

PROJECT DESCRIPTION

A Manufacturing Interface for 3D Design

M. R. Cutkosky, P. Losleben, R. Merz, F.B. Prinz
Stanford University

G. Fedder, S. Finger, L.E. Weiss
Carnegie Mellon University

1. Vision

Invention occurs when creative people have access to technology. We propose to provide researchers and educators with easy, affordable access to a range of rapid manufacturing technologies. We propose to create a common interface to Shape Deposition Manufacturing (SDM) and Micro Electro Mechanical Systems (MEMS). By creating the SDM And MEMS Unified Exchange Language (SAMUEL) service, we will give users access to a spectrum of material deposition and material removal capabilities. Our long term goal is to provide researchers and educators with the ability to fabricate multi-material, electro-mechanical artifacts that have features as small as 100 nanometers and as large as 100 millimeters.

Our hypothesis is that formalizing the manufacturing process constraints and providing proven design libraries will enable designers unfamiliar with the details of fabrication processes to explore innovative ideas and novel artifacts. Formalizing the interface between designers and the fabrication facility will help in decomposing and separating the presently highly coupled design and manufacturing domains. SDM belongs to the class of Solid Freeform Fabrication (SFF) processes that decompose 3D objects into planar layers. Geometric decomposition facilitates the formalization of manufacturing constraints as design rules for SDM and MEMS devices. While this proposal focuses on providing access to a manufacturing testbed, we are submitting a companion proposal that focusses on the design interface. We believe that tight communication between these two research thrusts is essential to the successful creation of a distributed design and fabrication network for rapid manufacturing.

The creation of the SAMUEL service will leverage the facilities that already exist at Stanford and Carnegie Mellon. With the existing facilities, materials ranging from metals to ceramics and plastics can be deposited selectively to create multi-material 3-dimensional structures. The material processing capabilities also include established fabrication processes common in VLSI and MEMS manufacturing, such as sputtering, reactive sputtering, and chemical vapor deposition. The combination of these processes has already enabled the creation of novel components such as multi-material tooling with complex cooling channels for injection molding, embedded electronic structures for wearable computers, and integrated multi-component mechanical assemblies with temperature sensors and strain gauges.

Incorporating SDM and MEMS in a testbed facility will not only enable the user community to manufacture new classes of artifacts, it will also enable us to test our services on a rich set technologies that form a superset of the capabilities of existing layered manufacturing technologies. That is, constraints on other layered manufacturing processes reduce to special cases of these two. So rather than fine tuning our network for a particular process, our goal is to create a network service that encompasses as many layered prototyping processes as possible.

We also believe that the network services must be developed through a process of experimentation and reflection. To date, the providers and users SFF technologies have formed a small community. The advantage of a small community is that informal communication is fast and easy. Over the last few years, by building parts for ourselves and our colleagues, we have learned a great deal about our unstated assumptions and the capabilities of our SFF processes. It is now time to reflect — and to generalize and formalize this learning in order to expand the community that has access to these technologies. In particular, by expanding the educational use of SFF technologies, we hope to create excitement and innovation in the classroom, much as the original MOS Implementation Service (MOSIS).

Stanford and Carnegie Mellon are already participating in collaborative projects with other universities. For example, through a DARPA-funded project called ACORN (Advanced Collaborative Open Resource Network) we have established a network of services that can extend the manufacturing capabilities of the SAMUEL service. We have already received preliminary proposals from colleagues at other universities to use the proposed SAMUEL service.

Successful dissemination of research and teaching depends to a significant extent on the way it is managed and on the prior experience of our team in creating such facilities. Our management structure is based on the successful Stanford MEMS fabrication service that is similar in spirit but which is aimed only at the creation of micro and nano structures.

2. Background

To create the SAMUEL service, we will address two important differences between the infrastructure that was needed to make VLSI technology and the infrastructure that is needed now — that is, the level of maturity and the diversity of technologies available. As reported for the “New Paradigms for Manufacturing Workshop” (Mukherjee and Hilibrand, 1994), the rapid prototyping technologies are not as mature as the VLSI technologies were. The facility that provided access to VLSI technology was the beneficiary of decades of development. Production sources for VLSI technology were well established and a substantial demand existed for access to the technology as a result of the VLSI design crisis of the late 1970s. The time was right for a revolution in VLSI design and the infrastructure was an important enabling component of the rapid expansion of design throughout the following decade.

In 1979, Carver Mead (Mead, 1980) produced a compelling argument, based on increasing the opportunity for innovation, for the adoption of a standard interface to fabrication facilities. He used an S-curve to illustrate how the semiconductor industry had reached a capital intensive, production stage of maturity while design was still in the early entrepreneurial stage. He argued that access to semiconductor technology through standard interfaces was needed to enable rapid development of design methodology. In contrast to the relatively mature state of the semiconductor industry in 1979, layered manufacturing technologies are fairly low on the S-curve as shown by the shaded area in Figure 1.

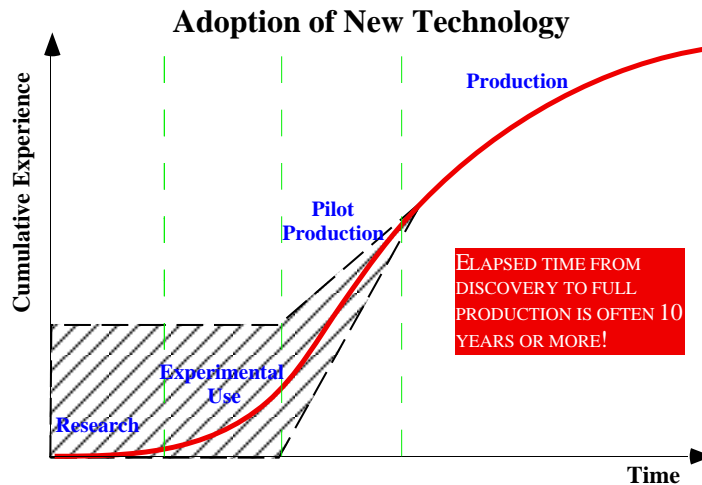


Figure 1. Maturity of MEMS and SDM Technologies.

