# NSF Progress Report

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## *A Design Interface for 3D Manufacturing*

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## *A Manufacturing Interface for 3D Design*

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# 1 OVERVIEW

The projects on *A Design Interface for 3D Manufacturing* [1] and *A Manufacturing Interface for 3D Design* [2] are companion efforts now in their second year of at Stanford University, Carnegie Mellon University and the University of Maryland. During the first year (June 1997 - April 1998), the focus of activity was on extending process capabilities and creating a preliminary design environment. A detailed description of the accomplishments during the first year is provided in the 1997-98 NSF Progress Report [3]. During the second year, the activity has been in three areas:

- **Advancing the Manufacturing Environment:** This work involves basic improvements to a class of layered manufacturing processes called Shape Deposition Manufacturing (SDM), developed at Stanford and Carnegie Mellon University. The improvements include new materials and smaller dimensions (mesoscopic parts). The work has also produced algorithms for automating the initial and final stages of process planning, and specifications for exchanging design and manufacturing information over the Internet.

- **Advancing the Design Environment:** This work has produced algorithms to support the creation of designs that exploit the capabilities of layered manufacturing. The designs are composed of elements drawn from design libraries and may contain discrete embedded components such as sensors and microprocessors. The work also includes the development of a language and protocol to support the communication of designs and manufacturability rules between a CAD system and a Design/Manufacturing Interface.

- **Advancing the Design/Manufacturing Interface:** This work includes the development of on-line "broker" services that automatically connect designers to layered manufacturing facilities, mediating the exchange of design and manufacturing information so that designers do not need to become experts in process planning. The interface also includes analysis programs to assess the manufacturability of evolving designs (e.g., to determine how best to satisfy requirements on tolerances and surface finish).

Details of the work in each of these areas are provided in the following sections of this report, followed by sections that discuss the Educational Impact, Outreach and Dissemination of Results.

# 2 RESEARCH ACTIVITIES AND RESULTS

## 2.1 Advancing The Manufacturing Environment

A manufacturing process that is operated as open and automated service needs to be very robust and well understood, and the tools to do the process planning need to produce plans that, while not necessarily optimal, are robust and guaranteed to produce the desired part. Developments in the layered manufacturing technology at Stanford have resulted in an increased range and number of built parts in the Rapid Prototyping Laboratory (RPL), achieved a wider user base for the technology and have initiated the commercial deployment of the Shape Deposition Manufacturing (SDM) process.

### 2.1.1 Metals Process Development

*(A. Nickel, G. Link, X. Li - Stanford RPL)*

Significant improvements have been achieved in the metal processing capability at the Rapid Prototyping Laboratory at Stanford University. Following are details about some artifacts recently fabricated in the facility.

**Turbine Blade:**

A turbine blade was developed for General Electric Corp. as shown in (Fig. 2-1). The blade was made out of 316 Stainless Steel and has two internal cavities. Air is blown into these cavities and then out through approximately 100 holes in the tail of the blade.

*Figure 2-1: Turbine blade with internal cooling channels*

The thin stainless steel wall between the internal cavity and the outside surface presented a technological challenge. Residual stresses that accumulate during the deposition cause the part to warp. If the part deflects more than the thickness of the wall, during machining the thin wall could be cut through exposing the internal cavity. To overcome this problem the part was annealed before final machining. In addition, from the knowledge gained from the stress analysis, the optimal deposition pattern was chosen to reduce the deflections. The final part was produced with minimal deflections and without exposing either internal cavity.

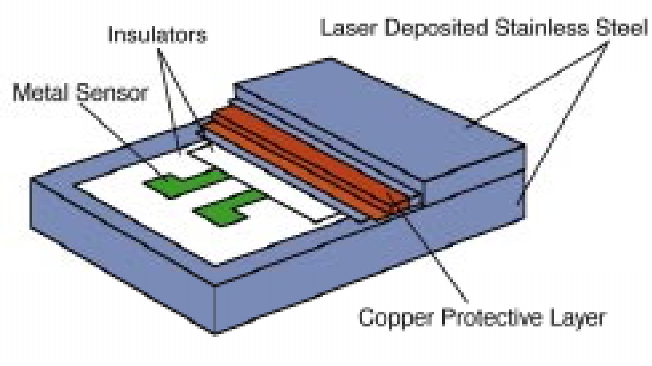


*Figure 2-2: Cross-section of embedded sensor structure*

**Integrated Sensors:**

The need to obtain information on the performance and lifetime of a tool in service is of prime importance to many industries. Some examples are the ability to monitor the condition of the drilling equipment for the oil industry, the strain and temperature of pipes and pressure vessels for the power industry, the temperature profile of the tools for the manufacturing industry. This need calls for on-line acquisition of information such as temperature and strain values from the tools and the structures and therefore introduces the challenge to bring sensor devices close to points of interest.

The embedding of sensors is currently being integrated into the SDM process [9]. The part is built up to the position where the sensor is desired. Then the laser deposition process is stopped and the part is moved to the thin film deposition station. Thin films of insulators and conductors with the aid of photolithography are deposited to produce a sensor (Fig. 2-2). A 1-2 mm thick layer of copper is electroplated on top of the sensor to protect it from the high temperatures involved with the laser deposition process. The part is then brought back to the laser deposition station and completed, producing a part with a working sensor embedded inside.

## 2.1.2 Metals Research: Stress Analysis

*(A. Nickel - Stanford RPL)*

All Layered Manufacturing process including SDM suffer from the accumulation of residual stress. These stresses arise from the contraction associated with the deposition of a layer. For metal parts produced using SDM, the contraction results from thermal strains when the layer is deposited at a high temperature and then allowed to cool to room temperature. These stresses cause distortions and possibly failure by layer de-lamination or cracking.

It was discovered that the pattern used to deposit a layer has a significant effect on the resulting residual stresses and deformation. The deposition pattern effect was investigated using a combination of experiments and finite element modeling employing the ABAQUS code. Patterns on two different low carbon steel substrates were considered, a 6 x 1 x 1/4 inch beam substrate and a 6 x 6 x 1/4 inch plate substrate. Two observations were made from the finite element analysis, first the highest stresses were found along the length of the deposition line and second, the highest stresses were found in the last region deposited. From these observations the pattern that produce the lowest deflection was determined for both substrates. For the beam substrate, a deposition pattern with lines oriented 90 degrees from the long axis minimizes the stress along the long axis, therefore minimizing the deflection. For the plate substrate, a spiral pattern produced uniform deflections and scanning from the outside to the inside minimized the area of the last line deposited. This produces a smaller region of high stress than scanning in the opposite direction resulting in lower deflections. Experimental results performed on the same substrates showed reasonable agreement with the finite element predictions verifying these trends.

### 2.1.3 Ceramics, Mold-SDM and Micro-Mold SDM Process Development

*(A. Cooper, S. Kang, B-H Park - Stanford RPL)*

Mold SDM has been used to build a wide range of polymer and ceramic parts [7], [8]. Polymer parts have included epoxy, polyurethane and silicone parts, as well as pre-assembled mechanisms and multi-material mechanisms where different parts of the mechanism were made from different materials. Alumina and silicon nitride ceramic parts have been built, including pre-assembled alumina mechanisms.

