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INTERNET-BASED DELIVERY OF CAD/CAM CAPABILITY: AN INDUSTRY CASE STUDY

Simon Szykman and Ram D. Sriram
Manufacturing Systems Integration Division
National Institute of Standards and Technology
Building 304, Room 6 / Building 220, Room A127
Gaithersburg, MD 20899

ABSTRACT

This paper presents a case study in the use of the Internet as a medium for exchange of information and delivery of computer-aided design and computer-aided manufacturing (CAD/CAM) capability. The case study describes a collaboration among researchers and staff at the National Institute of Standards and Technology (NIST), and Thar Designs, Inc., a small business in Pittsburgh, PA that designs and sells high-pressure fluid pumps. The objective of this case study is to identify the needs of small businesses in engineering industry in the area of Internet-based CAD/CAM services. The Internet-based interaction performed in this study encompassed various stages in an iterative product development process, consisting of design, data exchange, manufacturability analysis, and fabrication of a prototype.

1. INTRODUCTION

There are a variety of visions for the next generation of engineering software tools for computer aided design and manufacturing (CAD/CAM) applications. Most of these visions include some form of distributed software, either across local networks, the World Wide Web or the Internet. Present computing technology provides a number of opportunities untapped by the engineering community. One example of such opportunities is the use of the Internet to deliver CAD/CAM services to engineering industry consumers. However, this research area is still in its infancy, and applications of these technologies are only now beginning to transition out of the research stages. As such, industry's needs have not yet been well defined.

Although large aerospace and automotive companies are the more well-known U.S. manufacturers, small design and manufacturing businesses make up a large segment of industry in this country. Their role is growing as larger companies find themselves outsourcing a greater portion of their product development. Increasingly, companies in a supply chain have a role not only as suppliers, but they are also being asked to actively participate in the design and product development processes. When contrasted with large companies in the engineering industry, small businesses are less likely to have an extensive spectrum of expertise available in-house. Their limited financial resources are also often a barrier to the purchase of high-end CAD, CAM and analysis software, and the hardware that is typically required to run such software. As Internet-based CAD/CAM services find their way into the marketplace, small businesses will find an opportunity to make use of technical expertise and CAD/CAM capability at a far lower cost than bringing such capability in house, making small businesses among the main prospective consumers of such services.

This paper is an investigation into the technical and related cultural issues of small manufacturing businesses and the potential impact of emerging Internet-based technologies on them. Although this paper does not contribute to the technical state of the art, the study of small businesses needs is important given the significant and increasing role of small companies in the engineering industry. Such a study has not previously been undertaken because many large companies do not place high priority on small business needs, and the smaller companies who have the most to learn do not have the financial or staffing resources to perform one. The National Institute of Standards and Technology (NIST), with its focus on serving U.S. industry, has found itself uniquely situated to perform a case study to investigate the needs of small businesses in the area of Internet-based CAD/CAM services.

The next section provides some background into the company and the engineering artifact that are the subject of this case study. Section 3 describes the Internet-based design scenario that was developed as an exercise to provide information for the case study. This interaction spanned several stages in an iterative product development process including design, data exchange, manufacturability analysis, and fabrication of a prototype. Section 4 provides a discussion of the scenario as well as farther-reaching issues that were not covered in this experiment. The conclusions are presented in Section 5.

2 BACKGROUND

The design artifact used in this case study is the chassis for a high-pressure fluid pump, developed by Thar Designs, Inc[1]. In the case of Thar Designs, a business opportunity was seen in a market where most pumps already on the market did not work well. High pressure fluid pumps can be used with combinations of substances for various processes. For example, coffee and carbon dioxide can be combined to decaffeinate the coffee through supercritical fluid extraction; a similar process can be used to remove hops from beer. In some applications, these pumps must provide up to 69 MPa (10,000 psi) of pressure.

Existing pumps for such applications were designed for pumping fluids that could be assumed to be incompressible. However, carbon dioxide used in decaffeination processes is compressible. Dead volume in the pumps is an important consideration for such applications, as it leads to less efficient pump designs. Thar Designs' specialized pumps focus more strongly on cooling and material requirements. Stronger materials expand less, reducing dead volume. Improved cooling (through design and material selection) reduces operating temperatures, and therefore fluid compressibility, thereby further decreasing dead volume and improving efficiency.

