A Design Interface for 3D Manufacturing

and

A Manufacturing Interface for 3D Design

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Overview

An Internet-based infrastructure is being developed under two NSF contracts to provide designers with access to multiple layered-manufacturing services. These contracts are entitled "Design Interface for 3D Manufacturing" and "Manufacturing Interface for 3D Design" in order to stress the symmetry of the design/manufacturing interface. The projects focus on layered manufacturing techniques such as the Solid Freeform Fabrication (SFF) and Micro-Electro-Mechanical Systems (MEMS) processes. The design domain being addressed is that of small mechanisms or electromechanical assemblies that could be used in robots or other mechatronic devices. The approach presented relies on the formalization of the data exchange interface between designers and manufacturers. The primary operatives in this system are Design Clients, Manufacturing Services, and Process Brokers. The Design Client allows designers to submit completed designs for algorithmic decomposition, or alternately, to compose a design from primitives and library components that have been primed with some process-related information. During the first year, the Manufacturing Service developed a highly automated machine that can be used to build ceramic parts, and the associated software components for design decomposition, process planning and machine control. Progress is also reported on the collaborative use of MEMS processes that can be used to scale part geometry down to the mesoscopic range. An important new development has also been initiated with Georgia Tech to develop metrology for assuring the quality of small manufactured components. In later phases of the two main contracts, multiple service providers will be made accessible. The Process Broker implements a number of supporting services including process selection and optimal part orientation. Future broker services will include manufacturability analysis, directory services, and accreditation. Currently, the interface is being built and evaluated internally at Stanford and CMU. It will be made available for use by other selected universities in the near future.

Process Broker Functions and Services

The heart of the design/manufacturing interface is the process broker that acts as an intermediary between the design and manufacturing components, as shown in Figure 1. A fundamental goal of this infrastructure is to reduce the process-specific knowledge that individual designers need to possess. In keeping with that spirit, it is assumed that designers typically do not approach the system with knowledge of available manufacturing services, or the capabilities, turn-around time, or cost of specific services. The process broker assists the designer in discovering these facts as they become essential to the progress of the design.

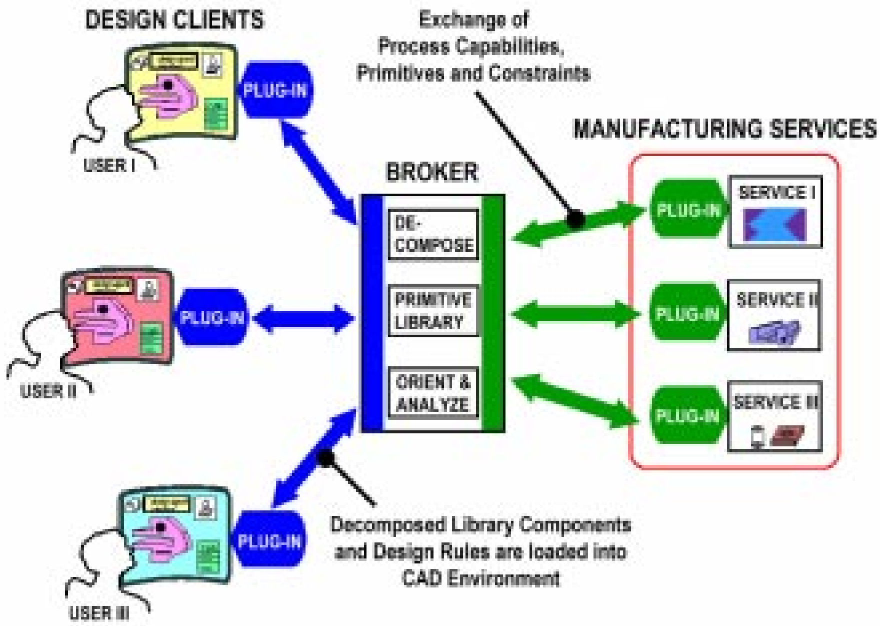

Figure 1. Design Interface for Rapid Prototyping. The designer uses "client" software that provides a plug-in for commercial CAD programs and communicates with a Broker to locate and select manufacturing services and with Manufacturing Service providers to submit designs and obtain manufacturability rules.

