PROJECT SUMMARY

A Design Interface for 3D Manufacturing

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Shape Deposition Manufacturing (SDM) and micro-electromechanical systems (MEMS) processes represent an exciting new class of three-dimensional manufacturing processes that expand the space of possibilities open to electromechanical systems designers. By using a layered approach to fabrication, these processes remove constraints associated with traditional manufacturing methods and simplify process planning. These processes can also generate dense multi-material parts with complex shapes and integrated structures containing embedded sensors, actuators and microprocessors.

The key impediment to the widespread use of these processes is not the limitations of the processes themselves but the ability of engineers to explore and master the expanded design space they enable. To overcome this impediment, a design interface is proposed for SDM and MEMS processes that is based on formal representations of process-related constraints expressed in terms of three-dimensional design features with associated rules to ensure manufacturability. The interface specification will include the development of a SDM And MEMS Unified Exchange Language (SAMUEL) developed in collaboration with process developers, and the development of a supporting infrastructure for exchanging design features, constraints, process capabilities and manufacturing analyses over the Internet. The implementation will build upon emerging standards for exchanging product specifications and representing manufacturing processes.

The interface must be flexible, because SDM and MEMS encompass a broad range of specific process and materials capabilities. The proposed interface captures process-related capabilities and constraints at different levels of detail so that designers can delay commitment to a specific process and still be assured that their designs satisfy the general constraints associated with a process class. By posting general requirements (e.g., regarding materials properties or surface finish) designers can also filter the pool of candidate processes and utilize the interface during early or detailed design stages.

It is anticipated that the interface and supporting infrastructure will foster a flurry of design exploration and tool development similar to that which accompanied the development of MOSIS and design rules in the VLSI circuit community. To promote this activity, a series of design exercises will be conducted, initially in collaboration with process developers at CMU and Stanford and subsequently with investigators at other institutions. The exercises will explore the ability of designers to construct libraries of re-usable elements for complex electromechanical systems, will test the ability of these design elements to be scaled and miniaturized to take advantage of MEMS technology, and will explore the feasibility of integrating designs and processes from different institutions to create miniature electromechanical systems.

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I. Background

The current design/manufacturing interface for mechanical parts

Limits on development time and manufacturing resources are among the constraints facing every design team, often profoundly affecting the final cost and quality of a product. Designing a part without regard for manufacturability leads to designs that are expensive to produce. Conversely, committing too early to a manufacturing process results in premature selection of design alternatives. Design for Manufacturability (DFM) methods can reduce overall development time and cost, but their successful application requires close interaction between designers and manufacturing engineers.

Today most information exchange between design and manufacturing occurs through informal human communication, often requiring several iterations to get a part right. Though there are formal methods available for limited domains such as assembly analysis and cutter path planning, most manufacturing knowledge still resides in the heads of experienced manufacturing engineers. Complex interactions of three dimensional geometries have largely prevented formalization of this knowledge. Consequently, generalizations and extrapolations are often not possible.

The situation is even worse for Micro-Electromechanical Structures (MEMS), where the fabrication process is often customized for each part design. MEMS designers must be experts in both the fabrication processes and device requirements.

A new way to create 3D parts

A new class of manufacturing processes called Solid Free Form Fabrication (SFF) or Layered Manufacturing has the potential to change the nature of design and manufacturing for mechanical parts. Several SFF processes are commercially available and others are being developed. Compared to traditional manufacturing processes, SFF processes make it easier to evaluate manufacturability and expand the range of what is manufacturable. As an example, SFF processes make it possible to build structural parts with embedded circuits, sensors, and electronics [Weiss et al. 1996] and to create molds with 3D internal cooling channels [Fessler et al. 1996].

MEMS processes also build parts in layers. Layered mechanical parts and MEMS are fundamentally equivalent. However, current MEMS objects are not designed with SFF methodology; in SFF complete designs are automatically decomposed into layers, while MEMS parts are manually designed layer by layer. A challenge for the future is to bring the advantages of the SFF paradigm to the MEMS domain and to integrate the two technologies to provide designers seamless access to feature sizes that span several orders of magnitude.

Avoiding the Black Aluminum syndrome

The key bottleneck with SFF is not the characteristics or limitations of the processes themselves, but the ability of engineering teams to master the expanded design space they provide. Indeed, the very idea of shaping integrated assemblies in a single process is so new that we have difficulty imagining the possibilities. The danger is that, as with previous major advances in materials and processing, designers will be slow to capitalize on the opportunities they provide.