**Pitch Shaft:**

The pitch shaft (Fig. 2-3) is a complex part from a missile guidance system. A variety of these were built to test the new build strategies. Many of the new build strategies were actually developed based on the experience gained from building this part. Recent parts have been built much more quickly and are of a higher quality than the initial parts demonstrating significant process improvements.

**Vane Doublet:**

The vane doublet is an engine part from a Rolls Royce jet engine used in the Harrier aircraft. This part is about 70 mm tall. It’s the first full 3D curved surface Mold SDM part. A variety of turbine parts were built. These feature a rotor that is free to spin about a captive shaft. All these parts were built as pre-assembled mechanisms. Polymer parts were built to test the minimum achievable radial clearance between the shaft and rotor. The minimum consistently achievable clearance was found to be 200 microns, although process refinements since them would probably make that value even smaller now. Some multi-material parts were built with epoxy rotors and polyurethane shafts. Alumina parts were also successfully made and sintered.

*Figure 2-3: Sintered silicon nitride pitch shaft*

**Shrouded Fan:**

The shrouded fan part was designed to illustrate the capability of Mold SDM to produce fine features (the very thin trailing edges of the blades) and smooth curved surfaces (the blade surfaces).

**Silicone Arteries:**

Several experimental silicone artery models were built to explore the possibility of using Mold SDM to produce parts for medical applications. These parts were built for experiments to investigate blood flow in arteries.

*Figure 2-4: Polymer flap assembly*

The part and feature size for conventional Mold SDM is limited by the capabilities of the CNC machine. To go beyond these size limitations, Micro-Mold SDM uses micro-machined silicon as mold for the part material. To produce the mold, a sequence of lithography and etching steps is applied.

First, the CAD model of the part is decomposed into prismatic layers. The shapes of each layer are written on a mask for photolithography. With this photomask a resist-coated silicon wafer is exposed. After developing the exposed resist, the wafer can be etched in a reactive plasma. With this method, nearly vertical side walls can be fabricated for each layer of the part. The layer thickness is defined by the wafer thickness. Commercially available wafers range between 10mm and 1000mm thickness, so nearly any desired thickness can be achieved. By stacking several etched wafers, more complicated shapes can be achieved.

Mold SDM process improvement has involved both improvements to the properties of the materials being used, or alternatively changes to superior materials, as well as the optimization of the operations performed during the course of part fabrication.

### Materials Improvements:

The properties of the waxes used as mold materials are critical to the success of Mold SDM. The principal issues are with the tradeoff between machinability and shrinkage. Machinable waxes tend to have high shrinkage which leads to warping or cracking of molds during construction. Low shrinkage waxes tend to be softer and machine poorly. A wide range of waxes were tested for use in Mold SDM and ultimately it was determined that the best properties could only be obtained by mixing a machinable wax with a low shrinkage casting wax. Extensive machinability testing was performed to identify the optimum mix ratio as well as the effects of machining parameters on the machinability of the wax mixes. Shrinkage was also measured to allow for the determination of the optimum tradeoff between machinability and shrinkage. Currently a mix consisting of 25% machinable wax and 75% casting wax is preferred.

The UV curing soldermask support material currently used suffers from poor machinability as well as small cure depth. The small cure depth results in slow material buildup because layer thickness is limited. Poor machinability requires very conservative machining parameters which again lead to long processing times. Water soluble waxes are being tested as an alternative to the soldermasks. These can be cast in thick layers and they machine reasonably well. They have a lower temperature resistance than the soldermask which is still an issue because the material may deform when hot wax is cast over it. Wax spraying is being investigated as a means for depositing mold wax without re-melting the water soluble wax

Parts produced using the Advanced Ceramics Research gelcasting slurries only had about half the expected strengths so formulations developed by Oak Ridge National Labs were tested as alternatives. Initially there were some issues with incomplete curing, caused by interactions with the mold wax, but this was resolved and parts were successfully made and sintered. The ACR slurries have since been improved and are now producing parts with strengths in the expected range (600 MPa for silicon nitride). Surface quality issues caused by the curing and sintering of the ACR slurries have just recently been resolved and parts with good surfaces can now be produced.

**Process Improvements:**

Wax machinability is limited by two factors: gumming and chipping. If the wax is too brittle it will chip when machined aggressively and produce poor surface and edge quality. If the wax is too soft it will tend to collect on the cutting tools and gum them up producing rough surfaces. It was found that gumming could be reduced by blowing cold air onto the cutting tools. This has the effect of hardening the wax which improves machinability. By using cold air it is possible to greatly increase the machinability of the low shrinkage waxes making them practical as mold materials.

As mentioned above, wax spraying is being investigated as a method for depositing wax while minimizing the remelting of the material being deposited over. This will be particularly useful with the water soluble waxes and may make it possible to use them as replacements for the soldermask currently used as a support material. Initial results look very promising, particularly in terms of surface quality achievable [11].

A range of new build techniques have also been developed to improve the range of features and the surface quality as well as to reduce the build time. One technique, called Overcut-fill-trim-backfill makes it possible, in most situations, to produce sharp concave corners using conventional milling. This overcomes one of the main limitations of milling which is the inability to produce truly sharp corners because cutting tools are cylindrical and can't cut square corners.

Improvements in the decomposition scheme allow for non-planar layers to be used. The more general layer geometries that this allows make it possible to build higher quality parts in fewer steps because the layers conform to the part geometry better. Another process extension was the first use of multiple build directions. Instead of building the whole part incrementally in the Z direction, a pitch shaft was built using build directions along the Z, +X and -X directions. This greatly reduced build time and also improved part quality.

### 2.1.4 Mesoscopic Devices

*(Rudy Leitgeb, Juergen Stampfl, Shelley Cheng - - Stanford RPL)*

For all Micro-Mold SDM parts micro-machined silicon serves as a mold. Starting with a silicon mold, the following materials can be used to fabricate parts. Metallic materials are electroplated into the silicon mold. This technique has mainly been used in conjunction with copper. Copper is useful for applications where a highly conductive material is needed. Parts made so far are a copper cage for an electromagnetic motor and electrodes for electro-discharge machining.

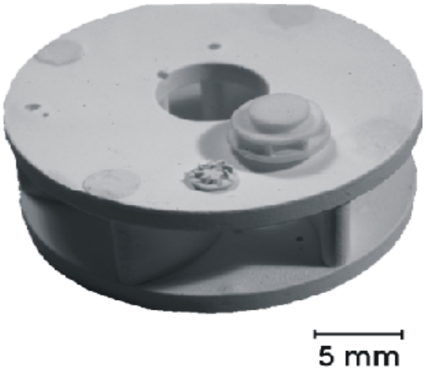


*Figure 2-5: A microfabricated impeller and its full size replica. Both parts where built from the same CAD data*

By hot-pressing metallic powder into the silicon mold, parts out of metals which cannot be electroplated, have been made. A powder mix of 33% W and 66% Ag has been used to hot-press EDM-electrodes into silicon molds. This material proved to be ideal for EDM since it combines the high melting point of W with the good thermal conductivity of Ag.