Two important broker functions are at an advanced stage of implementation [Rajagopalan *et al* 1998]. The first is a module for process selection, which includes consideration of materials handled, geometry required, and manufacturing lead-time/cost. The second is an analysis module for determining the optimal, or near-optimal orientation for building a part. Part orientation has important cost implications and greatly affects the build time and the part quality. This service is seen as an "interface" service mainly because the criteria that determine optimal orientation tend to be somewhat process specific.

Other services are being developed, including directory services, accreditation, and manufacturability analysis [Tan *et al* 1998]. It should be pointed out that the broker described here does more than just "brokering" in the traditional sense. It assists the designer in building a part by providing pointers to a suite of services as and when they become appropriate for the design. The broker could either directly provide these services, or could provide links to other software that implements them. Typically, the broker addresses those concerns that cannot be cleanly abstracted into either the design client side or the manufacturing service side.

The Design Client

The CAD system that the designer uses to design the part slated for layered manufacture is enhanced with several features which assist in making appropriate decisions during the design process. The designer has a couple of options - design the part independent of process related concerns embodied in the program (experienced designers who understand the process well may choose to do this), or alternately, accept and remain faithful to some design rules and constraints. The second alternative forces the designer to adhere to a design style that he/she may be unfamiliar with, but results in a design that is likely to be fabricated easily [Binnard and Cutkosky 1998]. Regardless of the mode of operation the designer chooses, the enhanced CAD program has routines that step in at the appropriate level to assist the designer with fabricating the part. The two alternatives include 1) a method for decomposing the design into simpler entities (layers or "compacts") or 2) a method for composing a design from primitives and library components (Figure 2).

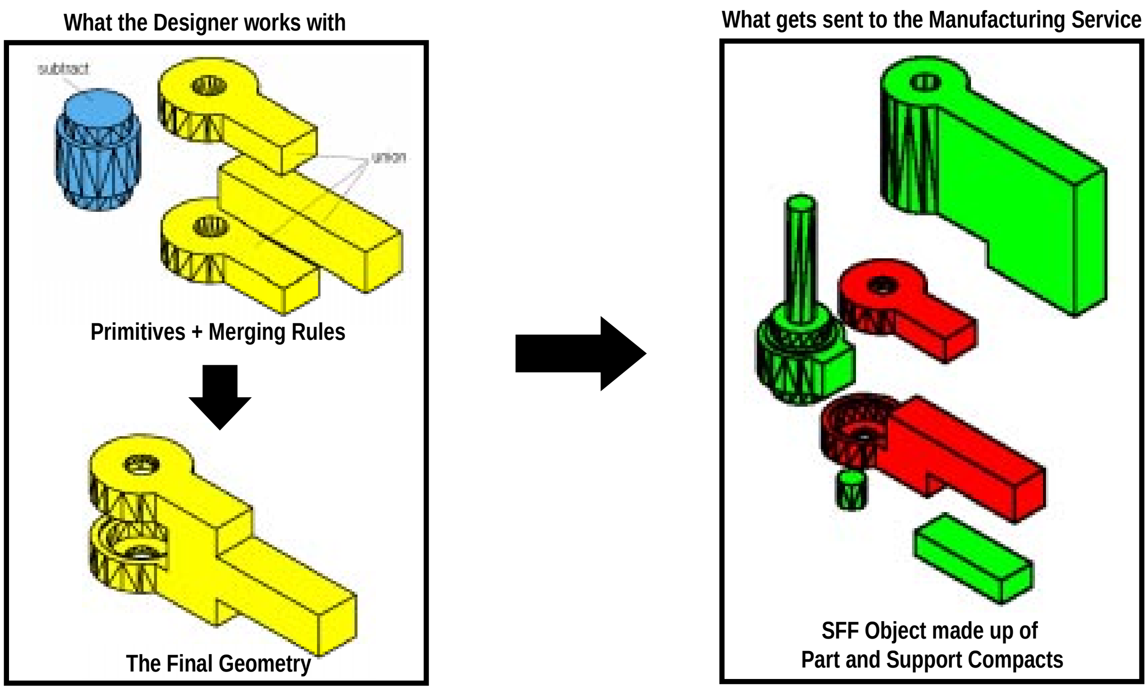

Figure 2. A designer can compose electromechanical devices from a library of components and simple shapes, with built-in manufacturing rules. A composition algorithm described in [Binnard and Cutkosky 1998] has been implemented as a plug-in for AutoCAD.

