Web-Based Process Provider Selection for Solid Freeform Fabrication

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Abstract

This paper describes a vision, now shared by many, of a networked design and manufacturing economy where information, goods, and services flow freely along engineering supply chains. One element of this new networked economy will be the integration of manufacturing supply partnerships using Internet technology. Prime contractors will now have access to a vast number of potential manufacturing service providers who can aid them in the prototyping and creation of new products.

In this markeplace, engineering firms require tools that will help select supply chain partners and analyze designs based on the manufacturing processes at their disposal. The vast size of the new Internet-based market, with its myriad of new manufacturing relationship possibilities, necessitates that software agents will be required to help process and navigate these complex possibilies.

In this work, we present an approach to selection of manufacturing service providers for solid freeform fabrication (SFF). SFF processes quite varied are being used for the production of prototypes as well as final products. Our research will help SFF designers and process providers by evaluating design tolerances against a given process capability; as well as in eliminating manufacturing problems and selecting the right SFF process (from those available through the many accessible suppliers) for the given design.

Introduction and Vision

Our vision is of a national and global manufacturing economy connected through Internet and telecommunications technology. In this vision, enterprises of all scales are active participants. Large companies leverage the information infrastructure to enhance the collaboration within their geographically dispersed organizations and manage their supply chains; smaller design and manufacturing companies benefit from increased specialization and access to huge pools of potential customers. The information infrastructure will enable groups of companies to organized themselves into virtual corporations and configure virtual intranets to support their collective activities; intranets that straighten the working relationships these organizations have, while protecting their most valued assets and intellectual properties. More generally, networking technology will enable manufacturers and designers to connect together.

Our opinion is that, although much has been touted about age of Agile Manufacturing and the Virtual Corporation, the potential of these concepts remains largely unrealized in practice. There are several critical technical and cultural factors at play, primary among them are those involving information access. For example, many of the promised benefits from agility follow from the assumption that there is a universal ability to communicate and share information with business partners and use this knowledge to make critical business decisions. In practice, however, these benefits have been largely crippled by the everyday incompatibilities among the information systems in the corporate workplace, coupled with the inability to directly link people with people and people with information. Further, and more significant as a cultural impediment, the majority of economic activity in many countries (including the United States) occurs in small- to medium-sized businesses. Many of the businesses which stand to

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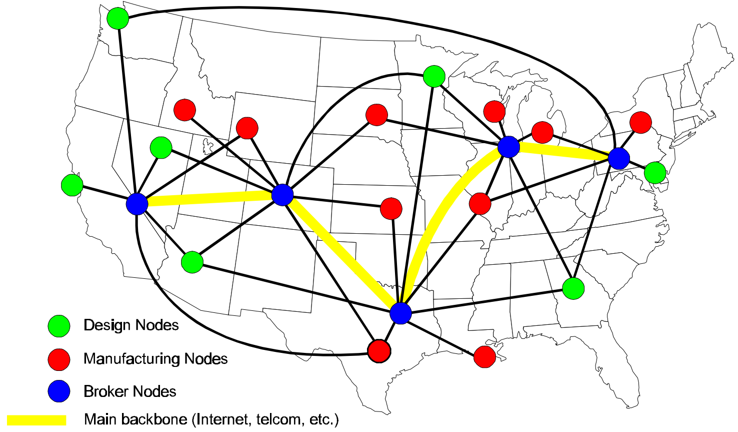


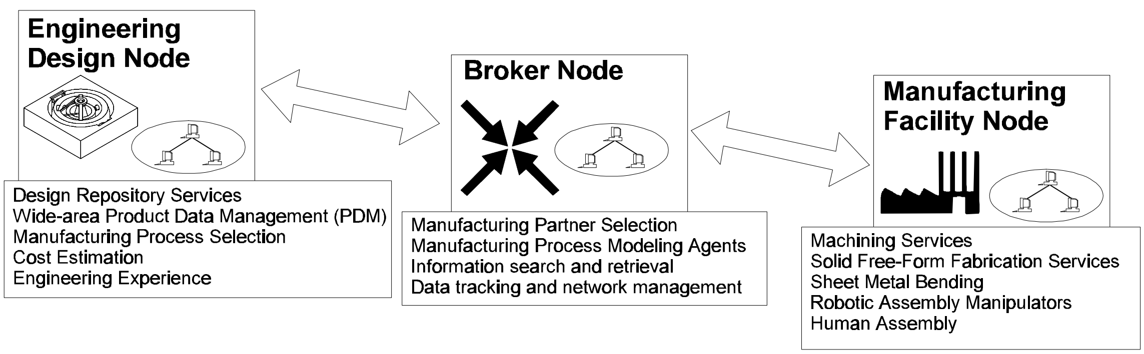
significantly benefit from these technologies lack the infrastructure and capital to invest in cutting-edge software, hardware, and fabrication systems and the people to support these systems.