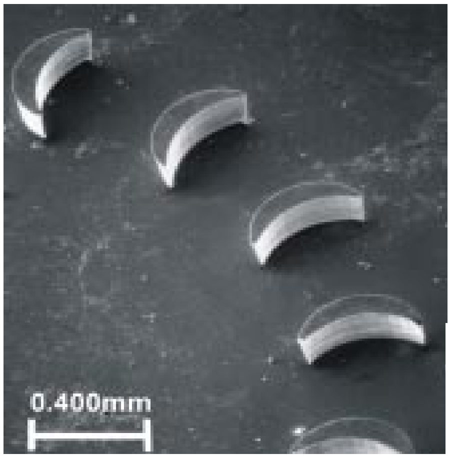


*Figure 2-6: Two layer part. $Si_3N_4$ ceramic slurry cast in a silicon mold*

The micro-machined silicon can also be used to build up molds for gelcasting of ceramics. In (Fig. 2-5) an example of a two-layer part is shown. In this case the silicon was used as mold for a ceramic slurry ($Si_3N_4$). The slurry was poured into the mold and after curing the mold was dissolved. A detailed view of the part obtained by this procedure is shown in (Fig. 2-6). In (Fig. 2-5) the impeller fan (4mm diameter) fabricated with Micro-Mold SDM is shown in comparison to two conventionally fabricated impellers.

### 2.1.5 CAD/CAM, Process Planning, Automation and Execution

*(J. Miguel Pinilla, Jianpeng Dong, Ju-Hsien Kao - Rapid Prototyping Laboratory, Stanford University)*

Process planning has two main components (Fig. 2-7) - model decomposition and individual stage planning. Model decomposition consists of splitting the part into volumes (called compacts) that can be manufactured in a single SDM cycle. This conceptually simple operation requires careful formalization and implementation in a CAD system to make it robust for a wide range of geometries. A preliminary decomposer that produced compacts in 2½ dimensions existed in the RPL. This year we have produced a fully 3 dimensional decomposer, seamlessly integrated in the Unigraphics CAD system. The choice of Unigraphics as the geometric platform has been driven by its high capability CAD system and the leading position in CNC machining.

The second part of the planning module consists of a CNC path generation module that is tailored to SDM characteristics. This module currently produces code for 3 axis machining and requires minimal input from the designer to execute. It is as well implemented within the Unigraphics environment. Both modules have been deployed in the RPL environment for use by part designers and process developers. Some early feedback has been collected which has led to changes in the user interface and integration of the modules in the UG environment.

A third part not yet integrated and deployed is automatically planning the deposition paths. Work in this area uses the fact that deposition is near net shape and some modifications to the geometry are allowable to improve part quality. It uses a shape optimization algorithm based on the Medial Axis Transform of the shape to produce smooth deposition paths.

These tools are in the process to be integrated to offer a seamless process planning environment for SDM that will relieve designers from knowing the details of SDM decomposition constraints and procedures.

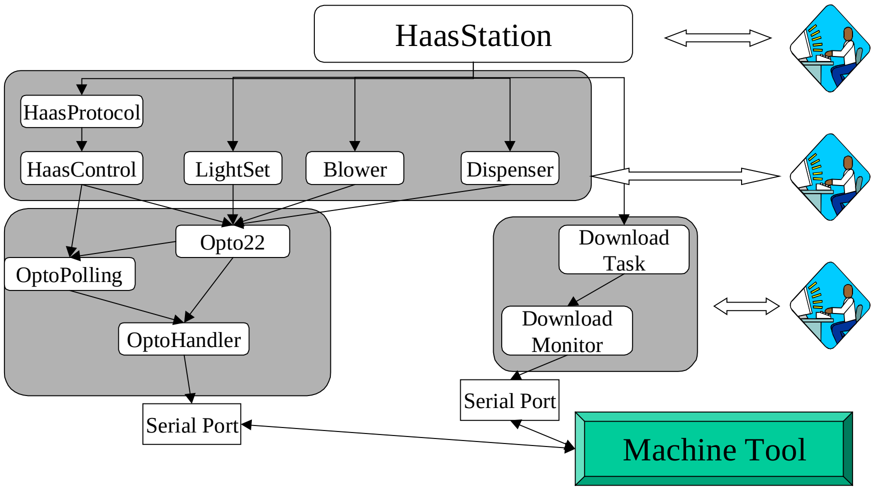


*Figure 2-7: Software structure for planning and machine control*

To achieve this seamless integration, the manufacturing process needs to be able to execute the process plans in an automated fashion, without the need for the operator to have extensive knowledge of the part being built.

An automated system has been built using the machine described in last years progress report that is able to take a Process Plan described in an specialized Process Description Language and execute them mostly unsupervised. The language has as primitives the basic operations needed to produce SDM parts: Mill and Deposit, together with some auxiliary operations required by some materials: Cure, Preheat, Cool, Wait. These primitive operations can be combined using three constructors: *Sequence*, which will execute the operations sequentially. *Alternative*, that allows the operator, or the on-line scheduler, to select one operation from a set. And *Unordered*, that requires completion of all sub operations, just like sequence, but allows the operator or the on-line scheduler to select the order in which they will be performed. The language allows these constructors to be nested arbitrarily.

The control Software is completely built in Java except for a small hardware access layer and prepared to work in a networked environment. The software architecture of the control uses multiple threads of control to monitor machine status, download CNC code and execute operations. It relies heavily on Object Oriented Principles to make it easily extensible and able to be integrated in a complete Shop Control System. Such system is current object of research to make it amenable to easy extension to the Internet environment to be linked with the broker architecture proposed in this project.

### Medial Axis Transformation:

Medial Axis Transform (MAT) encodes intrinsic shape characteristics into a lower dimensional metric. MAT together with boundary representation empowers shape manipulation and geometric reasoning. Though numerous algorithms have been proposed to recognize MAT of polygonal objects, a robust model for arbitrarily shaped regions, especially suitable for engineering designs, is still an art of research. The approach taken in this research [13] utilizes these two representations and describes MAT in terms of clearance functions along the boundaries. The algorithm efficiently computes the infimum of bisecting functions between distinct boundary segments and exhibits a time complexity of *O(n log n)*.