The second important difference is the wide range of layered manufacturing processes that are available or being developed. Through the SAMUEL service, we propose to address two layered manufacturing processes: SDM and MEMS. In this proposal, we address both the immaturity and diversity of layered manufacturing processes in a unified strategy to provide access to technology.

3. Issues to be Addressed

3.1 Providing Fabrication Services

The challenge of developing new fabrication methods is to balance the need to advance processes that are still emerging with the need to produce parts for the user community. Process development cannot be done without understanding the needs of the design community, and the design community cannot push the design envelope without access to novel processes. The goal of this proposal is to give the design community an interface to layered manufacturing processes. The majority of the processes offered are at a state of maturity that is insufficient for routine industrial use but is adequate for the fabrication of functional parts and prototypes. Greater exposure to designers will also accelerate the transition of these processes to industry.

3.2 Formalizing Processes to Build a Manufacturing Interface

Layered manufacturing processes facilitate the creation of a clean interface between design and manufacturing. Dimensional reduction of 3D models into layers allows for a more rigorous formalization of constraints in comparison to traditional processes. However, we are still in the early stages of formalizing SFF process constraints and expressing them as rules that can be automatically invoked during design. By creating a common manufacturing interface for SDM and MEMS, we believe that we will advance the state of the art for all layered processes.

3.3 Adopting SDM Planning Tools for MEMS

We hypothesize that spatial decomposition in layers as practiced in SDM can facilitate planning for MEMS processing. Evolving from VLSI processes, MEMS fabrication and planning uses the same tools as VLSI. Hence, the mechanical elements in most MEMS artifacts are designed using circuit design tools. By expanding the tool set to include the designing and planning tools for SDM, we will expand the capabilities of MEMS. We propose to use the same representational framework and planning tools that are developed for SDM for the fabrication of MEMS devices.

3.4 Building a User Community

We intend to build a user community for the SAMUEL service by soliciting proposals and working interactively with the design community in order to meet designers' needs while advancing the capabilities of the service. In a first round, we identified a number of proposals for fabrication by our service. Initially we anticipate that a close interaction with the design community will be required. Ultimately the formalization of the fabrication processes will enable a largely electronic communication between designers and the fabrication facilities.

4. Services to be Provided

To create the SAMUEL service for designers and to develop process descriptions and design rules, we propose to add the SDM processes, implemented at Stanford and Carnegie Mellon, to the MEMS processes already supported separately at the Stanford Nanofabrication Facility (SNF). The combination of these two classes of layered processes offers a unique opportunity to stimulate sharing of design methodologies and utilization of unique combinations of the processes in innovative new applications. The SAMUEL service will demonstrate the successful implementation of a common interface between design and fabrication for MEMS and SDM.

4.1 SDM Methodology Overview

The SDM methodology (Merz et al., 1994) combines the advantages of SFF (i.e., relative ease of planning, complex shapes, heterogeneous structures) with the benefits of more traditional material removal processes, such as the precision of CNC machining, and the high quality of material deposition processes, such as welding. SDM uses a flexible Computer Aided Manufacturing (CAM) implementation to integrate various material addition technologies with material removal

processes (Figure 2) to build high-performance, fully dense, heterogeneous (multi-material) structures.

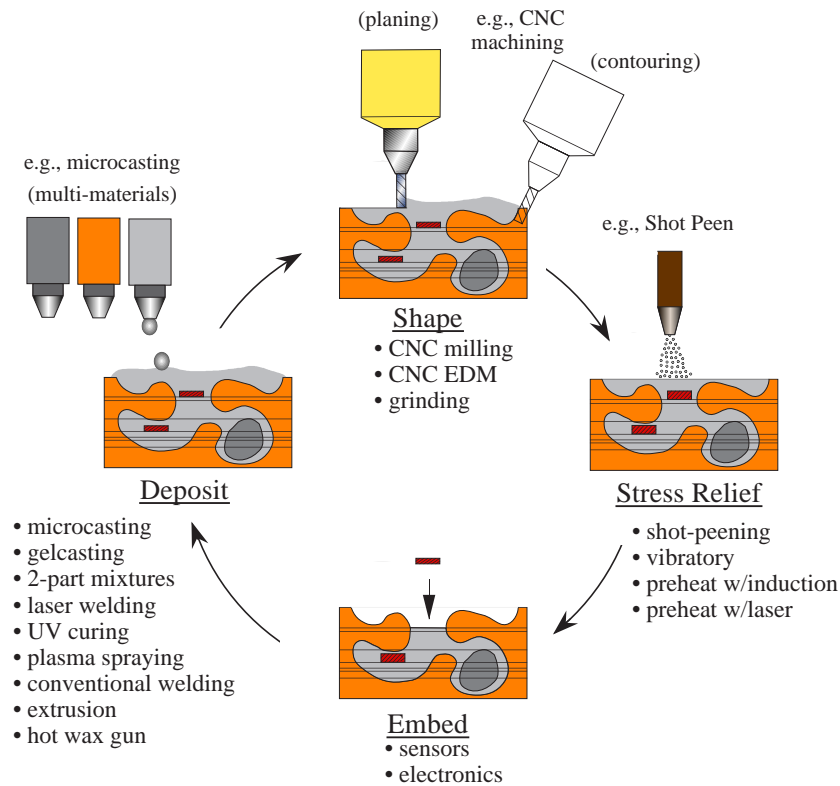


Figure 2 Shape Deposition Manufacturing

The planning strategy for the majority of SFF processes is to decompose the 3D Computer Aided Design (CAD) model into thin $2\frac{1}{2}$ D cross-sectional layers. The object is fabricated by adding material to build each cross-section. In contrast, SDM uses 3D layers. The layers are deposited as near-net shapes that are then machined to net-shape before depositing additional material. Sacrificial support material sections are built up simultaneously to provide fixturing for the object. Other intermediate processing operations, such as stress-control and inspection, can be added to the SDM cycle as required. Embedding is another operation that can take place within the SDM cycle. Discrete components can be placed on the current upper surface before subsequent deposition takes place. After deposition, the component becomes permanently embedded within the structure.