Our belief is that engineering brokerage services will emerge that will register and manage manufacturing and design services---allowing designers to locate and access highly advance manufacturing services and engage in commerce. Among the many benefits this connectivity will produce are just-in-time manufacturing and improved supply chain management. For engineering and manufacturing organizations, this will enable corporatations to become highly specialized and publish their capabilities, via the Internet, to a vast marketplace.

Problem Scenario: Selection of Manufacturing Service Providers for SFF

Increasingly, industries are choosing to subcontract a wide variety of manufacturing services. Selecting the most appropriate supplier involves significant human-to-human communication between people in the prime and the supplier organization. Most of this information exchange is achieved through telephone calls, exchange of catalogs, engineering drawings, financial information summary, etc. The supplier selection decision is based on a wide variety of criteria such as supplier capability, cost, lead time, and prior performance. In current practice, gathering the relevant information about a new supplier can be very time consuming. This forces many companies to limit their options and to only do business with previously known suppliers. Many times such restrictions eliminate the potential cost savings from doing business with new suppliers.

Most information that need to be exchanged between a prime and a supplier already exists in electronic form. We are developing ways for electronically gathering and suppling this type of information and decision support systems that allow a prime to match a supplier's capability and capacity against the current requirements in real time and automatically create an up-to-date short list of potential suppliers. We believe that such a system would allow a prime to explore many more production possibilities in a very short time.



Solid Freeform Fabrication (SFF) refers to the class of processes that build parts using a layered manufacturing paradigm. A three-dimensional CAD model of the part is sliced into layers and the numerical data on the geometry of the layers is then fed into the fabrication unit, which builds each layer sequentially until the entire part is fabricated. Some of the commercially available SFF processes are Stereolithography (SLA), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), Layered Object Manufacturing (LOM), etc. Figure 1 shows how a given part is decomposed into layers for SFF. The main advantages of SFF processes are that they do not require any part specific tooling and are completely automated.

Due to the inherent nature of the process and the high level of automation, SFF processes are conducive to the concept of distributed design and manufacturing [Raja98]. Increasingly, SFF processes are being accessed by designers over the network in a distributed environment. Figure 2 shows how our research on manufacturability analysis will facilitate distributed design and manufacturing of SFF parts. In the envisioned scenario, process providers will publish their process constraints at their web sites. Designer will be able to down load these constraints in their CAD system and perform manufacturability analysis to make sure that the design is manufacturable. This will help in drastically reducing the iterations of modifying the design when the manufacturing constraints are violated.

Until recently SFF processes were primarily being used for creating prototype parts. Increasingly SFF processes are being considered for creating functional parts. In such applications, SFF can either be used for creating tooling (i.e., patterns for casting, low volume molds, etc.) or directly creating the functional part itself. In order to create defect free functional parts, it is extremely important to fabricate the parts within allowable dimensional and geometric tolerances. In order to determine whether a process can produce the part within required tolerances, we need to analyze manufacturability of design tolerances with respect to process constraints. In this paper we will primarily focus on manufacturability of geometric tolerances.

SFF processes approximate objects using layers, therefore the part being produced exhibits stair-case effect. The extent of this stair-case effect depends on (1) the layer thickness and (2) the relative orientation of the build direction and the face normal. The minimum layer thickness for a given process is constant. Therefore for a given process, the primary factor that determines the extent of stair-case effect is the angle between the build orientation and the face normal. As shown in Figure 3, for two different orientations of the shaded face with respect to the build orientation, the extent of stair-case effect on the built part is different. Thus, the achievable accuracies in SFF processes are highly anisotropic in nature. Different faces whose direction normal is oriented differently with respect to the build direction may exhibit different values of inaccuracies. Whether a part face or a part feature can be produced within the required accuracy depends on the build orientation. If a part has many different types of tolerance requirements, it may be possible to find build orientations that can meet individual requirements. But it might be impossible to find a build orientation that simultaneously satisfies all of the tolerance requirements. This observation makes it impossible to examine each tolerance requirement independently.