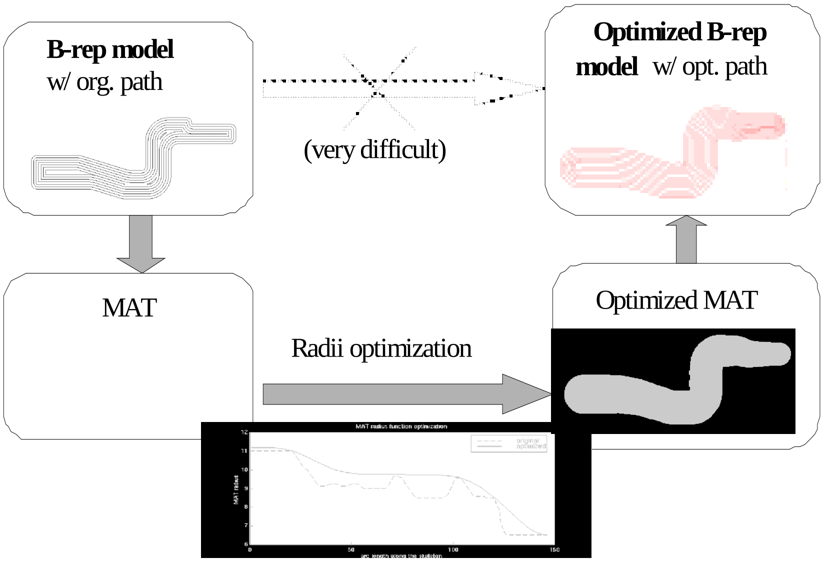


*Figure 2-8: Shape optimization for motion planning*

One of very important tasks in planning additive/subtractive SFF is to determine whether a computed decomposition plan is feasible for manufacturing. Although decomposed models may represent valid and manufacturing geometry, the presence of previously built layers may prohibit them from being feasible for fabrication. To assist determining such problems, an approach is proposed (Fig. 2-8) based on 2D medial axis transform and differential properties of decomposed geometry. In addition, surfaces that impose manufacturability problems are identified to facilitate design modification and to guide decomposition decisions.

Material integrity produced by solid freeform fabrication is closely related to topology and fairness of deposition paths. However, there are virtually no solutions to producing a connected and smooth spiral path that completely fills an arbitrary cross section. We propose a shape optimization algorithm based on medial axis transform to relax boundary constraints of cross-sectional geometry. The shape is optimized so that connected and smooth deposition paths can be produced. The resulting deposition paths are computed based on the medial axis transform.

Machine tool selection plays an essential role in automation of additive/subtractive SFF planning. However, it imposes rigorous computational challenges in that global shape interrogation needs to be accessed as opposed to just local geometric properties. Medial axis transform encodes global shape characteristics into readily available in 1D metrics and is particular suitable for such an application. A procedure based on histogram of shape thickness is suggested to efficiently compute an optimal set of machine tool for minimal machining time.

## 2.2 Advancing The Design Environment

Enhancement of the design environment is achieved by building tools that facilitate the creation of manufacturable designs that are slated for layered manufacturing. Extensions to the manufacturing capabilities described earlier require parallel extensions to the design environment. We envision a design environment in which two alternate approaches - design by *composition* and design *decomposition* - co-exist.

### 2.2.1 Design By Composition

*(Mike Binnard, Yanjie Sun, Beth Pruitt, Jorge Cham - Center for Design Research, Stanford University)*

**Basic Algorithms:**

Completely automated design decomposition and process planning are not feasible in the immediate future. To this end, we are developing a semi-automated approach that will make it easier for designers to build heterogeneous products created by SDM.

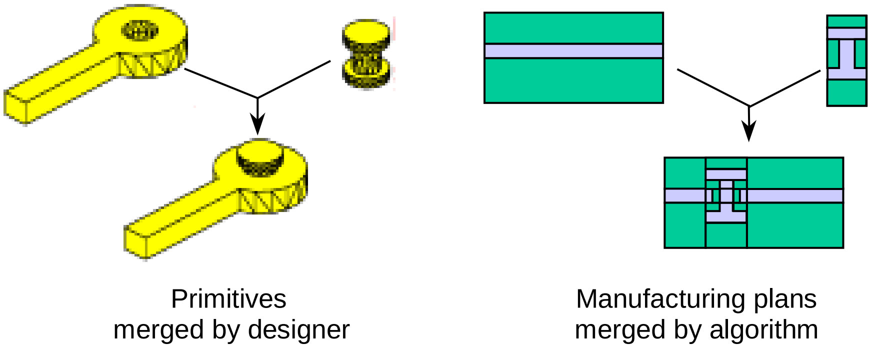


*Figure 2-9:. Design-by-Composition: The designer builds designs by combining primitives with Boolean operations. Each primitive contains its own high-level manufacturing plan.*

Our solution is an extension of the Design-by-Composition approach described in [5]. A downloadable AutoCAD plug-in is available to allow designers to create parts from a library of "primitives" which are used as design building blocks (Fig. 2-9). Each Primitive has an associated manufacturing plan, in the form of part and support material compacts and a precedence graph (a *compact* is a volume of material that can be manufactured in one cycle of shaping and deposition). When the user creates a new design from two primitives, the CAD system automatically combines the two manufacturing plans to create a plan for the new design. The merging algorithm (detailed in [20]) allows designers to merge primitives and automatically computes the resulting compacts and process ordering constraints. A tutorial has been developed which guides users who are unfamiliar with the SDM process and the RPL through the design and manufacturing process using the AutoCAD plug-in for simple urethane components. The tutorial assumes basic knowledge of AutoCAD and some familiarity with CNC machine operation. It is available at [23].

In order to free the designer from manually planning for the special considerations associated with embedding components, we create pre-defined libraries of generic embedded components. The embedded components, as defined in the library, include the necessary process modifications, such as spacers, channels for wiring and connectors, fixturing features for accurate placement, and standoffs for flow access of the next layer poured. An example is shown in (Fig. 2-10).

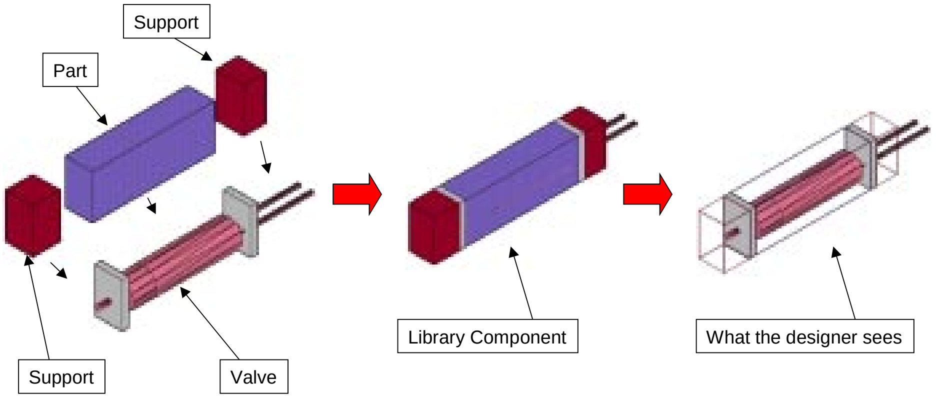


*Figure 2-10: Library Components - The designer places embedded components from a predefined library into an emerging design. These library components contain the extra steps needed to successfully embed them. In this example, the definition of an embedded valve already contains the necessary part, support and spacer compacts.*

The challenge then is to find ways to represent these specific manufacturing techniques, which have geometric and process ordering constraints, in the library components and to ensure that they are still valid after merging operations with other primitives. We believe that a solution lies in the following two directions:

- Expand the list of properties that compacts can have. This list already includes material type and geometry, but can be expanded to include material-specific Boolean operations and compact-list merging constraints.
- Encapsulate the manufacturing techniques discussed in earlier by constructing library elements from a collection of compacts of part, support, and embedded-component materials that have special material properties and ordering constraints.

As a starting point, we have expanded the previous merging algorithm to support primitives that are of "embedded" material. The designer can now create embedded components from libraries of simple shapes and merge them with other primitives. [6] provides an overview of the advances made in embedding parts into components manufactured with SDM.

