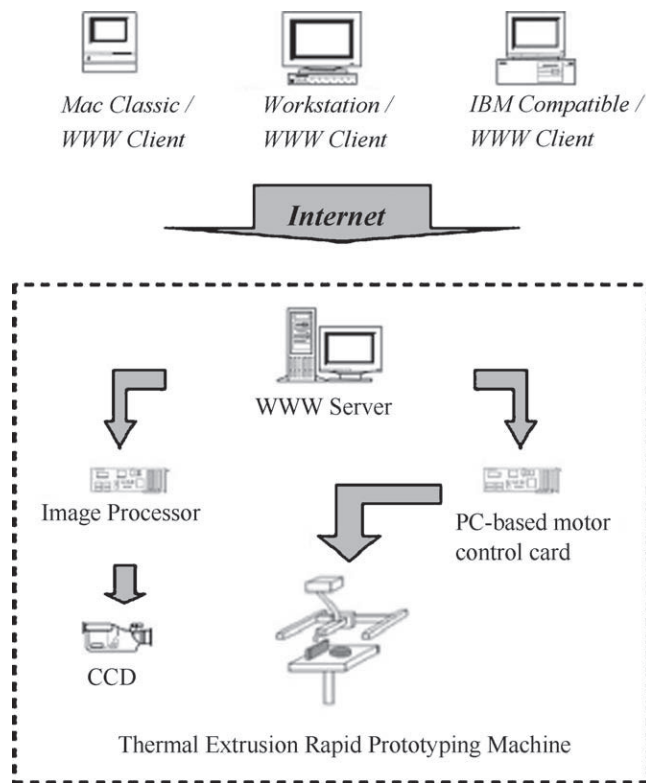


Fig. 1. Overall system architecture of automated tele-manufacturing system [16].

technology, (2) product quotation system, (3) select a suitable RP system, (4) joint alliance system, and (5) order scheduling program. The Open GL technology can be used to show 3D models with different color on different directions. The product quotation system supplies an on-line automated cost estimation related to the option of materials, manufacturing time and RP machines before the RP part being manufactured. This Web-based RP selection system can help users to select an appropriate RP

machine. After evaluating, the system shows the manufacturing time and cost. When customers are satisfied with this estimation, they can transmit STL file via the Internet to the RP Web server. After scheduling, the Web server can transmit the STL file to the RP machine that chosen by the customers. Then the RP part can be fabricated in the chosen RP machine. During manufacturing process, customers also can watch a live image of RP part via Internet, and monitor the RP machine which fabricates physical part through CCD camera. If customers or companies want to joint the alliances, they can joint the system as a member of the association and upload the information of their RP machine to the RP Web server. Fig. 1 shows the framework of the Web-based rapid prototyping system. Jiang and Fukuda [18,19] described a methodology to create an Internet-based infrastructure to service and maintain RP-oriented tele-manufacturing. One of the most important applications of such an infrastructure is to support the closed-loop product development practice. The java-enabled solution based on WWW/Internet computing model is used to implement the infrastructure. The main functions include the remote part submitting, queuing and monitoring. Under the control of different access competences, manufacturing sites and queues can be maintained, respectively, in distributed locations. A software test platform has been developed in Java to verify the methodology. A java-enabling architecture to implement RP-oriented tele-manufacturing is illustrated in Fig. 2. Liu et al. [20] addressed the development of a Web-based tele-manufacturing service system for rapid prototyping. Fig. 3 illustrates the architecture of the tele-manufacturing service system for rapid prototyping. The system providers geographically dispersed enterprises with a platform that permits them to share RP machines. In contrast with other similar systems, the proposed system is comprised of three parts: the on-line commerce, the on-line manufacturing service, and the on-line data management. Three supporting software packages are provided: a software package for self-check and self-repair of STL files, a software package for real-time collaboration, and a software package for remote scout and control. Lan et al. [21,22] developed a tele-service system for RP service bureaus to support the implementation of the Web-based RP manufacturing. The overall framework

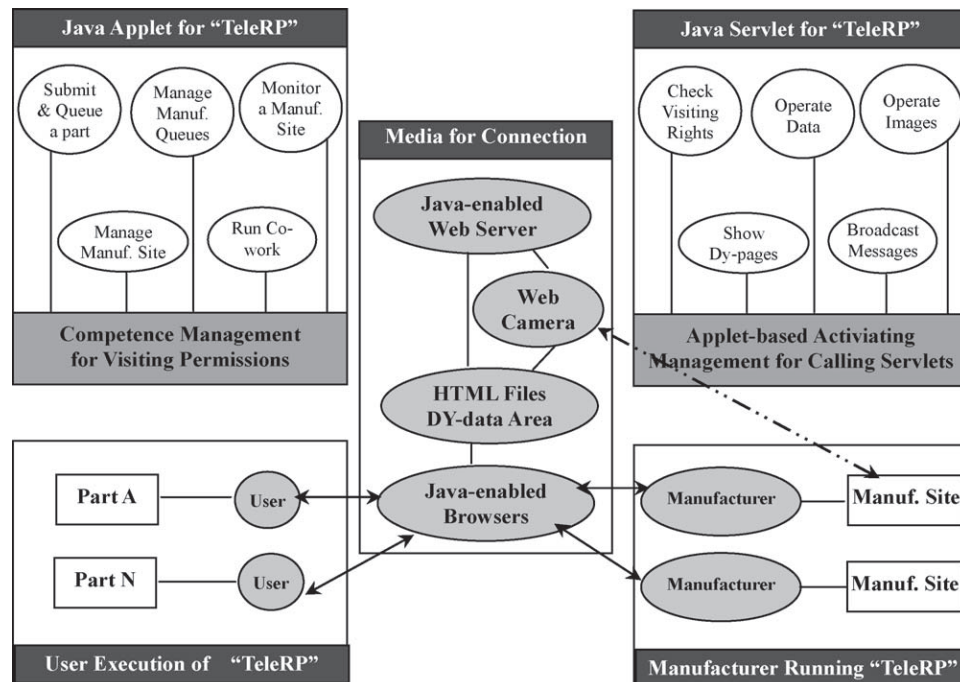


Fig. 2. A Java-enabled architecture to implement RP-oriented tele-manufacturing [18].