Our research will help SFF designers and process providers in the following ways. By evaluating design tolerances against a given process capability, it will help designers in eliminating manufacturing problems and selecting the right SFF process for the given design. It will help process providers in selecting a build direction that can meet all design tolerance requirements.

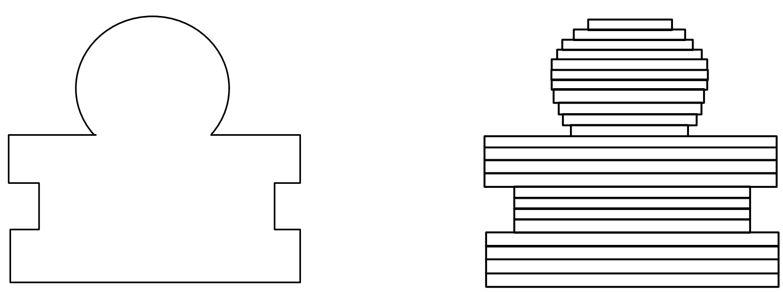


Figure 1: Staircase effect

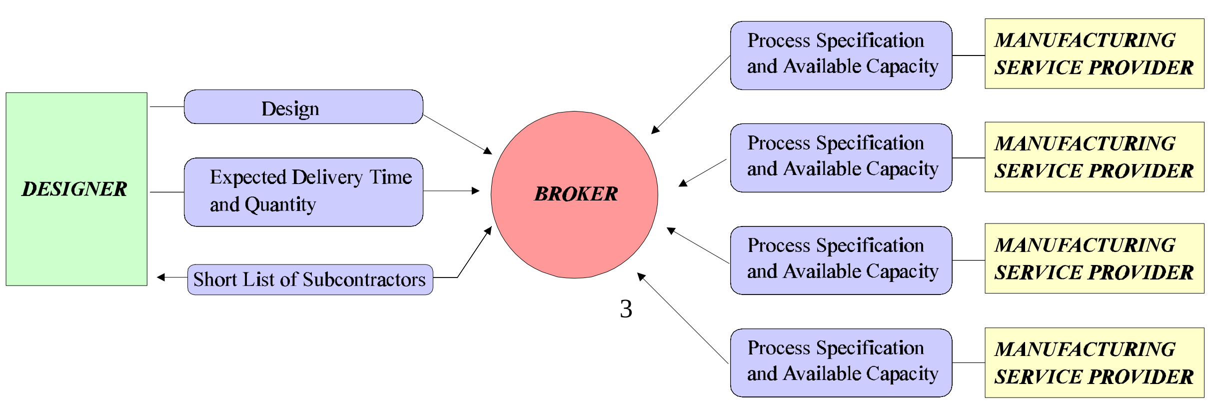


Figure 2: An architecture for interaction among designers, service providers and broker

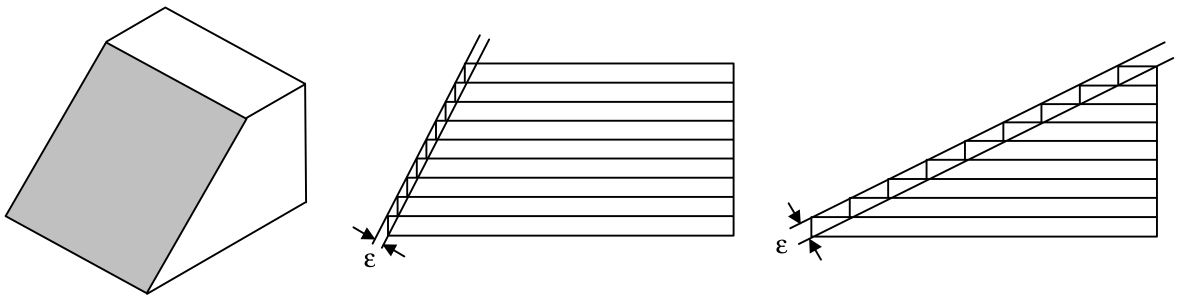


Figure 3: Effect of orientation on the accuracy.