The basic building blocks of SDM are called *compacts*, which are segments that maintain the 3D geometric information of the outer surface of the object (Merz, 1994). The SDM process planning strategy decomposes the CAD model into compacts, such that:

- undercut surfaces are not directly machined, but formed by previously deposited and shaped compacts, and
- each compact is composed of a single material.

Figure 3 shows the sequence for depositing and shaping the compacts and embedding a component in a layer of a heterogeneous (i.e., multi-materials, embedded components) structure.

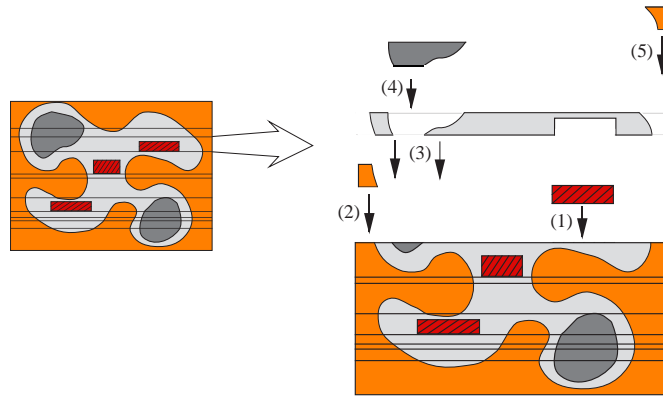


Figure 3. Shape decomposition

The deposition sources currently available for SDM include microcasting (deposition of discrete droplets of super-heated molten metal), laser cladding (surface deposition welding of powdered materials), conventional welding (high-rate metal deposition), thermal and plasma spraying (spray deposition of molten metals, plastics and ceramics), gelcasting (deposition and curing of ceramic and metal powders mixed in monomer binders), two-component deposition (dispensing of resin/activator mixtures of epoxies or polyurethanes), UV-curing (dispensing and curing of photosensitive polymers) and thermal extrusion (deposition of thermoplastics, waxes or adhesives).

4.2 MEMS Overview

MEMS technology is a general approach for the creation of miniature electro-mechanical components that leverages traditional semiconductor manufacturing. VLSI-based batch-fabrication methods can produce complex systems of sensors and actuators that couple physical effects from mechanical, electrostatic, magnetic, thermal, fluidic, and optical domains. Applications include a variety of sensors (e.g., inertial, pressure, infrared, flow), optical communications and displays, atomic data storage, and chemical analysis systems.

MEMS is not associated with one particular process, but rather encompasses a rich variety of process flows. Devices are fabricated by a sequence of conventional VLSI unit processes, such as oxidation, diffusion, photolithography, etching, sputtering, and chemical vapor deposition (CVD). Augmenting these are new processes developed specially for MEMS, such as wafer bonding, deep reactive-ion etching, double-sided alignment, and critical point drying.

As with VLSI fabrication, most MEMS processes are composed of repetitive cycles of material addition, 2D pattern definition, and material subtraction (e.g., deposition, photolithography, etching). Each cycle represents a new layer; however, unlike SDM, layers usually are not planed flat after each cycle.

Micromechanical processes historically have been split into two general categories: bulk micromachining and surface micromachining. Bulk micromachining involves the creation of microstructures by etching the starting substrate bulk material, which is usually silicon. Anisotropic silicon wet etching and silicon wafer bonding may be used to form cantilevers, through-holes, v-grooves, diaphragms, cavities, and channels.

Surface micromachined structures are created from materials deposited on the substrate surface. One of the most common processes is polysilicon surface micromachining, in which microstructures are made from thin-film CVD polycrystalline silicon that is deposited over a sacrificial phosphosilicate glass (PSG) layer. The microstructures are released from the surface by wet etching the underlying PSG. Several recent processes integrate aspects of both surface and bulk micromachining, thereby blurring the distinction between the two. Thin-film microstructures

made of oxide and aluminum may be released by etching the bulk silicon beneath the structures. These microstructures are compatible with standard CMOS process services, like MOSIS.

Currently, there are no design-based building blocks for MEMS. We believe that MEMS can be divided into compacts following similar rules to those used in SDM. The fabrication facility may decompose the compacts into a viable sequence of process steps. Figure 4 shows the sequence for deposition, patterning, and etching of compacts to form a structure having both surface and bulk micromachined components.

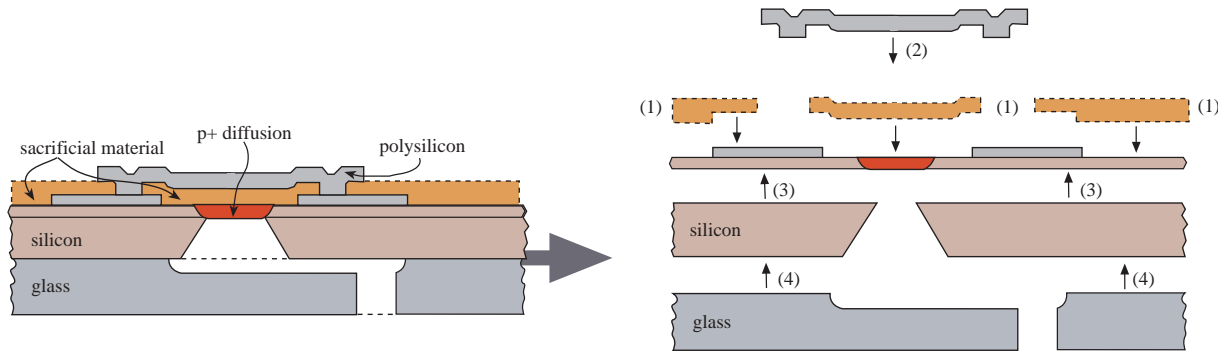


Figure 4. MEMS decomposition

4.3 Classes of SAMUEL Artifacts

The SAMUEL service will enable outside designers to learn new process capabilities and create designs to benchmark the capabilities of the design-manufacturing interface. We have received several proposals from potential outside users for part fabrication. These proposals include a next-generation turning tool with internal cooling and sensors for hard turning applications from the Georgia Institute of Technology, the layered manufacturing of advanced propeller blades from the University of Michigan, and the fabrication of biomedical artifacts from the University of Washington. In this section, we describe several classes of artifacts that can be manufactured using the facilities that will become part of the SAMUEL service.