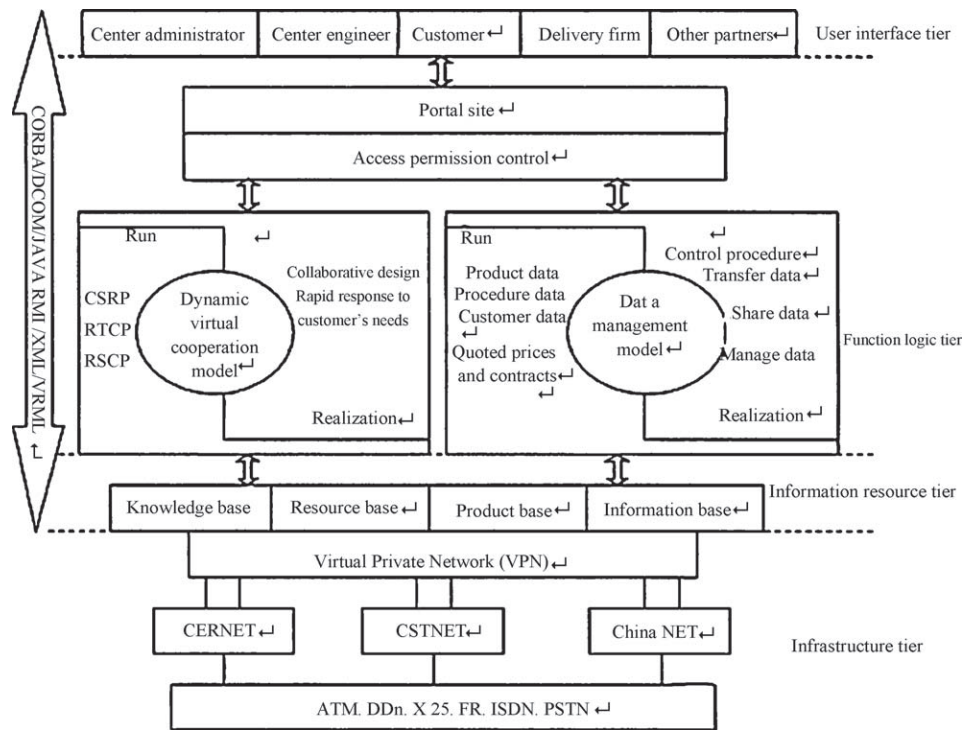


Fig. 3. Architecture of the tele-manufacturing service system for rapid prototyping [20].

for the tele-service system is shown in Fig. 4. The tele-service system consists of two components: software sub-system and hardware sub-system. The hardware involves not only the RP&M facilities of the service bureau itself but also the RP&M equipments from the other service bureaus. The software module includes eight functional components: the information center, ASP (application service providers) tool set, client management, E-commerce, manufacturing service, system navigation and collaborative tools. The crucial issues for developing the system which involve deploying the running platform, determining the system model, choosing a Server-side language, constructing development platform as well as designing the database and application, were also discussed in detail. Finally, a case study is given to demonstrate the use of the tele-service system. This system has been developed and employing in the Northwest Productivity Promotion Center in China. The practical results from the engineering application indicate that both service bureaus and clients can much benefit from the tele-service system. Tay et al. [23] introduced the development of a distributed rapid prototyping system via the Internet to form a framework of Internet prototyping and manufacturing for the support of effective product development. The proposed methodology is targeted at a wide audience using a disparate range of computer systems to access remotely located rapid prototyping facilities via the Internet for prototype fabrication. The methodology is useful for both educational research for teaching evolving rapid prototyping technologies and remote scientific visualization. This approach is based on the merger of object-oriented modular software architecture and client server communications for the remote control of rapid prototyping hardware (called fused deposition modeling) via the Internet. Other Web tools are used to allow the remote user to have higher interactivity with the server applications that have a direct link with the front-end terminals controlling the rapid prototyping hardware. Xu et al. [24] presented an Internet-based virtual rapid prototyping system named VRPS-I which was implemented by using Java and Virtual Reality Modeling Language (VRML). With

the aid of this system, not only the visual rapid prototyping process can be dynamically previewed, but the forming process and some part-quality-related parameters can also be predicted and evaluated. Therefore, the reasonable rapid prototyping parameters can be predetermined according to the simulated results without any physical RP machine. Hence, it can help optimize the prototyping process, improve part-quality, enhance fabrication efficiency, and lower the model making cost significantly. A RP-related tele-manufacturing investigation was also conducted at Stanford University, where both RP hardware [25] and software [26] have been developed. The hardware deals with an integrated mould-SDM machine and the software includes an agent-based infrastructure to implement the Internet-based RP manufacturing service. It has been emphasized to use the concepts of plug-in, broker, local tool integration, etc., under the Java-based agent environment named JAT [18]. Huang et al. [27] developed a rapid prototype-oriented tele-service system based on Internet and Intranet. Network construction of the system and configuration of the corresponding hardware and software were presented. The functional units of the SL-oriented on-line quotation, on-line bargaining and clients' information management were implemented. Huang et al. [28] introduced an Internet/Web-based rapid prototyping oriented tele-manufacturing service center to share a RP manufacturing service over Internet. Under the support of this virtual service center, RP manufacturers can provide and publish their manufacturing service by configuring their RP sites and users can submit the STL files of parts to their desired sites for manufacturing by comparing the requirements of their prototype models to the capabilities of RP sites. A software testbed was developed in Java. Remotely accessible laboratories are becoming increasingly popular across a wide range of disciplines. Fidan and Ghani [29–31] recently developed a remotely accessible laboratory for rapid prototyping. The objective of this project is to develop and disseminate a Remotely Accessible Rapid Prototyping (RRP) Laboratory at Tennessee Technological University (TTU). This laboratory facility is physically located on the TTU Campus, but