While a clear need for specialized pump designs was perceived, the target market was one that would not involve huge production volumes. Purchases might be on the order of tens or hundreds of units, as opposed to millions of units. Since production volume greatly influences production costs, it was desirable to reduce the number of models in a class of pumps, and increase the number of units produced for each model. Because scalability of pumps was a critical issue, the design of the chassis which holds the pump, and not the pump itself, was the most difficult problem. The final design developed by Thar Designs was highly scalable; the same design could be scaled to pump anywhere from 40 ml/min to 40,000 ml/min. Thus, a wide range of operating specifications could be accommodated with a small number of pump (and therefore chassis) sizes, all having substantially the same design.

Thar Designs exists as a profitable company, but a small one, having approximately a dozen employees. This impacts many aspects of the business. Two of the most important ones are technical expertise and in-house CAD/CAM capability. More specifically, because of the company's size, expertise among the designers does not parallel that which is available in large industry. As with many companies of this size, design at Thar Designs is done primarily in two dimensions, using tools such as AutoCAD. Consequently, they are missing out on some of the advantages provided by three-dimensional CAD, such as solid modeling and part visualization.

Analysis capability in general is similarly affected. While a spreadsheet program can be used to automate simple analyses using engineering approximations, something like finite element analysis requires the services of an outside consultant and is done infrequently due to the high cost. The company relies strongly on experimental work using a sophisticated test bench and data analysis software. Simulation packages would have the advantage of reducing the length of design cycles and prototyping costs, but are not used due to a lack of available financial and technical resources.

Finally, because of the production volumes involved, Thar Designs does not do manufacturing in-house, but rather contracts out the manufacturing work. A consequence of this is that the designers may not have the same knowledge about DFx (design for "x") issues that somebody who works closely with manufacturers may have. Examples of knowledge gaps include how to design for manufacturability, how to perform tolerance design, how to design for assembly, and others. In some cases, a design is sent out for fabrication and the manufacturer returns with feedback about cost or manufacturability of certain parts or features in a design. Redesign is required, after which a new design is sent back to the manufacturer. Each of these iterations can lengthen the product development cycle, thereby impacting competitiveness.

3 INTERNET-BASED PRODUCT DEVELOPMENT SCENARIO

To be able to complete this case study in a reasonable amount of time, we decided that the artifact to be used would be a design that already existed, rather than creating a new design as part of the scenario. In examining parts of the high-pressure fluid pumps as candidate artifacts for this scenario, a number of criteria were used. We wished to use a part that Thar Designs had actually designed and not simply purchased as an OEM (original equipment manufacturer) part, as is, for instance, the pump motor. We also wished to select a geometrically complex part, preferably an assembly of multiple components. The best candidate artifacts were a pump chassis and a pump piston-cylinder assembly. Of these, the pump chassis was selected for this collaboration because the designers at Thar Designs felt that the associated manufacturability issues were more interesting.

3.1 Phase 1: Data Exchange

As mentioned previously, one disadvantage faced by Thar Designs is that design is performed in two dimensions rather than three. This makes a detailed visualization of the part impossible. An experienced designer can create a mental image of a part given drawings of top/front/side orthographic views. For complex geometries, however, this does not substitute for three-dimensional visualization that allows part viewing and manipulation (e.g. rotating or enlarging a part model).

The scenario began with a set of AutoCAD drawings being uploaded to NIST using a web browser. Figure 1 shows an image of one of these drawings (with dimensions and other callouts removed to preserve proprietary data). These drawings were then converted to a three dimensional solid model using Pro/ENGINEER.[2] The Pro/ENGINEER model was then exported into VRML (Virtual Reality Modeling Language (ISO,

[1] Commercial product or company names in this paper are given for informational purposes only. Their use does not imply recommendation or endorsement by the National Institute of Standards and Technology.