Artifact Class 1: Multi-Material Structures

One class of artifacts of increasing importance to industry are structures composed of multiple and graded materials. Regions of dissimilar materials with different properties can be used to achieve many levels of functional performance, while a continuously varying microstructure can be used for optimization. Practical examples for multi-material structures are industrial tools used for injection molding (Figure 5) or for fabrication of composites for forming vessel airfoils. Internal copper sections allow fast and uniform heat distribution and heating/cooling channels that conform to the die cavity can be formed in the interior. In addition, thermocouple sensors for process control can be embedded inside each structure.

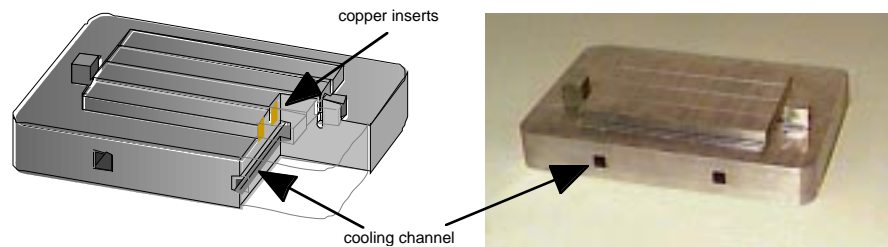


Figure 5. Next generation tool (Fessler et al., 1996)

Artifact Class 2: Mechanisms

The SAMUEL service will allow fabrication of “shape-assembled” mechanisms by using sacrificial support material as a buffer between components. During deposition, individual components (e.g., shafts, wheels, axles, sliders) are created simultaneously, divided and held in place by a support material that fills small spaces between them. When the building process is finished, support material is removed allowing individual parts to move freely. Figure 6 shows an example of a simple stainless steel crank/shaft/piston mechanism that was manufactured in one piece with the SDM process. Outside designers can use similar mechanisms not only to demonstrate the multi-material capabilities, but also to show the usefulness of design systems and rules for applications based on functional designs.

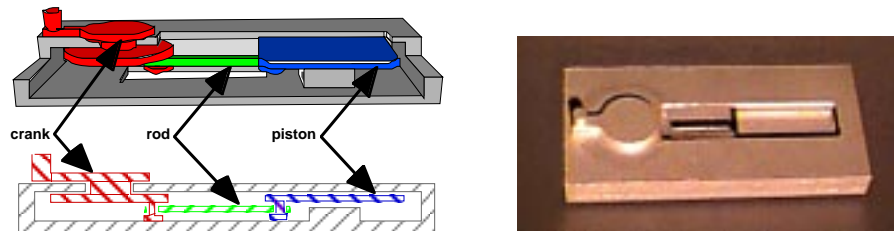


Figure 6. A simple ‘shape-assembled’ mechanism (Fessler et al., 1996)

Artifact Class 3: Integrated Electro-Mechanical Structure

Users of the SAMUEL service will also be able to fabricate combined electronic and mechanical structures. We have built conformable, wearable computers, like the VuMan-SDM (see Figure 7) and its waterproof version, the Frogman. These embedded electronic assemblies are built by depositing layers of two-component polyurethanes in a sacrificial wax support structure. A 3D circuit is built simultaneously from interconnected planar boards and embedded throughout the shape. Currently, design and fabrication of such artifacts are done manually, requiring detailed process knowledge. Many iterations are necessary for simultaneous electronic and mechanical design. In the future, designers will be able to use SAMUEL facilities for concurrent electronic and mechanical design to manufacture an embedded electro-mechanical device.



a. CAD model of VuMan-SDM

b. VuMan-SDM

Figure 7. Embedded electronic assemblies (Weiss et al., 1996)

Artifact Class 4: Integration of MEMS and SDM Technologies

With MEMS technology currently, it is not feasible to fabricate enclosed volumes of arbitrary shape and composition without the use of microassembly. The areas of main interest in the MEMS community are microfluidics, micropneumatics, and micromechanics. Devices in these

areas, such as micro-valves (Figure 8), gear boxes, pumps, or chemical reaction chambers, require enclosed, arbitrarily shaped, highly accurate, three dimensional volumes and, currently, the use of standard IC fabrication materials. SFF capabilities will be greatly advanced by the ability to fabricate these integrated electro-mechanical devices. A common interface will also allow a combination of both fabrication technologies, resulting in the integration (embedding) of MEMS into macroscopic structures.