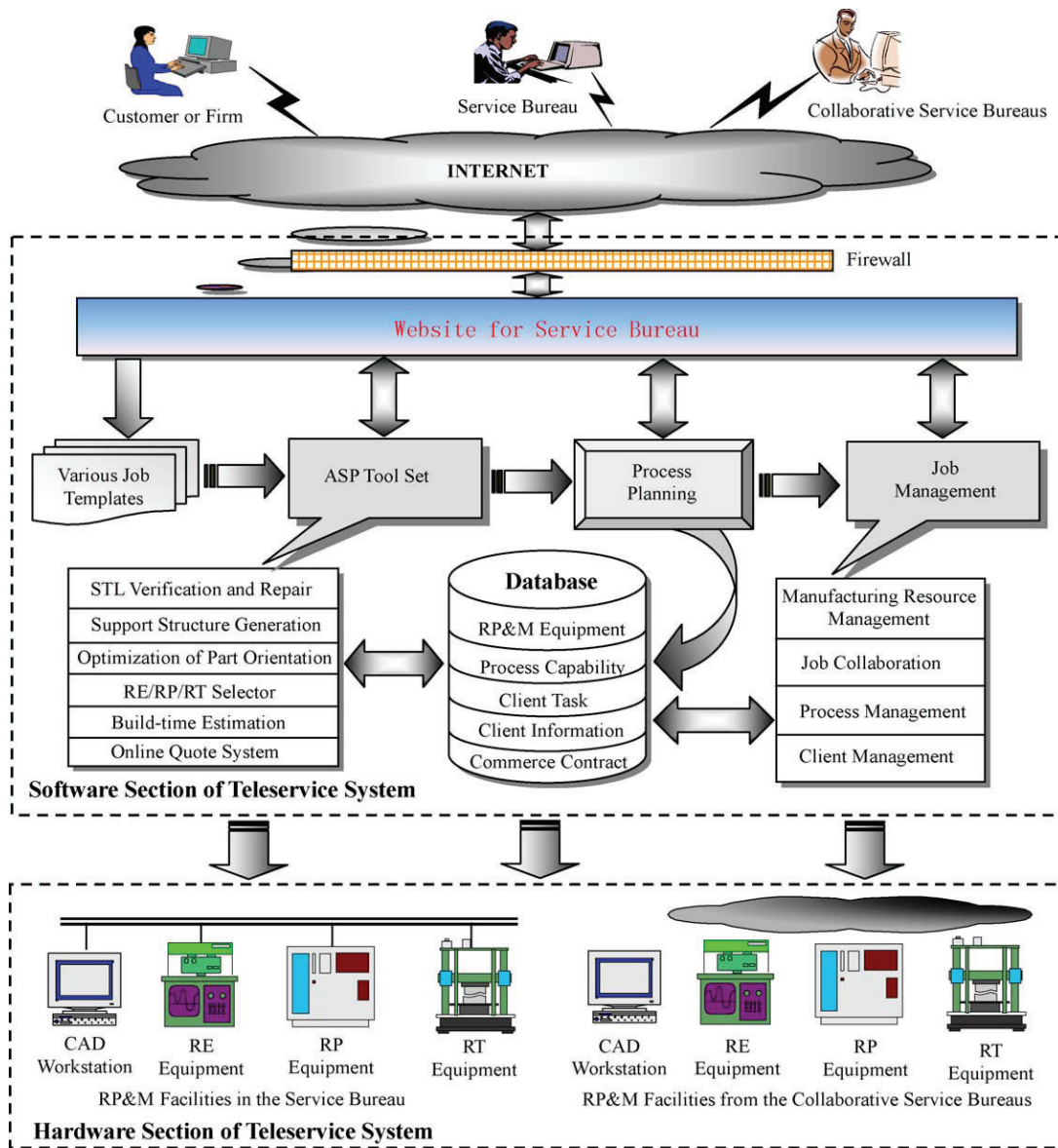


Fig. 4. Architecture of the Web-based RP&M system.

Internet-based controls, interactive tutorials and scheduling allow this equipment to be used across TTU, Tennessee Board of Regent (TBR) technology centers and community colleges across the state of Tennessee and eventually nationwide. In particular, adding a remote access capability allows many more users to benefit from state-of-the-art RP technology, thereby better justifying the cost of purchasing and maintaining the overall facility. Furthermore, the successful development of a remote RP lab provides new insights into the strengths and weaknesses of the remote access environments, and therefore provides vital insights for both the design/manufacturing technology and distance education communities alike. The overall architecture of the Remotely Accessible Rapid Prototyping Laboratory is illustrated in Fig. 5.

Based on above presentations, various architectures of Web-based RP&M systems have been proposed. Most systems mainly focus on functional implementation. For the architecture design of the Web-based systems, designers must simultaneously consider the implementing methods, whether Server-side or Client-side? Client-side scripting means all calculations are done by the computer of the visitor. Most of the time the script is interpreted by

their Internet browser (Javascript) or a specific browser plug-in (Flash action script or Active X control). Server-side scripting means all calculations are done by the Server your website is hosted on. The script is interpreted by the supported language parser, like JSP, PHP or ASP. Many factors like security issues have led to restrictions in both Server-side and Client-side possibilities. Both types have advantages and disadvantages, but the better solution is to attempt to combine both. According to the actual requirements of the Web-based RP&M systems and different functional modules, the suitable modes are determined.

In addition, in contrast to the Web-based RP&M systems, Web-based manufacturing systems have been profoundly and systematically investigated. During the architecture design for the Web-based RP&M systems, it is a good solution for designers to refer the previous research results from Web-based manufacturing systems [7,32–35]. The combination of Web services and software agents provides a promising computing paradigm for efficient service selection and integration of inter-organizational business processes. It is a good scheme for Web-based RP&M systems to establish an agent-based service-oriented open architecture to

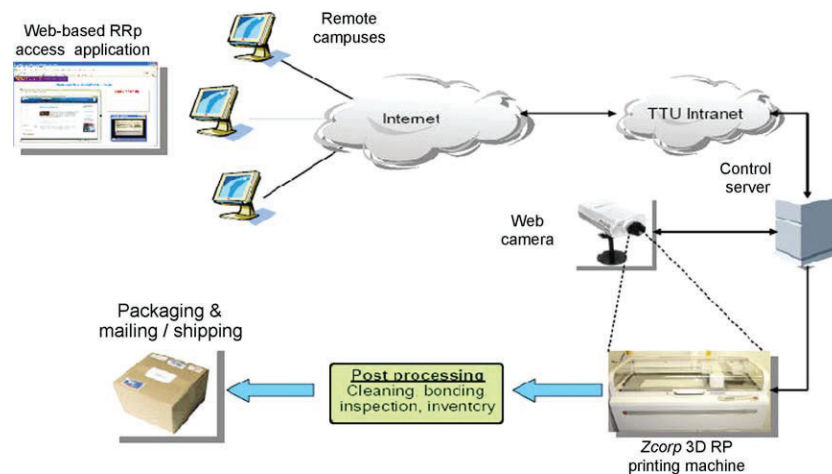


Fig. 5. Overall architecture of the Remotely Accessible Rapid Prototyping Laboratory [31].

better implementing collaborative and intelligent manufacturing for Web-based RP&M systems.

3. Key issues in developing Web-based RP&M systems

In the development of various types of Web-based RP&M systems, a number of key issues have been discussed. Based on the current research results for Web-based RP&M systems, these key issues can be divided into the following eight categories: (1) RP&M process selection, (2) RP price quotation, (3) .STL Viewer, (4) RP data pre-processing, (5) job planning and scheduling, (6) remote control and monitoring for RP machines, (7) security management, and (8) applying new technologies and concepts to the systems. Details of these key issues are described in the following subsections.

3.1. RP&M process selection

There are a variety of different processes for the RP&M technique, each of them has its characteristics and the suitable scope of application. It is especially difficult for many novices to select the most suitable process according to the individual task requirements and actual conditions. A number of studies have been carried out into the development of methodologies, decision support techniques and software tools for assisting RP users in selecting the most suitable RP&M process.