Mathematical Model of Achievable Accuracy in SFF Process

We have developed a process model by making an abstraction of the SFF process as a layer manufacturing and layer assembly process. The process model takes into account the dimensional errors, both in the direction of the build vector and in the plane of the layer being built. We identified the following three primary sources of part inaccuracies:

- *Stair-case errors*: Solid Freeform processes are based on the layered manufacturing paradigm. Layers of finite thickness are used to build the part. As a result, there will be a stair-case effect on the part. The effect of stair case error can be seen in the Figure 3. Every layered manufacturing technique has a build direction associated with it. *Build direction* is the direction, normal to which the part to be manufactured is sliced into layers. The extent of this stair-case effect depends on (1) the layer thickness and (2) the relative orientation of the build direction and the face normal. The minimum layer thickness for a given process is constant. Therefore for a given process, the primary factor that determines the extent of stair-case effect is the angle between the build orientation and the face normal. Various parameters like the surface flatness, dimensional accuracy, geometric tolerances, etc. are affected by this effect.

- *xy-errors*: As an electro-mechanical control system drives the head seating the laser source or fused material, every time a new layer is built, it may not be exactly located as desired due to the inherent inaccuracy of the control system. Depending upon the particular process, there would be other parameters like the width of the laser beam and the post-cure shrinkage in the case of SLA, which will affect dimensional accuracy in the plane of the layer. The *xy-error* denotes this inaccuracy in the layer due to the overall effect of the various parameters mentioned. Figure 4 shows this error.

- *z-errors*: As and when a new layer needs to be formed, the platform which supports the already formed part of the object being manufactured is lowered so as to accommodate the new layer that is to be built. The system that controls the lowering of the platform would have its own limitations and thus would introduce error in the z-direction movement and this would in turn affect the thickness of the layer being built. As in the case of the xy-error, depending upon the particular manufacturing process, other parameters like the post cure shrinkage, overcure, print through and build quantization in the case of SLA cause dimensional inaccuracies in the layer in the z-direction. This value of the inaccuracy of the layer thickness in the build direction, due to the combined effect of the various parameters stated, is the *z-error*. Figure 5 shows this error.

Depending upon the particular manufacturing process and the machine used to build the part; the xy-errors and the z-errors can be obtained from the data reported by the SFF equipment providers. A study of the process would help us in relating the specifications of the machine to the xy-error and z-errors. For instance, for the SLA process, a study of the various sources of error was made and a value of 0.025 mm was used for the xy and z errors for the purpose of the example presented in a later section.

The average values of these errors can also be obtained experimentally by manufacturing a rectangular block using one of the SFF processes and then measuring the deviations from the nominal dimensions using a co-ordinate measuring machine. We plan to perform such an experimental determination of the process parameters like z and xy errors.

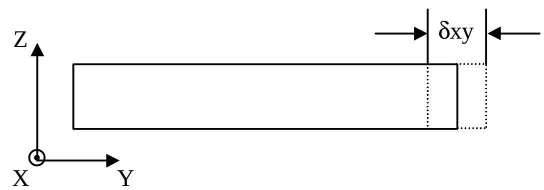


Figure 4: xy-error in a layer

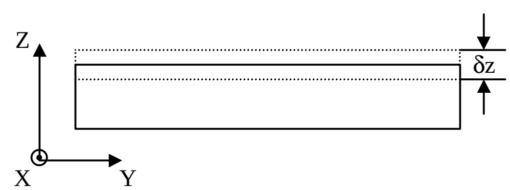


Figure 5: z-error in a layer

Figure 6 shows the model the we developed for the flatness accuracy of the planar faces

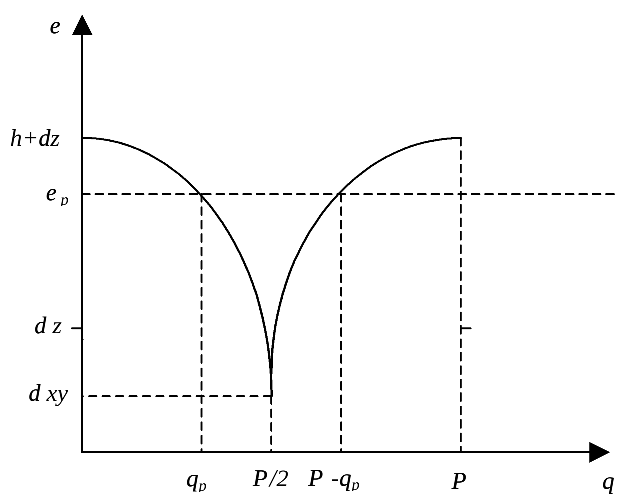


Figure 6: Effect of angle between build and face normal vectors on the flatness error

The definitions of the various variables in Figure 6 are as follows.

e is the flatness error on a planar face,
h is the thickness of the layer used to build the part,
q is the angle between the build and face normal vectors,
dxy is the xy-error,
dz is the z-error,
ε_p is the permitted value of the flatness error specified on a particular face, and
θ_p is an angle such that the interval $[\theta_p, \pi-\theta_p]$ represents the set of feasible orientations of the build vector for the specified value of the flatness error.