[2] In the case of this project, the 2-D to 3-D conversion was done manually. Automated conversion of two-dimensional drawings to three dimensions is something that continues to be investigated by various researchers. Although progress has been made in this area, reliable automated conversion is has not yet been achieved for complicated geometries.

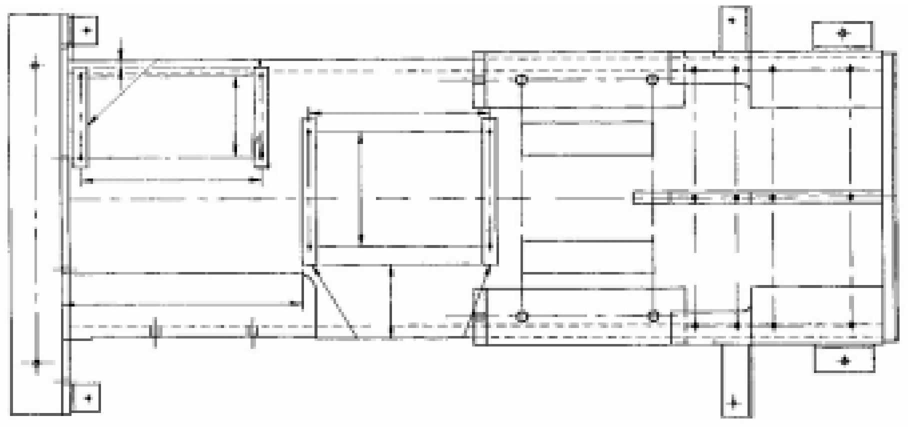

Figure 1. Two-dimensional drawing of the pump chassis (top view) (reproduced with permission).

1997)) format so that it could easily be viewed remotely by the designer. The VRML model of the pump chassis can currently be viewed at <http://www.nist.gov/edt/projects/Thar/> using a VRML viewer or a web browser with a VRML plug-in.

Once the conversion was complete, Thar Designs was notified by email that the VRML file was available for viewing. Thar Designs was also sent the web URL (universal resource locator) for an evaluation form that allowed the designer to submit to NIST an evaluation of the correctness[3] of the model, as well as provide general feedback. The designer could submit written change requests, request to be contacted by phone to give additional instructions, or indicate that the chassis was ready for manufacturability evaluation. The designer approved the model, indicated that the chassis was ready for evaluation, but wanted to be contacted to discuss some minor details by phone prior to the next phase in the scenario.

3.2 Phase 2: Manufacturability Assessment

After the first phase was complete, the fabrication experts at NIST evaluated the manufacturability of the pump chassis. The objective of the assessment was to address design issues that could affect fabrication time and/or costs. Based on the manufacturability evaluation, another web-based form was created. This form contained a number of annotated snapshots of the solid model, accompanied by several questions for Thar Designs' designers, and recommendations that they could approve or disapprove. In the latter case they were asked to provide a brief explanation of why a recommendation was discarded, to clarify the purpose or rationale for a particular aspect of the design which had not been clear to the fabrication expert.

Figure 2 shows an example of one of the annotated snapshots. Here, it was clear to the fabricator that the mounting pads for the bearings (labeled in the figure) required a post-assembly finishing operation to guarantee tolerances for alignment; however, it was not clear whether or not similar operations were needed for the other mounting surfaces. The designer indicated that they were not. Another query concerned the need for a finishing operation on the bottom of the chassis—the finishing operation was not necessary. Given the size of the surface (several square feet), omitting this would improve both the fabrication time and cost of the prototype.

3.3 Phase 3: Prototype Fabrication

If significant changes had been recommended as part of the manufacturability assessment, the chassis would have gone through another design iteration, and the steps described in Sections 3.1 and 3.2 would have been repeated. In general, some level of redesign is typical since the designers at Thar Designs do not have the DFx expertise that engineers at a company that does manufacturing in-house might have. In the case of this scenario, because the artifact of interest was an existing design that had previously been fabricated, rather than a new design, the suggestions were minor enough that a redesign and second iteration were not necessary. The designers at Thar Designs responded to the queries relating to the manufacturability assessment and approved the design for fabrication. The chassis prototype was fabricated in the Fabrication Technologies Division at NIST, using milling and boring processes and welding for final assembly. To fabricate the prototype, drawings with both 2D (orthographic) and 3D views were used. A photograph of the final prototype is shown in Figure 3.