Early attempts in selecting a conformable RP system based on benchmarking studies that compared different RP systems. Some benchmarking studies have been carried out in an attempt to determine working accuracy and strength of the systems that can then be used by industry to determine process suitability for their application. A variety of measurement methodologies have also been presented in papers previously published on the subject of the benchmarking of RP systems [36–38]. This approach may be time consuming and quite expensive. Hornberger [39] developed the Rapid Prototyping Program at Santa Clara University in 1993, which was perhaps the first attempt to develop a computer-based program in assisting the selection of a proper RP system. The program basically serves as an educational tool to provide general information on RP processes. There have been attempts at developing RP selection system which are based on relational database. Campbell and Bernie [40] established a database of the RP system capabilities to help RP users make the most effective use of RP. The system is based on the hypothesis that “once the capability of an RP system has been determined for individual features it’s capability for any component containing

these features can be predicted”. Muller et al. [41] developed a “RP system selector” which is a software tool based on the relational database management system MS Access. It can help RP users to select a better combination of material and machine to produce a physical prototype. The method of “Benefit Value Analysis” is used to evaluate various combinations of machine and material against the user’s requirements. The RP advisor system developed at Arizona State University by Phillipson [42], which uses Quality Function Deployment to identify those requirements that are the most important and relevant to the model (i.e. speed, cost and quality). Various mathematical relations based on multi-criteria optimization are then employed to find the most suitable prototyping process for the model in question. This program also uses MS Access, and includes six RP systems available from 3D Systems, Stratasys, Helisys, DTM, Schroff, and Sanders Prototype. Rao and Padmanabhan [43] presented a methodology for selection of a rapid prototyping process that best suits the end use of a given product or part using graph theory and matrix approach. A ‘rapid prototyping process selection index’ was proposed to evaluate and rank the RP processes for producing a given product or part. The index is obtained from a RP process selection attributes function, obtained from the RP process selection attributes digraph. The digraph is developed considering RP process selection attributes and their relative importance for the considered application.

More recent studies have been concentrated on developing the knowledge-based expert systems for RP process selection. Bibb et al. [44] introduced a RP design advice system that can recommend the most appropriate route to creating a physical prototype. Masood and Soo [45] presented a rule based expert system for the selection of RP system from all the commercial RP systems manufactured in the USA, Japan, Germany, and Israel. Bernard and Deglin [46] described a knowledge-based system for the choice of RP process which combines the case based reasoning and examining of the compatible inputs–outputs of the primary secondary, and tertiary steps in a process chain in order to arrive at a solution. Byun and Lee [47] described the selection of an optimal RP system that best suits the end use of a part by using multiple-attribute decision making and the test part designed with conjoint analysis to reflect users’ preference. Evaluation factors include only the major attributes that significantly affect the performance of an RP system such as accuracy, roughness, strength, elongation, part cost and build time. Crisp values such as accuracy and surface roughness are obtained with a new test part developed in this study. The part cost and build time are identified as falling within approximate ranges due to varying costs and many variable

parameters. They are presented as linguistic values that can be described with triangular fuzzy numbers. Based on the evaluation values obtained, an appropriate RP process for a specific part application can be selected using a modified technique of order preference by a similarity to ideal solution (TOPIS) method given crisp data and linguistic variables as the alternatives of attributes.

A Web-based RP system selector has been developed by the Helsinki University of Technology [48]. Through answering a series of questions, the selector acquires information about the part accuracy, layer thickness, geometric features, material, and application requirements. The user chooses one of 4–5 options for each question. Additionally, the user specifies preferences for each requirement using a five-element scale from insignificant to average to important. When all 10–12 questions are answered, the user will receive a “Results” page which lists three best systems to satisfy his/her requirements. This program is not perfect, not even close, but a friendly pointer to the right direction [49]. A RP Selector has been developed by IVF Industrial Research and Development Corporation mainly for designers, purchasers and others who from time to time need to acquire RP/FFF models for various applications and want fast, un-biased advice. The intention is not to give “the correct answer” to a question which most often does not have only one correct answer. Rather the Selector aims at guiding and educating the user, and at serving as a number of important functions. The RP Selector handles both plastic and metallic parts and covers all the way from making parts for an early design study to the production of small series. The program deals with many methods and process chains that are based on FFF and includes both rapid tooling, when FFF methods are used for manufacturing of tools, and Rapid Manufacturing, direct applications for the completed FFF part. A number of Swedish user companies as well as service bureaux were involved in the development and they have strongly influenced the design and verified the contents. The approach of guiding and informing instead of giving a fixed solution was decided upon as the best way to compensate for the fact that the fast FFF development will always make a system of this kind lagging somewhat behind as regards the influence of new product releases [50,51].

From the above analysis and literature review, it can be found that the RP process selection should be considered as a multi-alternative and multi-criteria fuzzy decision making problem. Most of existing systems are incomplete prototypes that have considered only a limited number of RP alternatives and criteria.

Another limitation of these systems is the failure to take into account the inherent vagueness and uncertainty on the descriptions and judgments of RP processes. Some of the decision criteria are subjective and qualitative, it is difficult for a decision maker to express the strength of his/her preferences and to provide exact judgment. Few research works are based on the mathematical model or the integrated method of quantitative and qualitative analysis to determine the most suitable RP process. Lan et al. [52] proposed a method integrating the expert system and fuzzy synthetic evaluation to select the most appropriate RP process according to user's specific requirements. Based on the proposed approach, a Web-based decision support system for RP process selection was developed. The system provides a platform mounted on the server. RP users or customers can access the system via Internet/Intranet to make a suitable decision making according to their specific requirements. The system is composed of four modules: (1) a database to store RP processes with their specifications; (2) a knowledge-based expert system for selecting the feasible alternatives; (3) a FSE model to choose the most suitable RP process; and (4) a user interface and an expert interface to interact with the system. Four modules work together to complete the decision making task. The overall architecture of this system is shown in Fig. 6. The first tier represents the visual aspect of the program, where the user keys in some required information by filling in a form (user interface). The middle tier is the web server and related logical functions. The third tier is associated with a database and a knowledge base (MS Access database used here). Using such a three-tier B/S structure, we are able to work with the same visual representation, independent of the remote database. Moreover, the B/S architecture allows developing professionals to focus on development and maintenance tasks on the Server-side in spite of the increasing number of distributed customers. The user interface of the system is illustrated in Fig. 7. The system has been run at a RP&M networked service platform that authors have been developing.