### Design of Heterogeneous Parts with Embedded Components and Structures:

Figure 2-11 shows an example of a device with embedded components. The device is a small robot limb with an embedded pneumatic cylinder and valves, a pressure transducer, and associated circuitry for signal filtering and amplification. There is also an embedded steel leaf spring at the joint. By embedding the components in a solid structure it is possible to locate the valves and pressure transducer immediately adjacent to the cylinder, avoiding some of the compliance and transmission delays typically associated with pneumatics connected through hoses or tubing. Encapsulating the electronics also helps increase durability.

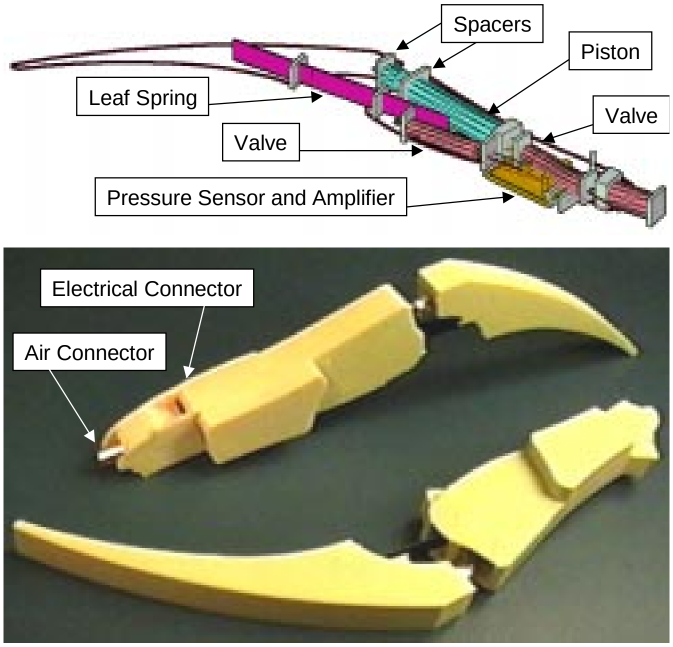


*Figure 2-11: A prototype linkage with embedded pneumatic components and a flexible joint developed at Stanford University.*

Designs such as those in (Fig. 2-11) show some of the potential for creating complex products using layered manufacturing with embedded components. However, these designs are not possible without special attention to the manufacturing process, including the addition of extra processing steps.

Additional advantages of embedding components with SDM include:

- Deposition can be tailored to obtain the best material properties and not be constrained by net shape tolerances that are achieved by the removal process.
- Discrete components can be used where local geometry is critical or exceeds the capabilities of the SDM process. Gap pieces can also be created explicitly and embedded to provide critical alignment or spacing
- Fully functional components like sensors, motors, or bearings with known performance specifications can be included in an SDM part or assembly rather than trying to build them in place or duplicate off-the-shelf items

The design by composition algorithms include the option to designate components as embedded material and thereby generate the appropriate process plan and machine code. Future work will refine the algorithm with more automation and provide library components for defining standard embedded sensors and actuators. Issues to be addressed when embedding components include component fixturing and positioning, characterization of multi-material interfaces, maintaining functionality, and integrated analysis of mechanical, electrical, fluidic, and thermal parameters.

### Extension to Non-Linear Primitives with U.C. Berkeley's CyberCut:

The original design and manufacturing interface only works with 2½-D parts. Currently, functions (library components) dealing with 3-D features containing free-form surfaces are being developed and added into the AutoCAD plug-in program. These functions combined with the 3-D free-form "CyberCut" tool path planner developed at University of California at Berkeley will enable the interface to automatically generate tool paths for many non-2½-D designs.

As in the 2½-D case, merging several simple 3-D shapes like spheres and/or tapered and horizontal cylinders can create complicated 3-D parts. The merging algorithm is valid provided that each support and part compact generated for one such simple 3-D shape is a valid compact and their union has only horizontal top and bottom surfaces and vertical sides. (Fig. 2-12) shows a simple sphere shape and its support compacts.

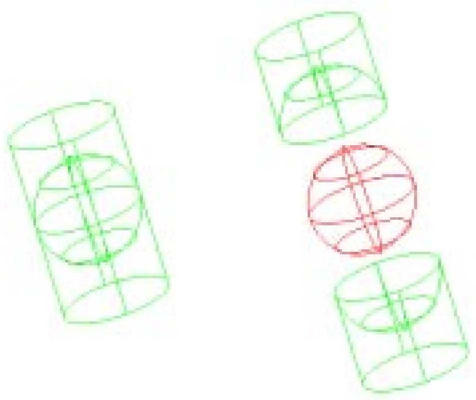


*Figure 2-12: Part and support compacts for a sphere*

After the model design is completed, geometry files associating with the negative volumes of each compact and union of compacts are generated automatically as the input files for the Cybercut planner. The Cybercut free-form path planner was originally designed for a feature based, constrained destructive solid geometry (CDSG) design environment. Therefore the input geometry files to the planner should be the part of the material that will be removed (the negative geometry). For a simple sphere shape illustrated in the figure above, two steps of milling is needed, in the first step, bottom support compact is milled, and then, we fill in the part material and mill the surface of the upper half sphere. There is no need to process the support compact above as it is the last in the compact list. The input geometry files for the two steps are shown in (Fig. 2-13).

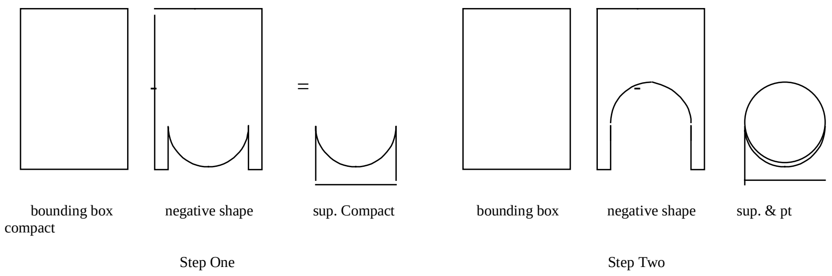


*Figure 2-13: Compact merging*

We are preparing to make some 3-D free-form parts using this newly expanded interface. Once the manufacturing quality and the reliability of the software is proved, the SDM process will be able to provide high-quality 3-D free form features as well as the 2½-D features it is providing now.

## 2.3 Advancing the Design/Manufacturing Interface

The vision that drives this project is to make advanced SFF and MEMS technologies available to the research community. Designers will be able to submit designs to a manufacturing service for fabrication without the need to fully understand the process involved. This vision has led to the target architecture shown in (Fig. 2-14). The manufacturing site takes a design, and after assessing its manufacturability, produces a process plan and executes it in the shop to obtain the finished part. The formats, technologies and services through which designers and manufacturers exchange information or data have collectively been termed the *Design/Manufacturing Interface*.