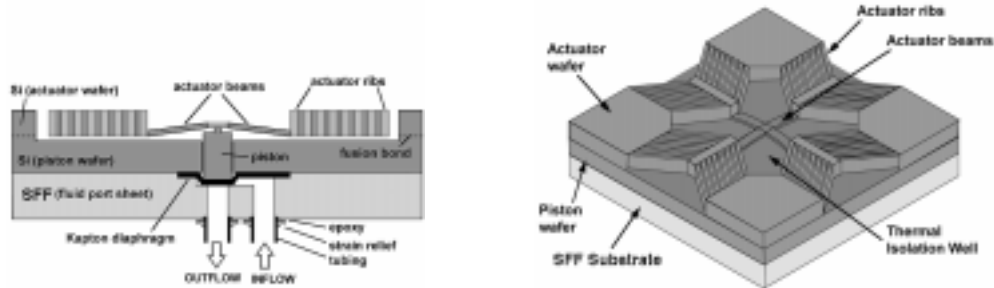


Figure 8. MEMS Micro Valve

5. Formalization of Manufacturing Constraints and Design Rules

Layered manufacturing processes like SDM and MEMS both expand the range of what is manufacturable and make it easier to automate the evaluation of manufacturability. The characteristics that make these processes amenable to formalization are:

1. Parts are manufactured out of thin *layers with relatively simple geometry*, for which it is comparatively easy to specify constraints (e.g., minimum radius of curvature) and capabilities (e.g., achievable tolerances).
2. For each layer, *manufacturability depends primarily on local geometry, material, and accuracy requirements*. In other words, layered processes localize geometric interactions and thereby avoid the combinatorics associated with global feature interactions, a well-known source of difficulty in automated CNC machining (Gupta and Nau, 1995), robotic assembly (Wilson and Latombe, 1994) and similar processes.
3. Layered processes also *remove traditional manufacturing constraints*, for example, fixturing requirements and tool access planning, which are major barriers to automatic process planning and manufacturability analysis.

These characteristics are also found in VLSI processes and underlie the success of scaleable design rules in MOSIS. We believe that similar formalization will be possible for SDM, MEMS, and other processes that have these three characteristics.

5.1 Decomposed Features

Although layered manufacturing processes are amenable to formalization, little progress has occurred because the processes have only recently passed their infancy. The present mode of communication between designers and fabricators is depicted in Figure 9. Manufacturers typically are concerned with detailed process constraints while designers want to create and express designs governed by (hopefully simple) rules which assure manufacturability. Currently, this difference must be worked out through direct human communication.

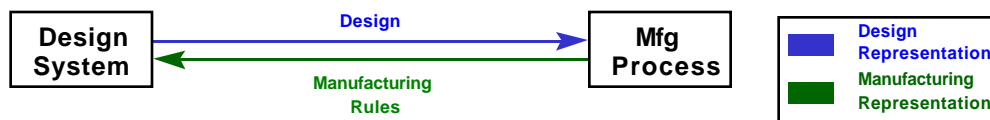


Figure 9. Existing communication between design and manufacturing. Manufacturers express process constraints about individual layers; designers model parts as 3D solids.

Our solution is to represent process-related constraints and characteristics based on “decomposed features,” that is, simple geometric elements that map straightforwardly to how parts are built with layered processes. The idea is that decomposed features describe geometry at a level for which manufacturability can be ascertained unambiguously and for which process planning can be automated. We restrict our attention to processes like SDM and MEMS for which a judicious choice of decomposed features will eliminate global feature interactions.

While most currently available SFF processes use uniform $2\frac{1}{2}$ D layers, SDM uses 3D layers. Therefore, a 3D representation of decomposed features is required for the general SFF class. For example, we are pursuing a description of decomposed features based on compacts. (See Section 4.1). Figure 10a illustrates a simple two-material part (or perhaps a horizontal slice of a larger part) with its support structure. Figure 10b illustrates the decomposition into compacts. Figure 10c shows the decomposition into a layered representation.

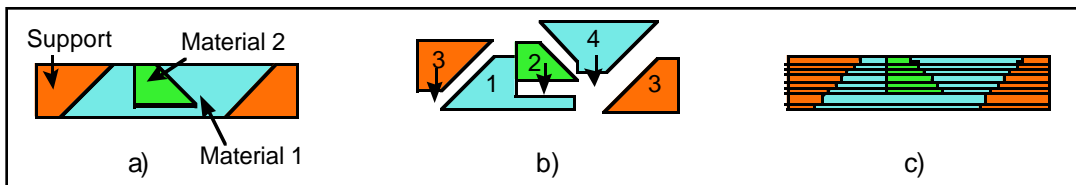


Figure 10. A two-material part embedded in support structure a) can be represented with compacts b) as decomposed features for SFF processes with 3D layers, or c) layers for processes with $2\frac{1}{2}$ D layers.

5.2 Process Constraints and Design Rules

Constraints can be specified for each of the compacts and on local combinations of compacts to ensure manufacturability. One of the motivations for combining SDM and MEMS in the SAMUEL service is to cover a broader range of process constraints. For example, in MEMS process constraints require a minimum overlap between layers because of photolithographic alignment tolerances. In SDM, this constraint has not arisen. Conversely, some process constraints in SDM are not relevant to MEMS.

The terms “rules” and “constraints” are sometimes used interchangeably; however, we make the following distinction. Processes are subject to *constraints* (e.g., “minimum horizontal feature size $\geq d$,” “available materials := {list}”). Process constraints are best provided and kept current by the developers of those processes. Designers, however, prefer design *rules* such that, if the design complies with those rules, the process constraints will not be violated. Examples of design rules are “Always make gaps $\geq d$ wide” (Figure 11a) and “Keep the aspect ratio ≤ 10 ” (Figure 11c).

While these rules represent manufacturing process constraints on design geometry, another mechanism is required to represent material selection constraints. Material selection is based on process capabilities, application requirements, and material compatibility. Rules reflecting these constraints are analogous to the electrical parameter rules for VLSI. Manufacturers must provide access through the interface to lists of available materials and compatibility information and tables with important mechanical, thermal and electrical properties (e.g., yield strength, thermal conductivity, resistivity, corrosion rates). In contrast to VLSI, material properties are not fixed *a priori*, but must be defined for each specific process. Furthermore, mechanical design requires more material variety between different parts produced with the same process.