Chung et al. [53] discussed a methodology for the selection of rapid tooling (RT) processes based on a number of user-specified attributes and relative cost and lead-time comparisons across a wide spectrum of available RT processes. The method is based on a combination of weighted functional and on the approximate mathematical models of metal casting process costs and their lead-time. The method has been put on the Internet for easy access. It is currently limited to only several of the most common RT processes

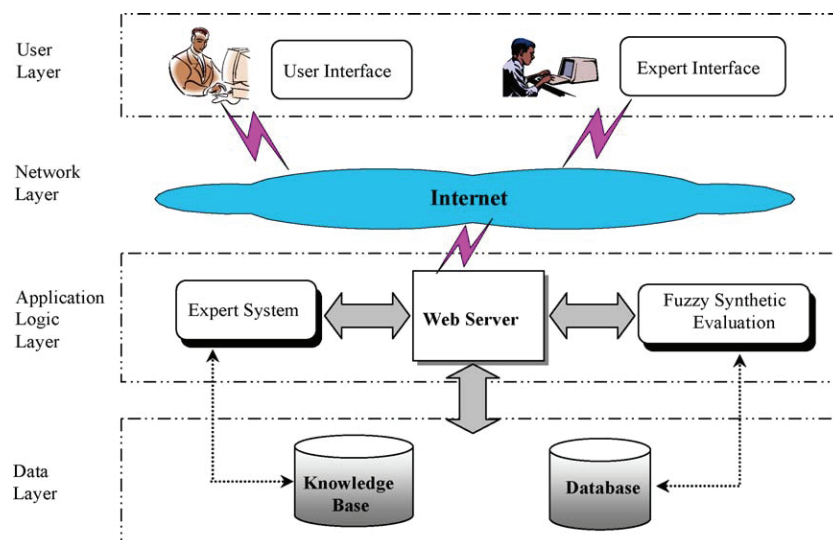


Fig. 6. Architecture of a Web-based RP process decision making system.

Fig. 7. User interface of a Web-based RP process system.

and materials. However, the database should be further expanded to include a majority if not all of the metal casting processes.

As one of the most important modules for Web-based RP&M systems, RP&M process selection has been profoundly studied. However, most investigations focus on RP selection, few research works involve RT processes selection, particularly RP&M process chain (RP, RT and functional parts) selection and decision making.

3.2. RP price quotation

In today's competitive market, quick and accurate price quotation for RP part plays an important role in the RP service process, is also a fundamental premise to win an order, gain a potential client and keep company competitiveness. The current major practice in the RP industry for quoting prices for building a RP part is either by experience or by comparison with a similar product. Web-based price quotation approach can provide instant price quotation for remote customer, quickly obtain the feedback from customer, and show a number of advantages: easy to use and update, simple operation, high interactivity with customer, user-friendly interface. In order to satisfy the current quotation needs of RP service bureaus and providers, several Web-based automated quotation systems have been developed. The "Quickparts.com" (and its software "QuickQuote") and "3T RPD" are now mainly commercial on-line price quotation system for RP parts. Quickparts.com, which is a privately held manufacturing services company dedicated to providing customers with an on-line E-commerce system to procure low-volume and high-volume custom manufactured parts, has developed a QuickQuote system. The QuickQuote is a proprietary geometric analysis and instant quoting engine behind Quickparts. With Quickparts' patent-pending QuickQuote technology, users simply upload their 3D CAD data (STL files), define their project specifications, and a

custom, binding quote is presented instantly. The new version instant quoting software, MyQuote 3.0 does not require the upload of CAD files. Geometry analysis is performed right on a desktop within the MyQuote software. To get an Instant Quote, users select a process, select CAD files for quote, select material, finish, and quantity, and then click on "Create Quote". The unique, binding quote is instantly calculated and presented to users. The system would be provided an instant price quote for SL, SLS, FDM, and Cast Urethanes/RTV Molding. Users can also compare these processes based on materials available, applications, and lead-time. The principle of quotation for QuickQuote is based on the geometry analysis of model (model and define Specs) [53]. 3T RPD developed an automatic quoting system that can be accessed around the clock. Working from key data precludes the need to upload sensitive information to a central server. The system can respond instantly with prices, as well as E-mailing out an official quotation. The quotation principle of 3T RPD is also based on the data model and product details (e.g. product quantity, material, finishing/coloring, desired delivery date, etc.). The system seems to upload several data models. The best way to send the data is recommended by E-mail [54]. Unfortunately, maybe due to the reason of commercial know-how (or secret), both of them do not describe and report the implementation mechanism of quotation, application effect and development details. Two quoting approaches which include the rough quotation based on weight and precise quotation based on build time were proposed to determine the price quotation for SL parts by using STL modes of parts built [55]. Based on the proposed methods, Lan et al. [56] developed a Web-based automated quotation system which can provide instant price quotations for SL parts to support effectively the Web-based RP&M systems. The system can provide the two quotation methods mentioned above and two use modes (Server-side and Client-side) according to the requirements from different users. For usage modes, users can upload their STL file or download and install the application of Active X control with functions for using the STL file, calculating volume and surface area, estimating build time on the desktop, by which users can get an instant price quotation. The functional model of the on-line quotation system for SL parts is shown in Fig. 8. The Web-based automated quotation system can satisfy the engineering requirements of price quotation at the early stage of product development, and offers a new option for RP customers to allow them to instantly quote and compare multiple rapid prototyping processes. The further service will be extended to allow customers to convert quotations into orders, which are subsequently processed by RP service bureaus and providers. Luo et al. [14] proposed an equation to estimate RP product cost, and developed a RP product quotation system to evaluate the cost of the 3D CAD models base on the proposed equation. The quotation system was implemented by using Visual Basic 6.0 with COM Object to code interface engine. Customers can open the STL file from Client-side homepage program, and carry out the action of the product quotation.

Web-based RP&M quotation systems have been considered as the most useful enabling tool for a number of RP&M service providers, many service bureaus have successfully developed the remote RP&M quotation modules and applied to the Web-based RP&M systems or service website. Future research should further improve the accuracy of the RP quotation, predigest the operation, and expand Web-based RT and functional parts quotation systems.

3.3. STL Viewer

Rosen [57] developed a collaborative design tool, called "STLViewer," which allows remote users to view STL model over the Internet. This software operated through a Java Applet in the user's Web browser reads the STL (StereoLithography) file format

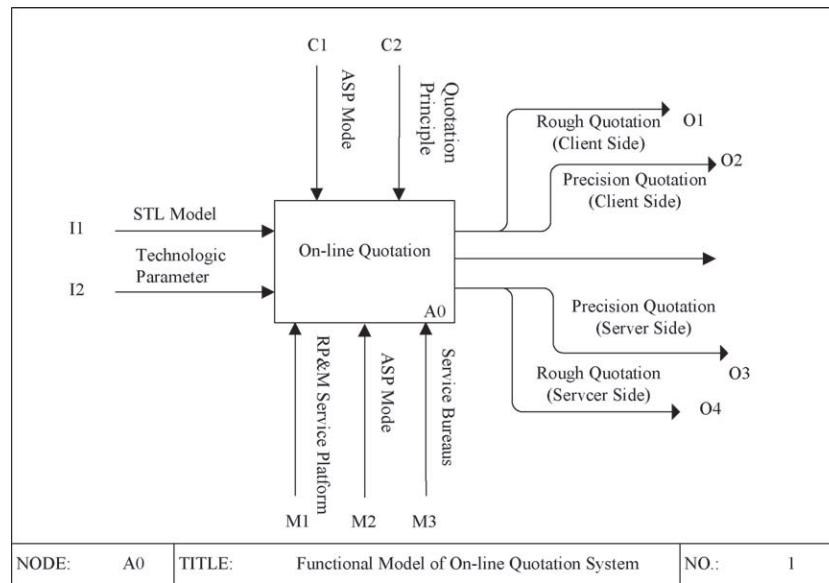


Fig. 8. Functional model of a Web-based RP quotation system.