4 DISCUSSION

Because of time constraints, we selected an existing design artifact that had already gone through design and prototyping before the initiation of this case study. Had a similar study taken place prior to, or in conjunction with the original design of the pump chassis, there would have been potential for greater benefits resulting from the Internet-based interaction. The manufacturability assessment would have saved redesign time and costs expended when the first design iteration was sent out for fabrication. More importantly, incorporating analysis into the loop could have reduced development time.

Finite element analysis is among the types of analysis that could have had a large impact on the design process. Based on customer/market requirements, Thar Designs knows the kinds

[3] Here, "correctness" refers to the gross accuracy and not the dimensional accuracy of the model. In other words, does the model look like the original design?

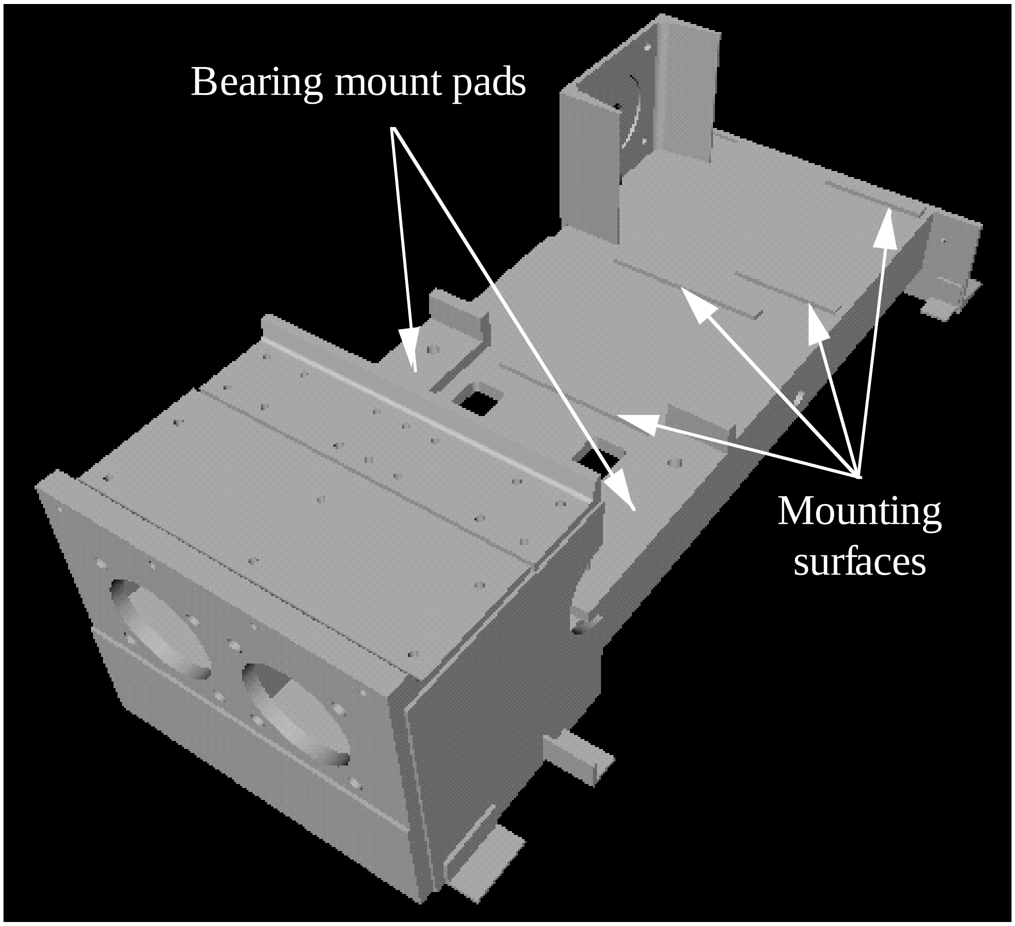

Figure 2. Annotated snapshot used to obtain feedback from designers.