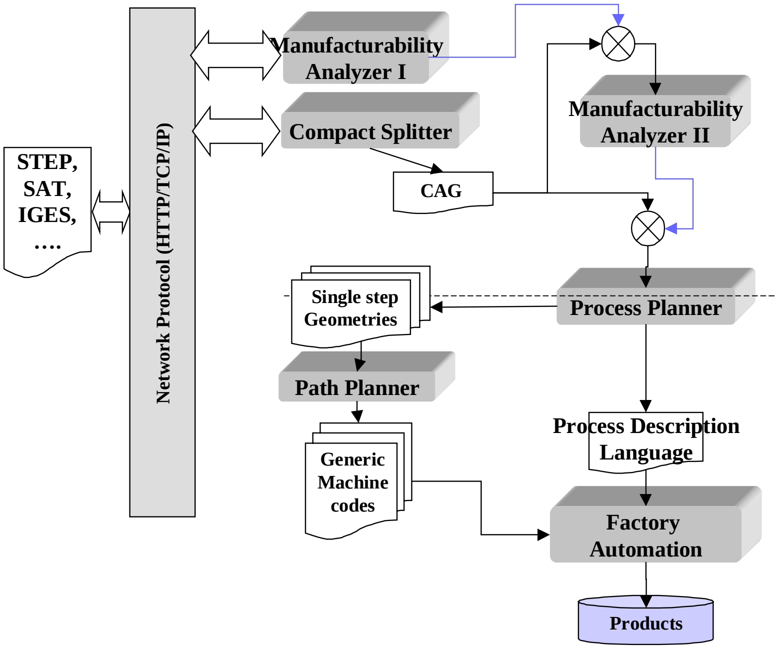


*Figure 2-14: Manufacturing view of the design interface*

There are two classes of components in the research pursued with regards to advancing the Design/Manufacturing Interface. The first class consists of interface *representations*, which implement an information exchange medium that is more sophisticated than existing exchange mechanisms. The new representations are more suitable and more efficient for the exchange of solid freeform fabrication data. The second class of components are interface *services*, which provide communication, process selection and manufacturability analysis assistance to designers and manufacturing service providers.

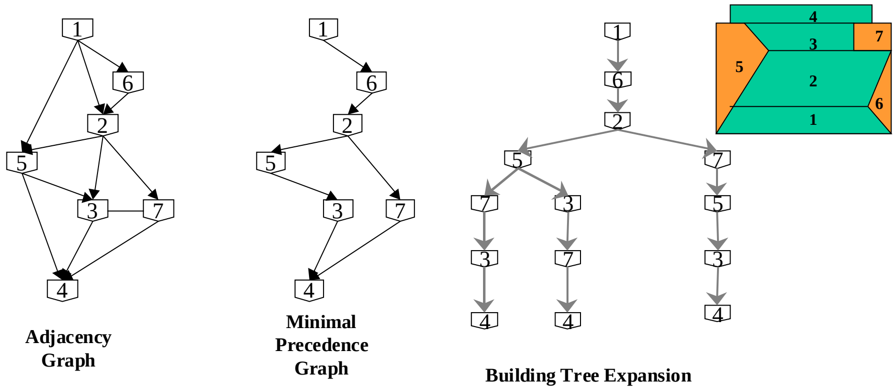
## 2.3.1 Interface Representations

*(J. M. Pinilla, S. Rajagopalan - Stanford, in collaboration with V. Kumar, D. Dutta - U. Michigan at Ann Arbor)*

### Compact Adjacency Graph:

To support the planning effort on the manufacturing side, a part representation that captures the nature of the SDM process has been developed which is also used in the design tools.

SDM builds parts by decomposing them into readily manufacturable volumes and then stacking or composing these volumes along a build direction to construct the final part geometry. These manufacturable units are called *compacts*.



Adjacency Graph

Minimal Precedence Graph

Building Tree Expansion

*Figure 2-15: The compact adjacency graph format*

Compacts that share a surface are called *adjacent* compacts. This adjacency relationship forms a graph in which the graph vertices are the compacts and the graph edges represent the adjacency between two compacts. Edges in this graph can be labeled with information of the surface that two compacts share. As a result, graphs thus constructed retain all spatial relationships among the decomposed volumes and inherently represent compact composition with respect to the given build direction. This graph is defined as the Compact Adjacency Graph (CAG) [17].

The CAG is only meaningful given the build direction. The build direction introduces a precedence relationship among compacts. This relationship is a partial order among compacts. One compact precedes another if and only if they are adjacent and building the first one is necessary to support building the second one. This relationship is easily represented in the CAG formalism by assigning a direction to the edges of the graph. Once this is done, the CAG becomes an acyclic directed graph that captures all the build order restrictions due to geometry under a given build direction.

The first use for the information captured in the CAG is to produce process plans. One individual compact is manufactured by a deposition and a shaping operation, uniquely determined by the compact geometry. The CAG provides then how these pairs of deposition and shaping can be sequenced so that the part is correctly built. In the graph formalism, This process planning involves two sub-steps:

- First, determining the minimal set of precedence relationships that capture the ordering constraints: in the CAG two compacts may have any number of transitive precedence constraints in the order in which they can be built. This step selects the precedence relationships that minimally enforce all the build order constraints. This defines the minimal precedence graph.
- Second, expanding the tree of all possible building sequences: The compact precedence graph provides the ordering constraints that any allowable build plan needs to fulfill. We can then generate all allowable sequences and express it as a tree of build alternatives.

### Representation and Processing of Heterogeneous Objects:

This research has also yielded a new approach to modeling and processing of heterogeneous objects slated for solid freeform fabrication. A fundamental advantage of SFF over conventional manufacturing techniques is the capability to access the entire volume of work-piece at some stage of the process (as opposed to only the external surfaces in conventional manufacturing). In order for designers to fully exploit this capability, the solid modeling system needs to accommodate the specification of geometry and (possibly varying) material properties within the entire volume of the part. A two-tier solid modeling method (using rm-sets and rm-objects) by which this can be achieved for arbitrary design geometries has been described in [15].

Process planning of heterogeneous objects described in this manner involves the determination of an optimal orientation for the part, the generation of a support structure and subsequent decomposition of the part into simpler entities that are conducive to automated fabrication. However, this mode of operation does not allow for easy and early communication of process-planning concerns to designers who are not already process experts. One method of early communication is to provide designers with pre-processed library components, and rules for transforming and merging them into designs. To achieve this goal, the heterogeneous modeling entities can be extended as SFF-Compacts and SFF-Objects (Fig. 2-16) to form an intermediate decomposed representation of the design.

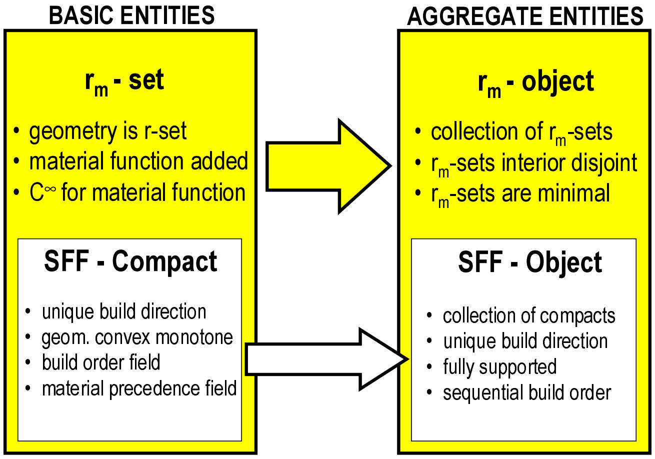


*Figure 2-16: 2-tier representation scheme for heterogeneous solids in SFF*

The representation, along with a compositional design library of heterogeneous parts, acts as the "interface" that enables a two way communication between design and manufacture. This interface preserves the flexibility available to designers today, postpones commitment to a particular process, and enables novice designers to quickly compose manufacturable parts.