The system (currently implemented for AutoCAD) operates with the assistance of two types of plug-in software modules: the generic module and the process-specific modules. These modules are implemented in the form of Dynamic Link Libraries (DLLs) that are loaded at run-time into the CAD program, and customize the CAD environment to provide the added functionality. The generic module implements all the software functionality that is not process specific (i.e. communication/messaging, broker interaction, downloading additional modules, uploading finished/semi-finished designs etc.). This plug-in is built on top of the Java Agent Template (JAT) infrastructure developed at Stanford [JAT], and uses its routing/name-serving and message queuing functionality.

The designer will typically obtain the generic plug-in by downloading it from the project web-site. Alternately, the plug-in could ship directly to the designer with the CAD package or associated software. Once the generic plug-in is loaded up and invoked, it assists the designer in contacting a process broker over the web and choosing a manufacturing process that is appropriate for the intended design.

Shape Deposition Manufacturing and Mold SDM

Shape Deposition Manufacturing (SDM) is a layered manufacturing process involving an iterative combination of material addition and material removal [Merz *et al.* 1994]. A wide range of materials is available, including metals, polymers, and gel-cast ceramics. These materials are deposited using a variety of deposition processes. Material removal is accomplished with three-axis milling, five-axis milling, or EDM. SDM requires a part material and a sacrificial support material. The final object is made of part material. The sacrificial support material is used to support overhanging features while the object is being built, and is removed when the object is complete. SDM has been used to make metal and polymer parts through direct material deposition and shaping.

A variant process called "Mold SDM" uses SDM to build molds for casting resins and ceramics [Kietzman *et al.*1997]. In Mold SDM, a layered mold is fabricated. When the mold is complete, the support material is either dissolved or melted, leaving the mold. After casting, the mold is dissolved or melted, leaving the molded object. Postprocessing operations, including sprue removal, binder removal, or sintering can be subsequently performed on the object. Figure 3 shows the steps required for the construction of simple parts processed by SDM and Mold SDM. Both polymer and green ceramic parts have been cast using polymer molds and the Mold SDM approach.