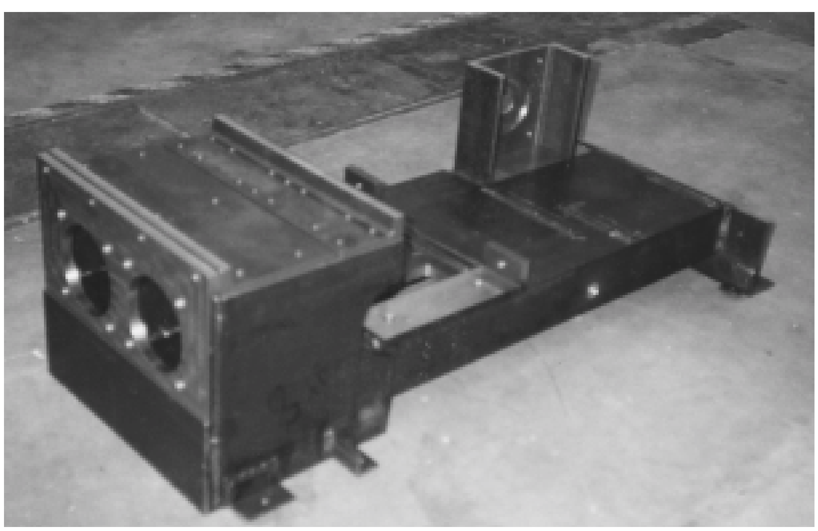

Figure 3. Final prototype for the pump chassis.

of specifications (e.g., operating pressure and flow rate) that pumps should meet. Then, for a given piston design, the pump specifications can be used to derive motor specifications. But for a given flow rate, what kinds of loads result from the piston action? What reaction forces does the chassis experience in critical areas such as the motor mountings, bearing mounts, and cam shaft? How will the chassis deflect under these loads? Providing answers to such questions early on can impact the design of a single chassis. A chassis which is too flexible can negatively affect the pump performance and efficiency. Knowing deflections would have helped with dimensional and assembly tolerancing issues. Thar Designs confirmed that as a consequence, they overdesigned the chassis used in this case study simply to avoid underbuilding it due to lack of analysis data. When a chassis weighs as much as a 150 kg, raw material costs become an important percentage of final product cost. In addition to reducing costs on a single chassis, analysis information would also be useful in the design of product families. For example, if a given pump provides a flow rate of 1 kg/min, can it be used with a larger motor to pump 10 kg/min, or is a piston redesign required? And can the same chassis be used with the higher loads, or does the chassis have to be redesigned?

At the low end of technological sophistication, the Internet could have been used to exchange product data to outsource analysis to a consulting firm. Fundamental advantages of the Internet are rapid information exchange, as well as reduced cost resulting from access to a greater number of providers for a service. In other words, rather than being restricted to local outsourcing, analysis could have been performed by somebody across the country offering more competitive fees.

But more technologically advanced solutions are now becoming available as Internet-based technologies become more widely used. Technologies initially developed as research are being commercialized into products that may play a significant role in the product development processes of small companies. Tools such as these will help surmount existing barriers for small businesses by providing analysis and simulation services remotely, quickly, and without having to establish expertise in-house.

Ideally, the Internet would have been used to perform a more comprehensive manufacturability assessment than the analysis presented in this case study. In this scenario, the part had already been designed as a welded assembly of parts machined from a specified set of stock material; this restricted the manufacturability assessment to process-specific issues. Another opportunity for improvement in the original chassis development would have been to use a manufacturability assessment to select the manufacturing process itself. As an example, to avoid assembly costs and dimensional inaccuracies introduced by the welding process, Thar Designs had wanted to investigate the possibility of casting a near net shape part and machining critical surfaces to obtain a final part.