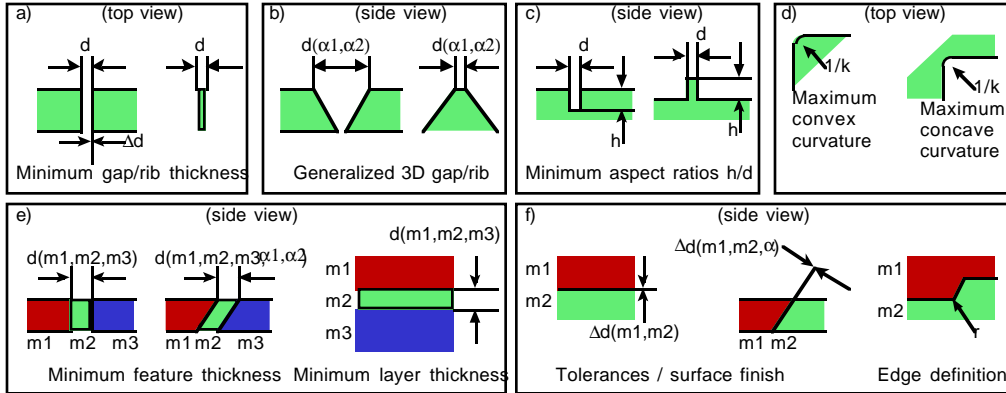


Figure 11. Design rules for SDM and MEMS.

In collaboration with the researchers working on the design interface, we propose to establish a set of manufacturing constraints based on decomposed features for SDM and MEMS technology. These manufacturing constraints must be compatible with the design rules so that process constraints from the manufacturing interface can easily be transformed into design rules at the design interface. We believe that decomposed, layered features provide this capability.

5.3 Development of a “Clean Interface”

The centerpiece of a clean separation between design and manufacturing is the development of a formal interface. This interface will be developed as part of the companion Stanford/Carnegie Mellon proposal on “A Design Interface for 3D Manufacturing.” In the present proposal we focus on the development of process constraints and rules that provide the necessary manufacturing knowledge to the interface. As shown in Figure 12, the interface allows the translation of manufacturing process constraints into simplified design rules for use by the design community, thereby allowing design and manufacturing engineers to communicate on their own terms.

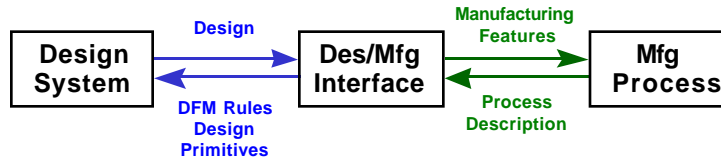


Figure 12. The interface lets designers and manufacturers use their preferred format.

The goal of the clean interface between design and manufacturing is to keep the structure of the design rules consistent across processes even though the sources of the process constraints may be quite different. For example, the value of d for SDM may depend on the cutter size and for MEMS it may depend on the photolithographic limits or etch directionality. However, in either case, the designer is presented with a rule about minimum feature dimensions. The rules are expressed in terms of decomposed features and are typically conservative to ensure manufacturability for a class of processes.

As discussed earlier, we will use decomposed features and associated design rules as the basis for the proposed interface. The important concept from the standpoint of the interface is that a description of a part in terms of decomposed features involves a dual commitment. On one side, the designer is responsible for verifying that the decomposed feature-based representation accurately captures his or her design intent; on the other side, the manufacturer must be able to evaluate manufacturability and manufacture the part if appropriate.

We envision three types of interactions between the interface and the designer. We will develop these interaction modules in close cooperation with the design groups. The design groups will be responsible for creating the interface and module structure, the fabrication groups for developing and providing the process knowledge in a format suitable for transfer from fabricators to the modules.

- **Decomposers** that convert design specifications into decomposed features that are acceptable to manufacturers¹. These are analogous to the software used to generate tooling (MEBES tapes) for VLSI manufacturing.
- **Process brokers** that help designers to select a process or process class and provide manufacturer-specific information to designers on request.
- **Manufacturability analyzers** that evaluate decomposed designs to provide feedback to the designer. These are analogous to the design rule checkers used by VLSI designers.

The level of interaction will vary, depending on the state of the design (early or detailed) and on whether the designer wants to optimize the design for a specific process or to evaluate it with respect to a broad class of processes. Brokers will be able to supply a list of feasible processes in response to general part requirements (e.g., size, material, tolerances) or provide specific design rules that can be loaded into a CAD system, thereby restricting design space to promote manufacturability. Libraries of design features, constructed from decomposed features, which can be synthesized to a manufacturable design will be made available, as well as feedback mechanisms to submit detailed designs for decomposition and subsequent analysis to identify problematic design elements.

Based on the representations that will be developed as part of the companion proposal and in cooperation with other fabrication and design sites, we will characterize and parameterize our process capabilities. This will include:

- Specifications of decomposed features and instructions for decomposer programs.
- Design rules on decomposed features for use by designers and manufacturability analysis tools.
- High level descriptions of process capabilities, including material properties, achievable accuracy and maximum part size expressed within the established framework.
- Libraries of design building blocks represented in terms of decomposed features.

6. Educational Objectives

Our primary educational objectives are to:

- provide students with educational activities of industrial relevance,
- enable undergraduate and graduate students to access advanced fabrication facilities for design and research projects,
- transfer research results into educational practice,
- broaden the dissemination of research results to industrial practice through our graduates, and

¹ This task is tantamount to automated feature extraction, a task that is acknowledged to be very difficult in the general case and may require some human input. In the case of layered processes, the decomposed features are sufficiently simple that automated decomposition appears feasible.

- create a new generation of engineers and scientists knowledgeable about layered manufacturing.

Therefore, in addition to educating graduate research assistants, we propose to expand involvement of undergraduate students in various aspects of this research project. To date, students in the Stanford design courses ME 113 (Undergraduate Design) and ME 210 (Graduate Design) and ME 217 (Design for Manufacturability) have had limited access to the SDM and MEMS facilities at Stanford. We plan to significantly expand access by creating new instructional material for the SAMUEL service and by building an infrastructure that enables 24 hour access to the laboratories. This will enable students to invent and realize design ideas within the typical time constraints of projects in the above courses.