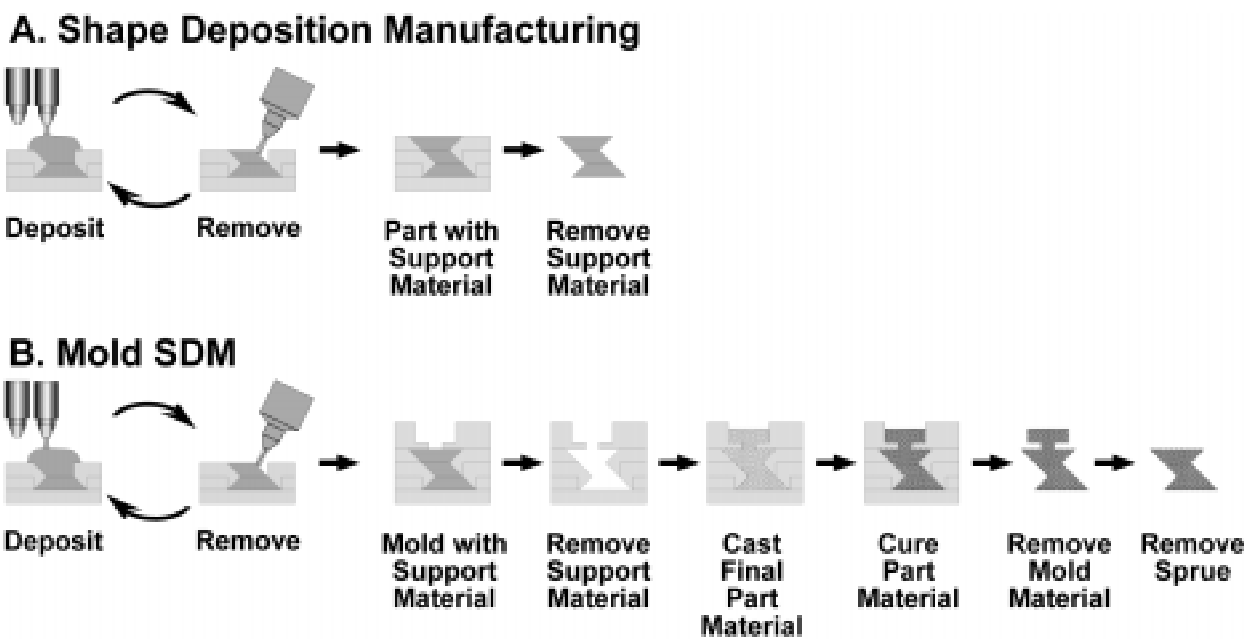

Figure 3. SDM and Mold SDM Processes

To improve the rate of production and the quality of parts made by Mold SDM, an automated mold-making machine has been built. The machine, shown in Figure 4, is based on a commercially available Haas VF-0E 3-axis CNC milling machine. The mill was modified by the addition of material deposition and curing hardware. Ultimately one could produce either complete Mold SDM machines or retrofit kits that could be installed on existing CNC machines.

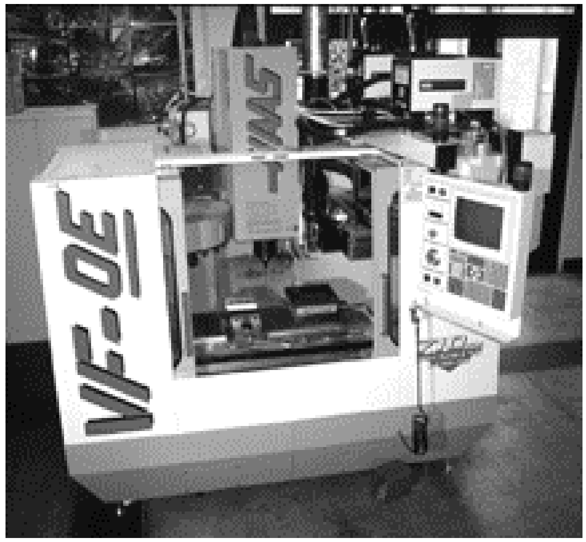

Figure 4. Automated Mold SDM machine

Figure 5 shows the main components of the Mold SDM machine. The CNC mill's machining functionality is used to perform all shaping operations. The add-on equipment together with the mill's positioning capabilities performs material deposition and curing. Mold material is dispensed from the wax melt units and allowed to solidify; support material is dispensed from the soldermask tank and then cured under ultraviolet light. Milling cutters are used to shape both mold and support material, resulting in the automated construction of wax molds. The support material is chemically removed from the molds, and final parts are manually cast into these molds. Figure 6 and Figure 7 show example parts made with the Mold SDM process.

The Solid Freeform Fabrication (SFF) technologies used in Stanford's Rapid Prototyping Lab (RPL) allow the manufacturing of macroscopic (feature size >1mm) parts out of metallic, polymeric, and ceramic parts. The idea behind the collaboration between the RPL and the Stanford Nanofabrication Facility (SNF) is to extend the feasible part sizes by two orders of magnitude into the mesoscopic range (feature size >10μm).

By using the existing facilities at the SNF, silicon can easily be shaped with sufficient geometric precision for mesoscopic parts. The plasma etchers available at the SNF also deliver etch rates high enough (250 μm per hour) to get a reasonable throughput of deeply etched silicon wafers (etch depth between 20 and 500 μm) which are necessary for mesoscopic structures.

Figure 5. Automated Mold SDM machine schematic.