Unfortunately, they were unable to explore such manufacturing alternatives. For small business, development time is always a critical factor. It is possible that for the initial design of the chassis corresponding to the first pump designed, pressures to get a product out the door before somebody else brought a competing product to the market would have somewhat limited the extent of the actual benefits mentioned above. However, because Thar Designs' pumps make use of scaled versions of a similar design, knowledge obtained through analysis and manufacturability assessment would help avoid repeated work from product to product.

This, in turn, would result in substantial time and cost savings when developing other pumps in a family (i.e., a similar product that provides a different flow rate or pressure). Thar Designs' estimate of the savings is up to 50% reduction in design cycle for new products that fall within a family of similar pumps. Potential cost savings resulting from analysis and the possibility of manufacturing using a different process were harder to quantify, but were expected to be significant. While in principle these types of analysis do not require the use of the Internet, in the case of small businesses it is the use of the Internet as a delivery and exchange mechanism that surmounts barriers (such as limitations on staff, expertise, and finances) and brings these capabilities within their reach.

5 CONCLUSIONS

The cost of a product is as important as always, but the importance of time-to-market has increased. These pressures have driven trends such as reduced physical prototyping, increased virtual prototyping, collaborative and concurrent engineering. These trends, in turn, have led to the development of CAD/CAM, analysis and knowledge based computational tools that are out of reach of many small businesses due to the cost of software, required hardware, and engineers with the expertise to use them. Among small companies, there has been an increasing reliance on external sources for these tools and skills, and therefore an increasing need for new technology to support this mode of operation. This paper has described an industry case study that investigates the needs of small businesses with regards to Internet-based delivery of CAD/CAM capability. An interactive scenario was conducted that included exchange of data, manufacturability assessment, and fabrication of a prototype.

Recent and ongoing efforts in the engineering research field are working toward the development of support and automation tools of various parts of the product development process. Varying degrees of success have been realized in areas such as data translation, 2-D to 3-D geometry conversion, feature recognition, manufacturability evaluation, cost estimation, and others. Clearly, automation makes it easier to provide such services via the Internet and intranets (Hardee et al., 1997; Regli et al., 1997; Sands et al., 1997). However, for many small companies, the issue is not one of automation, but one of access to capabilities that cannot be brought in-house due to staff and financial resource limitations. For small businesses, the Internet has the potential to provide that access even in the absence of automation at the receiving end. As technology matures and competitive pressures increase, small companies will be among the primary consumers of Internet-based engineering services.

As the world of electronic commerce continues to develop, the Internet will enable small companies to become even more competitive by providing a fast, low-cost, far-reaching medium for communication between producers, suppliers, and customers. Numerous companies have made electronic catalogs available online to aid in purchasing. Ongoing research at University of Southern California's Information Sciences Institute is working to develop electronic catalogs with advanced capabilities (Ling et al., 1997). Services have been created to allow companies to request quotes from multiple suppliers via the web, to obtain information (such as prices, inventory, delivery times, etc.) from multiple suppliers. A list of such catalog-based services can currently be found at the following website: <http://cdr.stanford.edu/html/SHARE/catalogs.html>.

We believe that these services will ultimately evolve into an Internet-based electronic marketplace, with more formal mechanisms for putting out an RFQ (request for quote) and allowing suppliers or manufacturers to make bids on them. Systems for supporting supply chain integration are already emerging in the research community (Gardner et al., 1997; Graser et al., 1997; Yang and Sarin, 1997)

The use of such services can reduce costs by giving small businesses like Thar Designs access to non-local suppliers, and will allow them to solicit bids from non-local manufacturers based on manufacturing capability. Such electronic bidding services would also improve Thar Designs' penetration into the marketplace by allowing them to submit their own bids to non-local companies who might otherwise never hear about Thar Designs given their small advertising budget.

The success of such a vision depends not only on technology but also on issues that have not been addressed in this paper, such as the business models that will support engineering service providers. Charging for a piece of software is routine in the CAD/CAM community, but new fee structures will have to be developed for things like charging for software on a per-use rather than per-license basis, or electronic bidding services. Through the collaboration described in this paper, Thar Designs has gained a new awareness of technological issues and resources concerning the impact of the Internet on their company. As a result, they have already begun investigating these emerging Internet-based avenues for improving their business.

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