Algorithm for Assessing Design and Process Compatibility

Selection of process providers for manufacturing a given design is based upon an assessment of the design and process compatibility. A software agent is needed in order to perform such an evaluation. We are developing a broker which will help in selecting process providers for a design with certain specifications on the flatness tolerances of the planar faces. We have implemented the mathematical model explained in the previous section in building the broker. When a designer needs to know the details of the process providers who can fabricate his design, he would submit his design electronically to the broker. The broker would analyze the feasibility of the design with respect to a series of processes which process providers register with the broker. It would report the list of the process providers, if any, who can successfully fabricate the design. The following is a description of how the algorithm to assess the design-process compatibility works.

For every registered process *p* do the following:

Step 1: For every part feature that needs control on its accuracy, the *feasibility region* is constructed on a unit sphere representing all possible build orientations. The *feasibility region* for a feature is the set of all the points on a unit sphere such that if the build vector lies inside this set, then the specified tolerance is achievable for that feature.

Step 2: Intersect all feasibility regions.

a If the final common feasible region is not empty, then the part is manufacturable to the specifications by the process *p*

b. Otherwise, the part is not manufacturable by the selected process.

Step 3: If the process *p* can produce the part then add the process to the list of processes that can successfully fabricate the part.

Implementation as a Web-Based Service

Our broker service will help the designers in selecting process providers for fabricating a design with specifications on the flatness tolerances of planar faces. When a designer wants to find out who can fabricate his design, he would submit his design to our broker electronically. He would also submit a tolerance file specifying the details of the various tolerances on the part. The tolerance file would be created by the designer by using a freely available program that we have developed. The broker would analyze the part with respect to each of the registered processes and report a shortlist of the process providers who can fabricate the design. After the short list is produced, the designer can directly contact various process providers to get the quotes and delivery time.

We are developing a distributed design and manufacturing environment by basically catering to two types of clients.

1. *Process Providers*: Whenever a process provider wants to register a particular SFF process/machine model, he would electronically communicate the details of the process/machine model in a format specified by us. The program we develop would filter the required details and update a register file which contains information on the model of the machine, its capabilities and a contact address. The process provider would be automatically informed about the registering of the process via email

2. *Designers*: A designer might have specific functional requirements for his design and would have specified detailed geometry and certain tolerance requirements on the part. He would like to know about the process providers who can fabricate his design. He would electronically submit to us the '.sat' file of the part in ACIS version 4.0 and a postscript file graphically showing the tolerance requirements on the part. Using a program that we developed, we assign the tolerances to the appropriate faces on the part. Using the database on the various registered processes, we would then perform a study on the feasibility of the design, and intimate the designer electronically about the processes that would successfully build the part. If the part is manufacturable, then our program would also report a set of build directions along which the build orientation should be aligned so that the part can be manufactured.

The input to our system consists of the following three main components:

- geometry of the part
- tolerance information on the part
- process parameter information

Our system is implemented using C++. We make use of ACIS and OpenGL libraries to perform geometric computations and graphical user interactions. The following sections describe various inputs in detail and show an example.

Part Geometry Representation

We use ACIS "*.sat*" representation to represent part. Currently tolerances are only assigned to the faces that are planar in nature. Input geometric models may contain curved surfaces. But these surfaces are not analyzed by our system. To maintain correspondence between various faces and tolerances, we assign a unique face numbers to each face in the model. Our current implementation is based on ACIS version 4.0.

Part Tolerance Representation

We developed a graphical user interface in C++ using the OpenGL graphics library that allows the user to interactively assign flatness specifications on various faces of the part to be manufactured. After the specifications have been assigned, a tolerance specification file is created. Tolerances for the part are written in a *.tol* file. Following is the format for our *.tol* file. Various face numbers in this file correspond to the face numbers in the geometry file. An example of a tolerance file is given below.

```
#example.tol file
#tolerance specification file (all dimensions in mm)
#index feature_type feature_parameter(s) tolerance_type tolerance_value(s)
index 1 feature_type face face_id 26 tolerance_type flatness value 0.1
index 2 feature_type face face_id 28 tolerance_type flatness value 0.1
index 3 feature_type face face_id 22    tolerance_type  flatness value 0.1
index 4 feature_type face face_id 19    tolerance_type  flatness value 0.1
index 5 feature_type face face_id 2     tolerance_type  flatness value 0.1
```

where,
index is a serial number of the tolerance feature,
feature_type denotes whether the tolerance feature involved is a face or an axis, etc.
feature_parameter(s) denotes list of attributes of the features involved in representing the tolerance value,
tolerance_type denotes the type of the tolerance specification, whether flatness, parallelism, etc.
tolerance_value(s) denotes the list of attributes that define the tolerance.