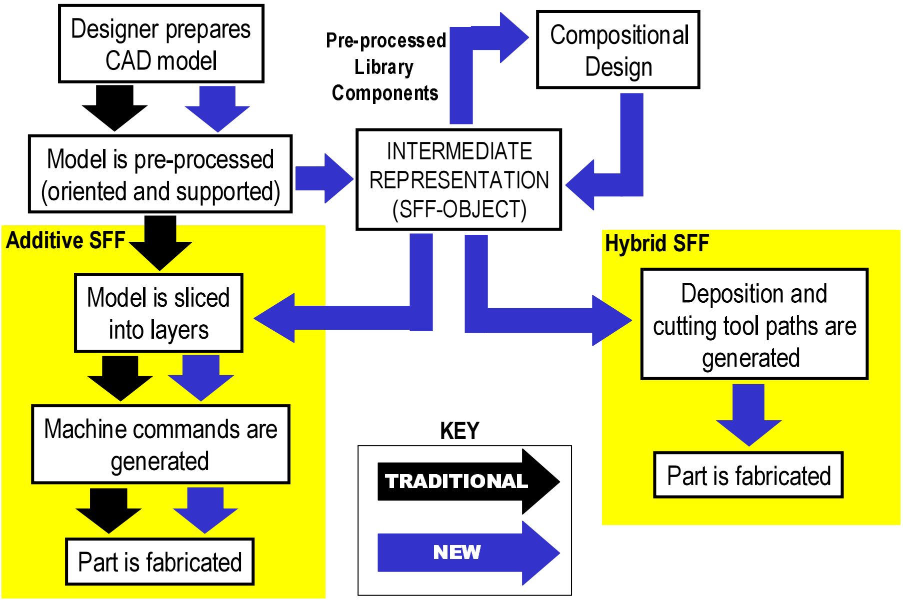


*Figure 2-17: A new approach to process planning heterogeneous solids*

We believe that the techniques demonstrated can form the basis for a expressive and robust information exchange language between designers of mechanical systems and rapid-prototyping service providers (Fig. 2-17).

## 2.3.2 Interface Services

*(S. Rajagopalan, P. Goel - Stanford; R.K. Arni, S. Dhaliwal, S.K. Gupta - U. Maryland; Q. Tian, L. Weiss - CMU)*

### BROKER SERVICE

The primary aim of the process broker under development at Stanford University is to reduce the process-specific knowledge that the designers need to possess. The manufacturing broker specifically will assist a designer in choosing an appropriate prototyping process, allow manufacturing analysis and provide directory services.

The broker will at one level provide a broad level process selection module in which the designer will be able to get a selection of prototyping processes based on high-level characteristics of the part (like material, high-level geometry and tolerances). This will be useful to the designer at the preliminary stages of the design so that the designer can be acquainted with the processes available and carry out detailed design while considering the needs of the processes. At the next level, when the part has been designed, the designer will have the option of getting optimality analysis for the various processes that may be used for fabrication. For example, an analysis module that can determine the near-optimal build orientations for layered a part is currently under development at the University of Maryland [4]. These kinds of tools will help the designer extract information regarding suitability the various alternative processes for a specific part.

At the current level of implementation the broker communicates with other (design and manufacturing) agents to provide the high-level process selection service. The communication is implemented using the JATLite software developed at Stanford [26]. KQML (Knowledge Query and Manipulation Language) is the language used for exchanging information with other agents.

## DESIGN FOR MANUFACTURABILITY SERVICES

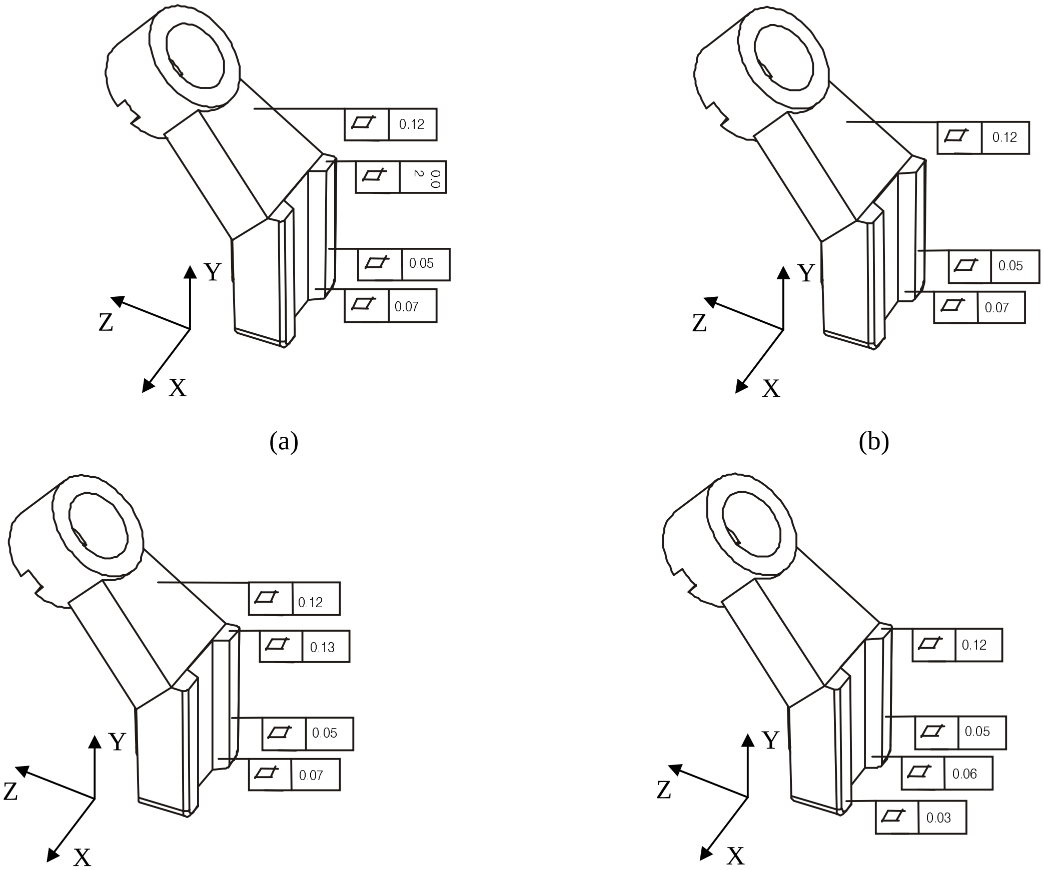
### Optimal Pose Selection for Fabrication of Mechanisms

Solid Freeform Fabrication (SFF) techniques allow the *in-situ* fabrication of fully-assembled devices with mating/fitting parts. An interesting issue that arises during the fabrication of such mechanisms is the determination of an optimal *pose* in which the mechanism should be built. For example, should the mechanism be built in a folded or stretched-out position? What is the best configuration in which to build the mechanism? In conventional manufacturing these issues do not arise, as each individual link is typically manufactured separately and then the pieces are brought together during assembly.