(the *de facto* file format for rapid prototyping) and displays the model for the remote user to inspect. The user is able to rotate, pan, and zoom the model. Utilities are also provided for verification of the validity of the model. STL Viewer has a wide variety of potential applications. On-line 3D catalogs, infusion into an on-line ordering process for a SLA laboratory, and sharing of design concepts over the Internet are all potential uses for this software. STL Viewer provides a crucial enabling tool (a collaborative visualization tool) to effectively aid the Web-based RP manufacturing systems. Fig. 9 shows the complex shapes visualized by STL Viewer. Further investigations would be to thoroughly check STL file, correct the STL File, and increase inherent robustness.

Apart from the STL Viewer, other Web-based collaborative visualization tools in distributed product development have also been applied to the Web-based RP&M systems, e.g., Auto View for Java, 3D Visualization and Collaboration, etc. [58–60].

3.4. RP data pre-processing

Because the various data pre-processing of RP process in different RP vendors are incompatible now, Lan et al. [61] described an ASP tool set for RP data pre-processing based on STL model to aid effectively the networked service for RP&M. The architecture and functional model of ASP tool set were established. The checking and fixing system for STL models, as a typical example, was systematically studied and developed, and used to demonstrate the detailed

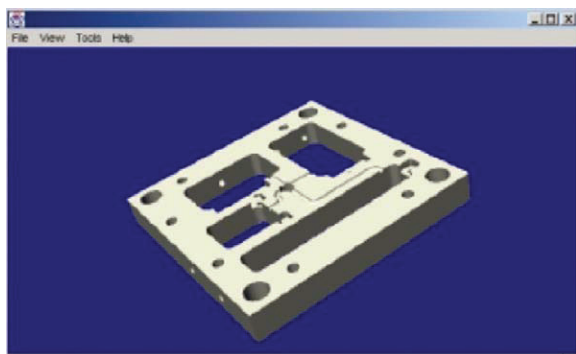


Fig. 9. Complex shapes visualized by STL Viewer [57].

development process of the ASP tool set. In order to meet the demands for the distributed application, a new algorithm was discussed. The J2EE architecture was employed to carry out the ASP tool kits based on the three-tier Browser/Server mode. The ASP tool set has been integrated the networked service system of RP&M that the authors have developed. Various parts with different complex geometries have been chosen to verify these ASP tool kits, and the actual results show that the ASP tool set provides an effective tool to aid the implementation of RP&M networked service. Liu et al. [20] developed a software package for self-check and self-repair of STL files. Roy and Cargian [62] described the implementation of an object slicing algorithm that runs through the World Wide Web (WWW). The WWW allows this software to connect to other CPD products to be utilized after design for tele-manufacturing. In addition, they also addressed enhancements to the current slicing algorithms. This work was completed with tools such as HTML and Java. In the intelligent Web-based rapid prototyping manufacturing system [14], Luo et al. presented a new adaptive slicing algorithm for RP system. According to the algorithm, the 3D CAD model can be sliced with different thickness automatically by comparing contour circumference or the center of gravity of the contour with those of the adjacent layer. In addition, Zhang et al. [63] addressed Web-based study on rapid prototyping data intelligent processing techniques. They proposed some algorithms for correcting common errors, and optimized the algorithm of gaps or holes errors leading to open loops in the data structure based on analyses of the rules and errors in the STL file. Furthermore, effectiveness of the approach is demonstrated by a simple model view example of STL files based on Java 3D technology.

Currently, studies on RP data pre-processing based on Web are very lack compared with other key units. It is necessary for designers to further explore the issue based on ASP.

3.5. Job planning and scheduling

Today's commercial RP systems rely on human intervention to load and unload build jobs. Hence, jobs are processed subject to both the machine's and the operator's schedules. In particular, first-in-first-out (FIFO) queuing of such systems will result in machine idle time whenever a build job has been completed and an operator is not available to unload that build job and start up the next one. These machine idle times can significantly affect the

system throughput, and, hence, the effective cost rate. Wu [64] addressed this problem by rearranging the job queue to minimizing the machine idle time, subject to the machine's and operator's schedules. This is achieved by employing a general branch-and-bound search method, that, for efficiency, reduces the search space by identifying contiguous sequences and avoiding reshuffling of those sequences during the branching procedure. Lin et al. [65] proposed a real-time scheduling approach to maximize the system utilization and minimize the average response time for scheduling non-preemptive aperiodic tasks so that it is suitable for the distributed Web-based RP systems. The idea is to incorporate Shortest-Job-First (SJF) into Earliest-Deadline-First (EDF) scheduling algorithm. The result of the proposed scheduling algorithm is very close to the optimal solution and the scheduling overhead can be neglected. Using the approach, new requests can be accepted dynamically and all accepted requests can be finished before deadlines. The Web-based RP platform is able to fully utilize Web resources for RP manufacturing and the quality of service is significantly improved. A distributed RP platform scheduler proposed by authors is shown in Fig. 10. Jiang and Fukuda [18,19] addressed the selection of a feasible RP manufacturing site and submitting and queuing a part for remote RP manufacturing. Selection a valid and feasible RP manufacturing site registered in the RP tele-manufacturing web server depends on mainly on two factors, i.e., site manufacturing capability and delivery time constraints concerning all the queues inside the site. Here, the delivery time constraints deal with the total manufacturing time of all submitted parts in each queue. They presented the build time estimation of a RP part. Furthermore, together with the browsing manufacturing capability, remote users can select a suitable RP through calculating possible delivery time. After determining the RP manufacturing site, a part in .STL file format can be uploaded to the dynamic data area of the web server, and then be put into the corresponding queue by using the Applet–Servlet pair. Tzou [13] presented a framework of order scheduling system, as shown in Fig. 11. In TMF [10] queuing a part depended only on the time when the part arrived in the queue.

Networked manufacturing enterprises need a wider support from external manufacturing resources. A challenging issue on networked manufacturing resource services is how to discover these socialized manufacturing resources and provide the effective resource support services. Optimizing external manufacturing resources, integration and interoperability in a collaborative

environment play crucial roles for Web-based manufacturing modes. However, current studies for Web-based RP&M systems seldom involve the points. Future research must be reinforced them. Researches should explore the suitable approach and mechanism based on the specific requirements of the Web-based RP&M systems.