During the last three years, Carnegie Mellon has created two inter-departmental, undergraduate courses that integrate research, education and practice — a course on wearable computer design (Amon et al., 1995; Finger et al., 1996) and a course on rapid prototyping (Finger, 1996). We also conducted an experiment in which graduate students at Carnegie Mellon took the Stanford ME 210 course over the Internet (Reddy, 1996). These courses are based on the belief that students learn best when they are active participants, gaining knowledge through guided experience. Reducing the barriers to access our layered manufacturing facilities has the potential to increase students' creative productivity. Teaching these courses requires the time and effort of many people. To reduce the burden of teaching experience-based courses, we propose to create modules that can be used not only by the members of our team, but also those at other universities. During the second and third year we plan to organize short courses for teachers who will be given hands on experience with the SAMUEL service.

7. Plan of Operation

As part of the SAMUEL service, MEMS services will be provided at no additional cost under the existing management structure of the NSF supported National Nanofabrication Users Network (NNUN). For SDM services, Stanford will be the lead site and will undertake the initial establishment of electronic network access and overall program management. SDM services will be added to SAMUEL beginning with Stanford and Carnegie Mellon. Subsequently, we will invite other SFF sites, including those developed under the ACORN project, to participate. Fritz Prinz will be the director of the Stanford site and will be responsible for overall management of this project. Lee Weiss will be the director of the Carnegie Mellon site. They will be assisted by Paul Losleben who is responsible for remote user access to the SNF and who has fifteen years experience in providing access to shared fabrication facilities including the early development of the MOSIS capability for VLSI. Robert Merz will be responsible for articulating process constraints.

For the development of the interface, we will take a more flexible approach than was used for VLSI technology. The interface specification will initially require close cooperation between the designer and the various fabrication facilities. As experience with the specification is gained, we expect remote access to increase. Consequently, initial operation of the facilities must accommodate both remote and at-site use. The SNF has trained staff and an established procedure for performing fabrication services for remote users. The SDM facilities at Stanford and Carnegie Mellon, by contrast, will initiate this class of service in this proposed project. We will build on the successful SNF experience of the past two years to guide the development of remote access for all facilities.

7.1 Building a Network of Facilities

It is critically important not to narrow the number of fabrication process options too early. To do so would be to miss potentially important new developments. Likewise, we must assure that whatever infrastructure is put in place to support fabrication can accommodate additional sites. Otherwise, overall progress will not scale to provide access to the resources and creative ideas of

the community at large. Our goal is to create an infrastructure that facilitates sharing of resources, not only at the research stage but throughout the maturing of a new technology. Ideally, we want to create an open market in which any site can share the cost of a facility by providing access to researchers, who otherwise could not afford a fabrication facility. The problem is to provide some practical means to direct new users to the most appropriate site while maintaining the autonomy and competitive rights of each site. We believe that we have put in place a system that meets these objectives.

The most knowledgeable advocate for any technology is the site that owns and maintains the equipment. Each site will maintain information on the World Wide Web about the specific equipment, processes, and expertise available at that site. On-line forms will allow potential users to request additional information or to submit a proposal. A key agreement between the participating sites in the NNUN, which we will extend to this project, provides shared information about new projects. Any site may compete for a new project by working with a user to prepare a proposal, but the final decision to fabricate a part is made by mutual agreement between the site and the user.

7.2 Selection of Projects

Each Site Director will be ultimately responsible for the efforts at his or her facility. Projects typically begin with a discussion with a site about the technical feasibility of a task prior to submitting a brief proposal. The Site Director and a small team of technical advisors review the proposal informally to assure that it is consistent with the site capabilities. Proposals from researchers at the fabrication sites, those from other academic institutions, and those from government and industrial facilities are treated equally. Proposals from for-profit organizations for services that are routinely available commercially are denied as a matter of policy. Proposals from non US institutions are evaluated on a case-by-case basis, with the goal of establishing relationships with reciprocity and mutual benefit. In all cases scientific merit is the basic criterion for acceptance or rejection of a project. We expect to approve the majority of proposals.

To promote efficient use of facilities and partially recover costs of operation, the member facilities will assess user fees. These fees are assessed by mechanisms that are consistent with federal, state, and local legal requirements, NSF guidelines, and university policies. Each site is responsible for developing a reasonable cost recovery algorithm that attracts users to the facility and allows the site to operate on a sound financial basis. The basic fee schedules are two-tiered: academic and non-academic. Academic rates apply uniformly to faculty, student, and postdoctoral users from academic institutions. Non-academic rates apply to federal labs, industrial and other for-profit sector users. In general, users of each facility are charged user fees that cover the incremental costs associated with their use of the facility.

7.3 Institutional and Industrial Support

At Stanford, over \$100K per year of industrial grant money is made available as small grants (approximately \$5K to \$10K) to cover laboratory costs for users of the SNF. We will extend this funding with an additional \$160K for users of the SDM facility (\$80K industrial grant funds plus \$80K identified in this proposal). The respective SNF and SDM teams will administer these funds with the advice of the industrial contributors.

Stanford has invested \$800K in the new SDM facility, which has already become a campus resource for a range of educational and research projects. Physical and virtual prototyping is a major theme at both Carnegie Mellon and Stanford that provides a stimulating intellectual environment reflected in ongoing and planned initiatives. Stanford recently announced a new tenure-track faculty billet in this area. Carnegie Mellon has just attracted S. K. Gupta to the Robotics Institute to explore new ideas related to feature recognition and process planning algorithms. The Engineering Schools at both organizations strongly promote multi-disciplinary research and project based learning, key ingredients in the present proposal.

8. Scientific and Industrial Outreach

The SDM testbeds have significant industrial exposure. The USAMP (U.S. Automotive Materials Partnership) consisting of GM, Ford, and Chrysler has chosen SDM as a candidate technology for fabrication of production quality tooling. General Motors has placed an engineer from its Rapid Prototyping Laboratory in Warren, Michigan at Stanford's Rapid Prototyping Laboratory to perform a Ph.D. exploring the use of SDM for a class of automotive dies. Other companies including Alcoa in Pittsburgh and UT Technologies in Los Angeles are helping to refine the SDM process for factory use. SDM is an emerging node on the ARPA-sponsored ACORN project that provides network based design and manufacturing services for applications such as fabrication of wearable computers. Two commercially available SFF processes are part of ACORN. Stereolithography is offered by ALCOA and Soligen is offering 'Metal Parts Now' using the MIT 3D printing process for producing ceramic shell molds for casting. We will make these services available through SAMUEL if they are needed for the artifacts selected.