As part of the research supported by NSF, we address the issue of finding a preferred (or optimal) pose for *in-situ* fabrication of planar mechanisms [19]. There are many factors (e.g. achievable tolerances, non-interference, workspace size limitations, thermal considerations etc.) which can determine the suitability of a candidate build pose so that pre-specified task requirements are met. At this time, we have limited our analysis to finding the optimal build configuration given achievable (in general, non-homogeneous, anisotropic) accuracy on joint position. We also make the simplifying assumption that the task requirements can be best satisfied by minimizing variability of link-lengths. Alternate task requirements, for example, maintaining end-point accuracy within a tolerance region, are being considered as part of ongoing work. We cast the problem of minimizing variability in link length as that of determining the relative position of two location tolerance regions for which the difference between their extremal distances is at a minimum (i.e. as they undergo constrained relative motion in the Euclidean plane). The method is similar to computational geometry techniques that have been developed in pattern matching and robot motion planning.

### Optimal Orientation Selection

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.



(a) (b)

(c)

(d)

*Figure 2-18. Optimal orientation analysis applied to an example part*

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. Therefore 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.

Given the CAD model of a part to be manufactured and the requirements on the accuracies of the planar faces on the part, we have developed a systematic approach to finding out whether the part is manufacturable. We use a two step approach. 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 is considered manufacturable. Otherwise, the part is considered non-manufacturable.

Figure 2-18 shows four different cases of flatness requirements on an example part adopted from the NIST Design Repository. For the specifications shown in (a), the part is not manufacturable when analyzed by the program. In (b), one of the tolerance requirements is removed and the part becomes manufacturable. In (c), one of the requirements from (a) is relaxed so that the part becomes manufacturable. In (d), the design specifications are changed to make the part manufacturable.

This work is described in more detail in [4], [10].

# 3 EDUCATIONAL IMPACT

- In February, Yanjie Sun, a Master's student in Mechanical Engineering at Stanford University, fabricated parts for an undergraduate course on Rapid Prototyping taught by Prof. Susan Finger course at CMU. This was a continuation of a collaboration started last year with Prof. Finger. Before transmitting their designs, Prof. Finger's students referred to the on-line manufacturing guidelines for LaserCam prototyping compiled by Scott Stanford [24]. The process went smoothly.

- Layered Manufacturing, and SDM in particular, were featured in "Understanding Manucturing Processes," a course taught jointly by Prof. Mark Cutkosky and Prof. Samuel Wood of the Graduate School of Business. Students produced term papers that considered future directions for commercializing layered manufacturing processes from a technical and business standpoint. Details are available at the E611/T611 web site [27].

- The SDM process and environment were featured in a course taught by Prof. F.B. Prinz in the MSE Department. Students accessed the RPL machines to building prototypes for a course contest that involved maximizing strength while minimizing weight.

- Two Ph.D. theses were generated in the course of this year [20], [21].

- There are currently 3 PhD students and 3 MS students involved with with project.

# 4 OUTREACH AND DISSEMINATION OF RESULTS

## SFF University/Industry Workshop

Stanford University is organizing a two day workshop aimed at bringing together the SFF community to discuss the advances made in the Interface arena. The workshop, to be held at Stanford University on May 3-4, 1999, features a mix of academic and industry participants and guest speakers. Following is the agenda for the workshop:

### AGENDA

| DAY ONE | | DAY TWO | |
|---|---|---|---|
| TIME | EVENT | TIME | EVENT |
| 8:30 | Orientation, registration, reception | 8:30 | Introduction to Day Two activities (Cutkosky) |
| 8:45 | Brief Introduction to workshop, goals, plans (Cutkosky or Prinz) | 8:45 | SFF Infrastructure Issues (Cutkosky) |
| 9:00 | Overview of the state-of-the art & industry in Rapid Prototyping (Prinz) | 9:00 | Emerging SFF services network (ARRK Enterprises Inc.) |
| | | 9:45 | short break |
| 9:30 | Rapid Prototyping for Product Development at ALCOA (Paul Fussel) | 10:00 | Toward a design/manufacturing interface agents,brokers, services (e.g. tolerance analysis) (Rajagopalan) |
| 10:00 | short break | 10:20 | Discussion |
| 10:15 | RP for tool and die making (Dawn White, Ford Motor Company) | 10:30 | short break |
| 10:45 | Discussion | 10:45 | SFF Infrastructure research (process planning, optimization) (Pinilla, Kao) |
| 11:00 | short break | | |
| 11:15 | Introduction to SFF research issues, emerging capabilities, trends (materials, size scale, volume and speed). Preview of the afternoon talks, tours & what to expect. (Prinz) | 11:30 | Workshop summary and overview + general discussion (Prinz) |
| | | 12:00 | Lunch |
| 12:00 | Lunch | 1:00 | Continuation of optional evening hands-on CAD/CAM sessions at CDR, RPL. |
| 1:00 | SFF with engineering materials - Ceramics, Metals (Cooper,Kangsk) | | |

| | | | |
|---|---|---|---|
| 1:30 | Discussion | | |
| 1:45 | Mesoscale manufacturing (Leitgeb) | | |
| 2:15 | Discussion | | |
| 2:30 | RPL Tour | | |
| 3:15 | Design issues in layered manufacturing (Cutkosky) | | |
| 3:45 | Discussion | | |
| 4:00 | short break | | |
| 4:15 | Example: Design by composition with embedded components | | |
| 5:00 | Break for dinner | | |
| 6:30 | Optional evening hands-on CAD/CAM sessions at CDR, RPL For those who want to try the Software | | |

The latest information on the workshop can be found at [25].

### Technology transfer to ACR

Mold SDM Technology has matured this year to the point when qualified commercial firms can start trying it. Advanced Ceramics Research (ACR) is Tucson, AZ has set up an integrated Mold SDM machine, clone of the one available at the Rapid Prototyping Laboratory. The Control Architecture and Software that runs this machine is the same one developed by the laboratory team. ACR is in the process of incorporating Unigraphics to its design practice to be able to deploy the process planning tools developed at the RPL in the near future.

### U. Maryland - Drexel University Planned Collaboration

The University of Maryland team is planning to collaborate with researchers at Drexel University to get access to process characterization data to verify accuracy of predictions related to optimal orientation selection for parts generated by SFF processes.

### Stanford - U. Michigan Collaboration

Stanford University researchers will continue to collaborate with Prof. Debasish Dutta and the CAD/CAM group at U. Michigan for the development of a unified representation, process planning and fabrication infrastructure for heterogeneous parts.

### Stanford - Georgia Tech Collaboration

Prototype parts and inspection algorithms were exchanged with Prof. Tom Kurfess in the Dept. of Mechanical Engineering.

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