Figure 6. Ceramic turbines

Figure 7. Polyurethane pitch shafts

Adoption of MEMS for Scaling to Mesoscopic Dimensions

Although, in some respects silicon has excellent mechanical properties (high strength and stiffness at low density), it is not well suited for many applications: its fracture toughness is very low and it has low electrical conductivity and magnetic permeability. Furthermore, its high temperature properties are rather poor compared to some metals and ceramics. Thus, techniques have been developed for using silicon in conjunction with the SFF processes to shape a rich variety of materials.

The development of a meso-motor has been chosen as benchmark for these newly developed techniques. In order to take advantage of lithographic pattern transfer techniques, all processing steps rely on micro-machined silicon. The silicon is first patterned by optical lithography and then etched in a conventional plasma etcher. Then, depending on the final part material, the following steps are undertaken:

1) For metallic materials that can be electroplated, a thin seed layer of the desired material (e.g. copper) is sputtered onto the shaped silicon wafer. The coated wafer is then put into an appropriate plating bath and the final part material is electroplated into the silicon mold. After plating, the silicon is etched away with potassium hydroxide, an etchant which does not attack most metals.

2) For metallic materials which cannot be plated easily, an additional processing step is necessary: A negative of the final shape is fabricated out of copper as described above. This negative is then used as electrode for electro-discharge machining (EDM), which can shape any conductive material.

3) To obtain ceramic parts, a mold is built up, either out of silicon or out of plated copper. This mold is then filled with a slurry containing ceramic powder and a liquid monomer. After casting, the monomer is cured and the slurry solidifies. The mold is then etched away and the resulting ceramic green part can be sintered.

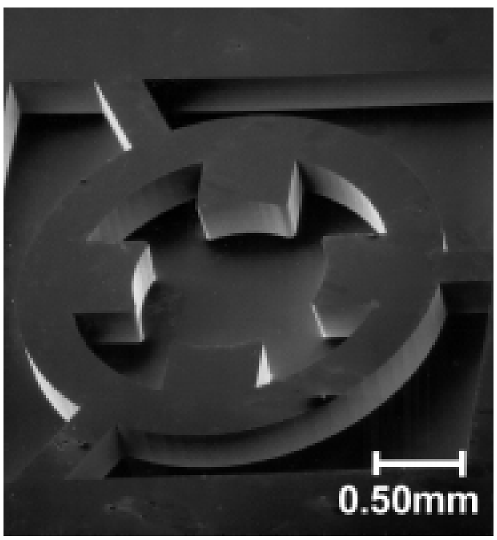

Figure 8. Silicon mold

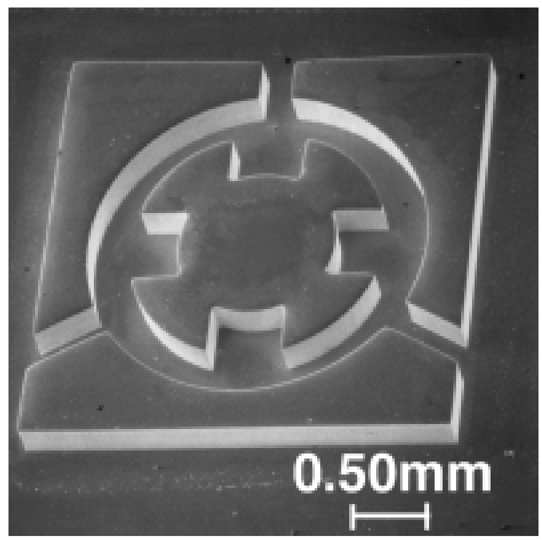

Figure 9. Copper electrode

A typical process sequence for producing a micro-shaped sheet of amorphous metal is the following: First, a silicon wafer is etched to make a mold (Figure 8). Copper is then plated into this silicon mold. After etching away the silicon, the copper electrode is obtained (Figure 9). This electrode is then used to shape amorphous metal (Figure 10).