3.6. Remote control and monitoring for RP machines

Tele-control or WWW-based remote control of RP machine can make the client user to share the benefit of the remote RP machine. Luo et al. [9,17] profoundly discussed a tele-control and remote monitoring system for the RP machine. It allows user to directly control a RP machine via the Internet. Also the remote user can receive real-time images, e.g. the completed RP model parts captured by a CCD camera that is mounted on a RP machine. The remote control system has proven itself as a feasible and useful tool to share RP machines with others via Internet. The different RP systems may not communicate to each other easily because they are built on different operation systems, using different communication protocols, common object request broker architecture (CORBA) has been proposed to integrated heterogeneous environments such that these different RP systems can be easily integrated regardless of what language they are written in or where these applications reside with any commercial CORBA solutions [13,15]. Instead of using a CCD camera, Wang et al. [66] addressed a Java 3D-based remote monitoring system for a FDM machine. A project was introduced to solve the problem of the model motion simulation based on the sensor signal data which was transformed from the application server so as to meet the requirements of remote real-time monitoring. Gao et al. [67] described the development of a tele-control system for rapid prototyping machine based on Internet. Among different remote control methods, Winsock was adopted to implement of tele-controlling a RP machine. Kang et al. [68] investigated a remote monitoring and diagnosis of breaking-down fault for a FDM rapid prototyping machine. To solve the problem of remote diagnosing faults for high-automatic long-period minute machines in their running period, the VPON remote monitoring system and image processing technology were used to carry out the remote diagnosis of a FDM rapid prototyping machine breaking-down fault.

Web-based remote control and monitoring techniques (networked control and monitoring) have been studied for many years,

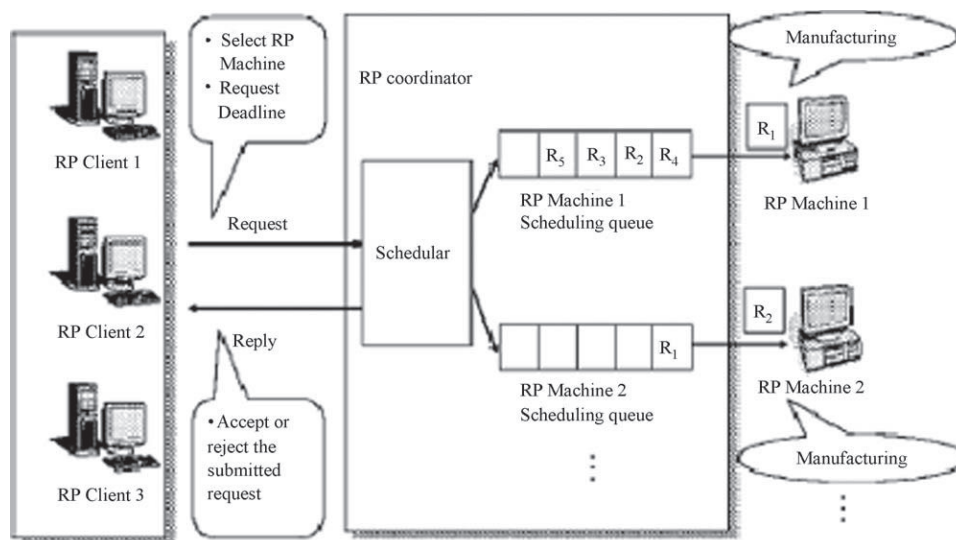


Fig. 10. Distributed RP platform scheduler [65].

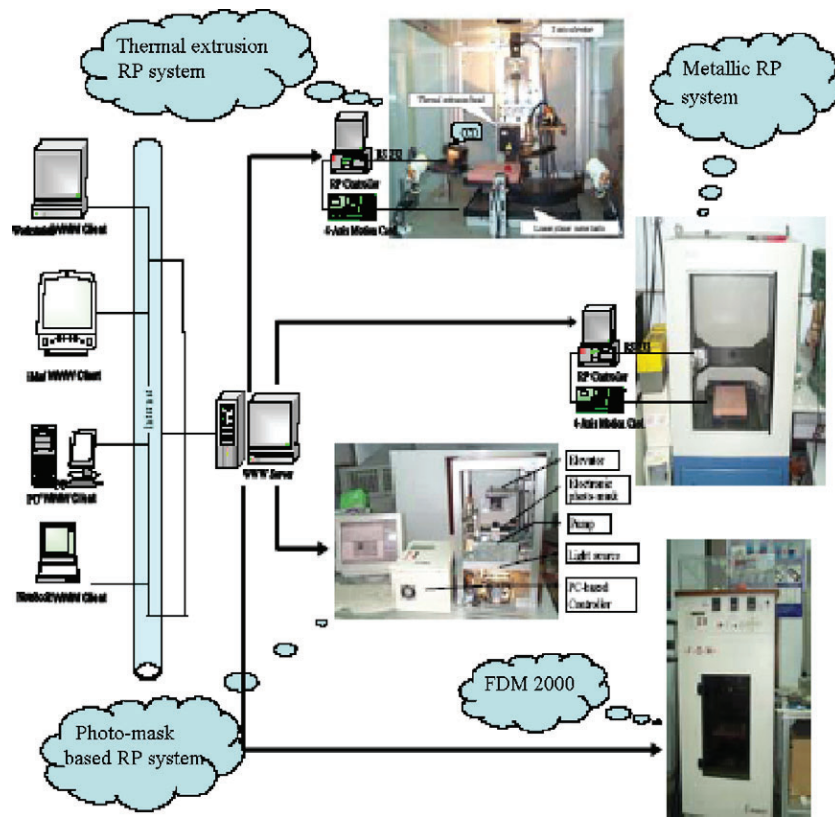


Fig. 11. Architecture of the order scheduling system [13].

and widely applied in various industrial fields. Compared with other modules, remote control and monitoring for RP machines cannot be considered as a difficult issue, designers can refer and use the previous research results related to Web-based remote control and monitoring techniques [69–71].

3.7. Security management

Since Web-based manufacturing systems allow the clients to download client application programs from the Server-side, access the client programs using local Web browsers, and execute programs at the remote Server-side, security management mechanisms are required to specify different levels of accessibility permissions for different users for preventing the local machines from being damaged by poor programs and viruses from the remote Server sides and preventing the Server machines from being visited by the unauthorized clients [1]. In the Tele-RP system developed by Jiang and Fukuda [18,19], the general security strategy is mainly concerned with (1) collection of information from clients and confirmation of the clients' certificates at different levels, (2) clients' access security considerations to Web servers, directories, and files inside the servers, including individual Web pages and (3) secure encrypted data transaction over the Internet. In their research, the currently available data encryption transaction methodologies, including RSA, digital signatures of users for payment and reliability, Security Socket Layer (SSL), and Secure HTTP (SHTTP), were investigated [1]. In the Web-based RP system presented by Lan et al. [21,22], in order to prevent hacking system, two firewalls based on package filtration and proxy Server, namely, Cisco2511 router and Proxy Server 2.0, were utilized.