Process Accuracy Description

The following is a typical process specification file which the process providers would register with the broker. The data shown in this file is data for a low-end SLA machine.

```
#SLA.pro file
#process specification file   (all dimensions in mm)
envelope 250 250 250
minimum_layer_thickness 0.1
z_positioning_error 0.025
xy_positioning_error 0.025
```

where “`envelope`” represents the dimensions of the largest part that can be manufactured by the process.

Example

In this example, we consider the design shown in Figure 7 which the designer submitted to the broker. Let us assume that the eight process providers have registered their process with the broker. The broker analyzed the design with respect to each of the processes . Table 1 shows the results of the analysis of the broker. It can be seen from the table that some of the processes cannot build the part. The designer is intimated of the process providers who can fabricate the part.

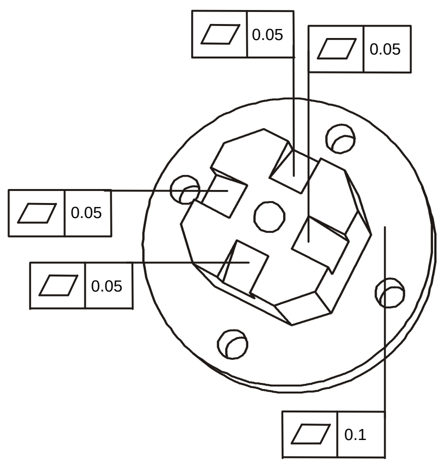


Figure 7. An example part.

Layer Thickness	z_error	xy_error	Result
0.1	0.01	0.01	NO
0.1	0.025	0.01	NO
0.1	0.01	0.025	NO
0.1	0.025	0.025	NO
0.05	0.01	0.01	YES
0.05	0.025	0.01	NO
0.05	0.01	0.025	YES
0.05	0.025	0.025	NO

Table 1. Results of the analysis of process selection.

Note: In Table 7, NO denotes that the process cannot fabricate the part, and YES denotes that it can. All the dimensions given in Figure 7 and Table 1 are in mm.

Conclusions

Summary. This paper describes a web-based brokering service for selecting SFF process providers. We first analyze each specified tolerance on the part and identify the set of feasible build directions that can be used to satisfy that tolerance. As a second step, we take the intersection of all sets of feasible build directions to identify the set of build directions that can simultaneously satisfy all specified tolerance requirements. If there is at least one build direction that can satisfy all tolerance requirements, then the part-process combination is considered feasible. Otherwise, the combination is considered infeasible. Our research is expected help SFF designers and process providers in the following ways. By evaluating design tolerances against a given process capability, it will help designers in eliminating manufacturing problems and selecting the right SFF process for the given design. It will help process providers in selecting a build direction that can meet all design tolerance requirements.

Current Limitations and Future Work. Our problem formulation is capable of generating feasibility regions for a wide variety of tolerances on planar surfaces. But our current implementation only handles flatness tolerances. We are in the process of extending our feasibility region generation scheme to handle tolerances on curved surfaces. At the same time, we are extending our implementation to handle a wider variety of tolerances on planar surfaces. We are also planning to collaborate with researchers performing large scale process characterization experiments to verify accuracy of our predictions.

Research Contributions and Ultimate Goals. We envision a proliferation of materials and manufacturing technologies to become accessible to engineers via the network. Getting designs prototyped or manufactured will be as easy as sending a document to a laser printer. A new manufacturing economy will emerge involving highly specialized facilities, continually operating efficiently and near capacity, accessible by their current customers and vast groups of new customers through the Internet and global telecommunications infrastructure. This network-centric and information-intensive marketplace for products and services is not only going to greatly enable just-in-time manufacturing, but it will also bring the capital costs of manufacturing down by increased business volume through highly specialized facilities. Our work represents one instance to enable networked manufacturing in the area of Solid Freeform Fabrication.

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