9. Work Plan

The activities required to create the SAMUEL service fall in two major categories: a) formalization of process rules and constraints and b) fabrication services. Formalization of the interface will be tightly coupled with the efforts of the design groups during the early phases of the project. During the definition phases, decomposed features and process constraints will be proposed and reviewed with the design groups. Once the constraints for a given process are identified, we will develop constraint parameters through experimental efforts. After identifying the features, we will formulate decomposition rules for use in the decomposer module of the interface. Our experimental efforts will also verify established constraints, parameters and decomposition rules. Funded by other research contracts, process improvements will continue during the three year period of this research program and will require periodic efforts to update process constraint parameters.

For this project, we will provide fabrication services for our companion design effort in which we have proposed a set of three design exercises at the end of each project year. In addition to this internal evaluation, we propose to provide fabrication services to external groups or designers. In the first two years we have planned several cycles for outside fabrication proposals. After selection of one proposal in each cycle, the outside sources will use the developed interface to create a detailed design that will be fabricated by the SAMUEL service. The exact time slot of these cycles and the duration of the fabrication phase will vary with the complexity of a particular design. MEMS fabrication will accept proposals continuously during this period, as this technology transitions from custom, hands-on processing to using the new interface. At the end of year two we will start to allow continuous use of the SAMUEL service by selected external groups and allow submission of detailed designs for on-demand fabrication in both technologies.

As part of the educational effort, we will provide short courses with hands-on experience in the SAMUEL service for teachers in the summers of years two and three. Depending on the start date of the research project the position of those courses as shown in the time chart in Figure 13 will shift to accommodate teacher availability during the summer break.

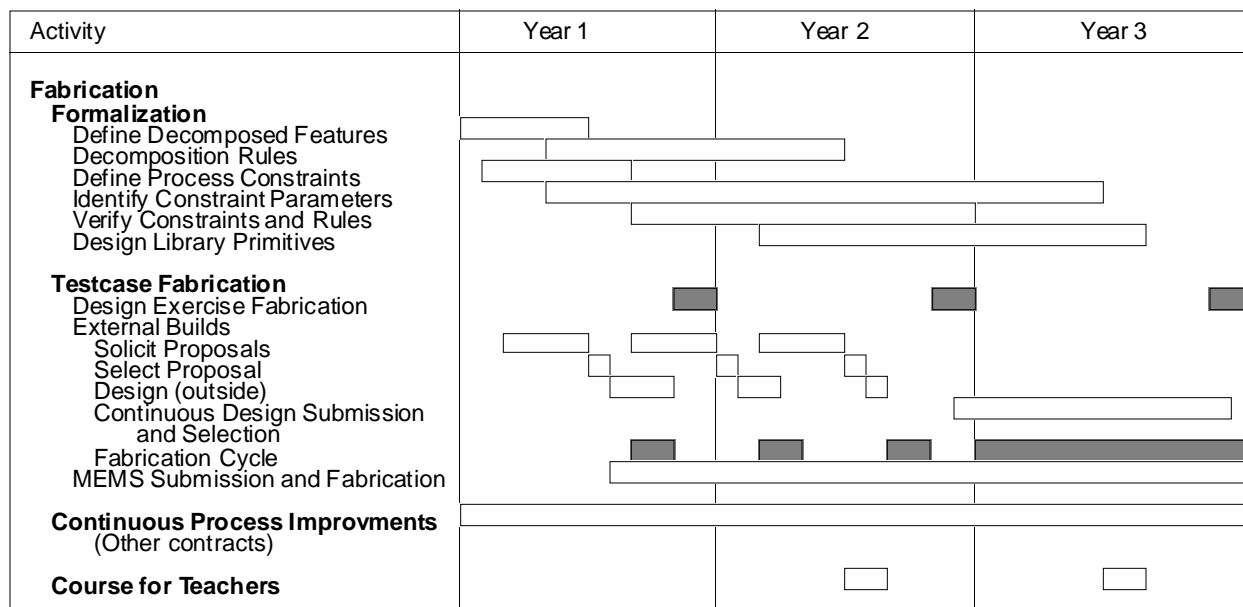


Figure 13. Fabrication Project Chart

10. Results of Prior Work

Title: Rapid Design through Virtual and Physical Prototyping

PIs: David Baraff, Mark R. Cutkosky, Susan Finger, Fritz B. Prinz, Daniel P. Siewiorek, Lee E. Weiss, Andrew Witkin, Paul K. Wright

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This research initiative has provided us with the opportunity to expand the design and analysis capabilities of the virtual prototyping system to ensure that virtual prototypes can be transformed into physical prototypes. We are exploring the incorporation of continuous, incremental analysis and process planning into the virtual prototyping environment. We have also been working towards creating interactive simulation environments that can accurately model the behavior of complex parts and assemblies, including the effects of contacts and friction. On the physical prototyping side we have been working towards deepening our understanding of the underlying physical phenomena that govern the manufacturing processes in order to develop robust models of the processes and facilities

This research has also helped us to expand the variety and performance of materials available for use in physical prototypes. We are focusing on classes of materials useful to design students and identified as crucial by our industrial team members.

The efforts of the Rapid Design Through Virtual and Physical Prototyping project and other DARPA-related research programs have created a demand for our services from students and industrial partners which in many instances has outstripped our resources. It is precisely the time consuming communication between the design and manufacturing community that prevents us from creating and realizing sometimes complex design artifacts in a timely fashion. The work of the present proposal will help in formalizing that interface and significantly increase the productivity of our design build cycles.

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