For practical application of Web-based RP&M systems, security management is indeed a crucial issue. However,

designers can be directly consult and employ the methods and schemes of other Web-based application systems (e.g., Web-based manufacturing system, Web-based information management system, etc.).

3.8. Applying new technologies and concepts to Web-based RP&M systems

As advances in Internet and distributed computing, some new technologies and concepts such as, Web services, XML, common object request broker architecture (CORBA), Agent, Grid manufacturing, Application service providers (ASP), E-manufacturing, e-Service have been applied to Web-based systems (e.g., networked collaborative design and manufacturing systems) [72–85]. Service-oriented computing (SOC) is considered as a new computing paradigm after the object-oriented paradigm. It utilizes services as fundamental elements for developing applications/solutions. Services are autonomous platform independent computational elements that can be described, published, discovered, orchestrated and programmed using XML for the purpose of developing massively distributed interoperable applications. Web services technology is part of the SOC paradigm and can be considered as an implementation of the SOC model. Web services are featured with application, platform and provider independence. They provide an appropriate paradigm for building open large-scale application environments. In such environments, services are not treated as isolated and one-time affairs but rather as elements of an interactive, dynamic and collaborative architecture. Web services technology provides a higher level interoperability for leveraging business activities across the Web either within an enterprise or among collaborating. Web services provide an industrial standard for deploying, publishing, discovering and invoking enterprise's services. From its emergence, many specialists have predicted that

Web services will revolutionize the distributed computing paradigm and it will make various kinds of e-business (e.g., inter-enterprise collaboration and ASP paradigms) a reality [77]. Web services have been applied to many Web-based manufacturing systems. Solutions based on semantic web services are promising and they are being actively researched. These technologies can offer answers to some key challenges such as semantic mediation and interoperability [72,74,78,79]. XML is a standard for data representation and exchange on the web. The data are represented in XML schema, as it can be easily applied to Web-based systems. XML-based resource is well-structured with good expandability and flexibility. XML has been widely used in industry for the publishing of enterprise information and communication of enterprise business process [76,80]. It is especially difficult for current technologies to meet industrial demands on dynamic sharing of various resources. Grid Manufacturing has been suggested as an efficient method to share dynamical resources through the Internet. It aims to solve the problem of distributed and heterogeneous manufacturing resource sharing and collaborative operation [82,83]. An application service provider (ASP) is a business that provides computer-based services to customers over a network. Software offered using an ASP model is also sometimes called On-demand software or software as a service. The need for ASP has evolved from the increasing costs of specialized software that have far exceeded the price range of small to medium sized businesses. As well, the growing complexities of software have led to huge costs in distributing the software to end-users. Through ASP, the complexities and costs of such software can be cut down. In addition, the issues of upgrading have been eliminated from the end-firm by placing the onus on the ASP to maintain up-to-date services, 24 × 7 technical support, physical and electronic security and in-built support for business continuity and flexible working. Nowadays, networked manufacturing system based on ASP has become one of the hotspots of research and application. E-manufacturing is a system methodology that enables the manufacturing operations to successfully integrate with the functional objectives of an enterprise through the use of Internet, tether-free (i.e. wireless, web, etc.) and predictive technologies. It covers all aspects of manufacturing—sales, marketing, customer service, new product development, supplier relationships, logistics, manufacturing, strategy development and so on. E-manufacturing is opening up opportunities for data intensive activities such as on-line monitoring and diagnostics of machine tools conditions and knowledge intensive processes including new product development, complex systems modeling and simulation, and real-time decision making supports and complex problems solving. It has been considered as an essential and inevitable technology for the future manufacturing organizations, working along the extended supply chains in particular [84,85]. Using these new technologies and philosophies, the development of Web-based application systems can become much simpler and effective. For example, in order to better fulfill the intercommunication and interoperability of heterogeneous software and hardware systems among different RP service providers and users, these implementation techniques, which include desktop sharing, remote procedure calling and service encapsulation by distributed component object model (DCOM), common object request broker architecture (CORBA), Web services, etc., can be introduced to the remote RP&M systems. Furthermore, the developed systems using these new technologies and concepts have better functions, higher reliability and intelligence. However, the development of current Web-based RP&M systems is seldom based on these new technologies. In the future, it is necessary to develop the Web-based RP&M systems using these new technologies and concepts, in particular ASP, Grid Manufacturing and Multi-agent.

4. Conclusions

Computer network and information technologies have the potential to further improve the traditional manufacturing and service mode, moreover, they will become more and more important for current manufacturing industry. Web-based RP&M systems have been developed and employed to implement remote service and manufacturing for rapid prototyping, enhance the availability of RP&M facilities and improve the capability of rapid product development for a large number of small and medium sized enterprises. This paper reviews the state-of-the-art in Web-based RP&M systems. The future improvement tasks for the systems should further focus on the following four aspects:

- The combination of Web services and software agents provides a promising computing paradigm for efficient service selection and integration of inter-organizational business processes. It is a good scheme for Web-based RP&M systems to establish an agent-based service-oriented open architecture to better implementing collaborative and intelligent manufacturing for Web-based RP&M systems.
- In a collaborative networked environment, the integration and interoperability can enhance the competitive advantages of RP service providers. Therefore, the integration and interoperability in Web-based RP&M systems is an important issue. Web services represent a step forward in enabling collaborations between various entities on the web and in overcoming the interoperability problems that may appear. Web services technique may provide a solution for this issue.
- Some new technologies and concepts such as, Web services, XML, CORBA, Agent, Grid manufacturing, ASP, E-manufacturing, e-Service, provide effective enabling tools for Web-based application systems. Future research and development on Web-based RP&M systems should be based on these new technologies and concepts, in particular ASP, Grid Manufacturing and Multi-agent.
- Further research will be focused on collaborative product commerce (CPC), collaborative planning and control of production, enabling tools, concurrent process for RP and RT, optimizing external manufacturing resources, remote fault diagnosis, on-line services to customers, and the detailed structure and formulation of the central-monitoring mechanism of such a partnership system.

Web-based design and manufacturing system is a new product mode in term of mission, structure, infrastructure, capabilities, and design process, which need more detailed research and theory building. The significant contribution of this paper is to present a comprehensive review of recent advances in Web-based RP&M systems, and discuss the future research directions. That may provide a reference and direction for the development of Web-based RP&M systems.

Although Web-based technologies have been applied to collaborative product design and manufacturing for many years, real industrial applications have not been in place yet. As one of the most typical cases for Web-based collaborative product design and manufacturing system, Web-based RP&M system has shown a promising prospect for networked manufacturing and service modes. However, there is still a long way for really commercial application of the Web-based RP&M systems.

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