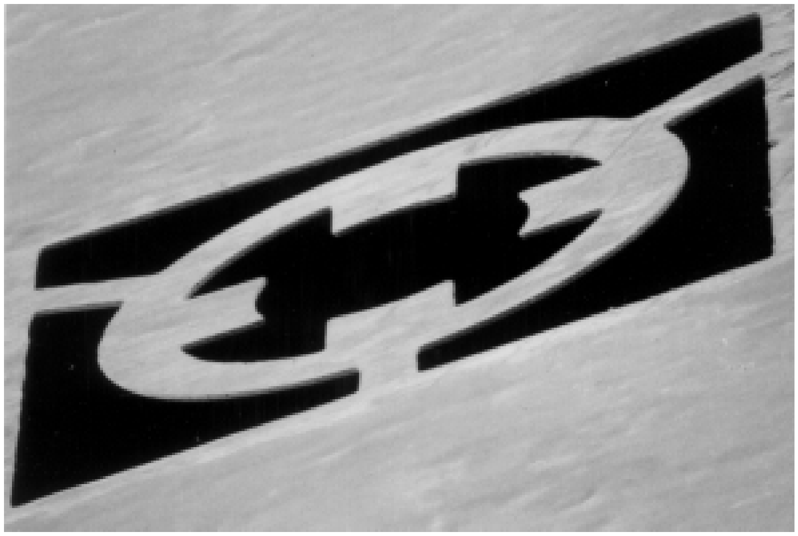

Figure 10. Amorphous metal stator ring

For designing lithographic masks for MEMS devices several commercial software packages are available. But since none of these packages are compatible with the CAD software used for SFF (especially SDM), a software interface between MEMS and SFF has been established. The software interfaces slices parts, which have been designed using conventional CAD packages, into appropriate layers and translates this layer information into files used for generating photo masks.

Quality Assurance in Remote Manufacturing

A collaborative task has been undertaken with Georgia Tech to develop metrology to assure quality in small parts that are manufactured by remote services. In particular, parts manufactured by SFF or MEMS processes may have internal structure which cannot be measured in conventional ways. Furthermore, the separation of the designer and the manufacturer introduces additional labor costs if the manufacturer must develop unique quality tests for each part. Therefore, the objective of this task is to develop metrology, which measures the quality of the manufacturing process independent of the individual part being manufactured.

The mold SDM process described above was selected to help develop the metrology methodology. Sample ceramic parts in the "green" state were provided to Georgia Tech with the intent of measuring these parts before and after sintering to determine shrinkage. It is intended that Georgia Tech will use the manufacturing interface to develop standard test structures which can be manufactured at the same time as custom parts and measured to independently determine the quality of the process.

References

[JAT] The Java Agent Template http://java.stanford.edu

"Tolerance Representation for Mechanism Assemblies in Layered Manufacturing", Rajagopalan, S. and Cutkosky, M. R., proceedings of the 1998 ASME DETC/DFM Conference, Atlanta, GA, Sept 13-16, 1998.

"Integrated Design and Rapid Manufacturing over the Internet", Rajagopalan, S., Pinilla, J.M., Losleben, P., Tian, Q. and Gupta, S.K., proceedings of the 1998 ASME DETC/CIE Conference, Atlanta, GA, Sept 13-16, 1998.

"Building Block Design for Layered Shape Manufacturing", Binnard, M., and Cutkosky, M.R., proceedings of the 1998 ASME DETC/DFM Conference, Atlanta, GA, Sept 13-16, 1998.

"Tradewind: A Prototype Internet Marketplace for Solid Freeform Fabrication", Tan, S., Rothkopf, A., Pinilla, J.M., proceedings of the 1998 ASME DETC/CIE Conference, Atlanta, GA, Sept 13-16, 1998.

"Shape Deposition Manufacturing," R. Merz, F.B. Prinz, K. Ramaswami, M. Terk, L.E. Weiss, Proceedings of the Solid Freeform Fabrication Symposium, The University of Texas at Austin, August 8-10, 1994, pp. 1-8.

“Layered Manufacturing Material Issues for SDM of Polymers and Ceramics,” J. W. Kietzman, A. G. Cooper, L. E. Weiss, L. Schultz, J. L. Lombardi, F. B. Prinz, Proceedings of the 1997 Solid Freeform Fabrication Symposium, The University of Texas at Austin, Austin, Texas, August 1997.