As an example of what typically happens, consider the adoption of composites in the aircraft industry. Early attempts replaced metal parts with graphite composites, without significantly changing the part geometry or loading, earning the label "black aluminum," [Bouchard 1995]. The resulting parts often performed poorly, making other designers hesitant to experiment further. Only recently, decades after their introduction, have composites become widely accepted and effectively used.

The VLSI exemplar, and necessary modifications

The MOSIS project for VLSI fabrication suggests one way to promote widespread adoption of new processes such as SFF and MEMS. Indeed, many analogies between SFF and VLSI fabrication have been drawn [Mukherjee and Hilibrand 1994]. In both instances objects are built by incremental material deposition and shaping of layers. Design rules expressing fabrication constraints have a long tradition in the VLSI community. The early coding of these rules helped establish a community which could exchange designs through formal interfaces. The success of projects like MOSIS is largely based on making process constraints automatically available (as simple design rules) to designers who are unfamiliar with process details.

The challenge in the present case is that we are dealing not with a single semiconductor fabrication process but with a variety of mechanical processes and facilities, any of which may be of interest. Moreover, designers use a variety of CAD tools and work at higher or lower levels of detail. In the following sections we propose to develop and test a new protocol and exchange language, based on PDES/STEP standards [ISO 1993] and EXPRESS [Schenck and Wilson 1994], which allows us to represent 3D geometry, material attributes, tolerances, and other part qualities. The proposed protocol and language will let us develop an interface between design and manufacturing that will make layered processes more accessible to designers.

To test the feasibility of our approach, we propose to work with Shape Deposition Manufacturing (SDM) [Merz 1994] and MEMS processes. These processes have the most varied geometric and material capabilities of layered fabrication techniques. Access to simpler (2½D layer, single material) SFF processes will follow once issues relevant to SDM and MEMS are resolved.

II. Vision

Our objective is to promote design innovation by making an exciting new class of 3D layered manufacturing processes accessible to a wide community of designers. We envision a design-manufacturing interface that enables designers to find, evaluate, and experiment with these processes, exploring the expanded design possibilities they enable.

In this section we briefly describe the main ideas behind our approach and the issues they present.

Capitalize on the intrinsic advantages of layered processes to reduce planning complexity and expand the design space.

The nature of processes like SFF and MEMS is foremost what makes our approach possible. SFF processes reduce geometric complexity by decomposing complex parts into simpler geometries with predominantly local interactions. This decomposition permits formalization of process characteristics and constraints. Layered processes also expand the design space by removing traditional manufacturing constraints. The research challenges include finding representations that can accommodate the wide range of SFF and MEMS processes and size scales, and that allow materials compatibility and related issues to be addressed in addition to 3D geometries.

Develop an interface to decouple design from particular manufacturing processes.

To glean the greatest benefit from these advantages, we must provide process information to designers in a form they can use. Likewise, manufacturers should receive design information in a convenient format. The ability to formalize characteristics and constraints allows us to develop a "clean interface" between design and manufacturing — with scalable design rules on the design side, and robust, automated process planning on the manufacturing side. As a result, Design for Manufacturability (DFM) will no longer require extensive human interactions and frequent iterations. Designers will use the Internet for access to process descriptions and manufacturability analyses and will submit parts to be manufactured by remote sites. The research challenges include defining representations, software tools, and a language and protocol for interaction that meet the needs of both designers and manufacturers. In this proposal we focus on the Design side of the interface; in a companion proposal on "A Manufacturing Interface for 3D Design" we focus on the manufacturing side, including the creation of a network of SDM and MEMS Unified Exchange Language services that can be accessed through the interface.

Preserve flexibility to foster innovation

To promote innovation, the interface and its supporting infrastructure must be flexible, allowing designers to delay commitment to a manufacturing process and to operate at different levels of design specification. The system should let designers try new ideas quickly, without having to learn about process constraints or to invest significant effort in detailed design. At the same time, designers who do want to learn about processes should have the opportunity to access low-level details and process-specific information. Challenges include the development of a framework that will support different levels of interaction and commitment, and the development of robust tools for geometry decomposition and manufacturability analysis.

Provide an infrastructure and interface that can form a foundation for higher-level design

Decoupling design and manufacturing will allow each side to develop their own tools and processes independently. Manufacturers can continuously improve the accuracy, production rate, or material capabilities, of their processes. When they update their process descriptions, the interface can accept new designs, without invalidating existing designs. On the design side, the ability to re-use and re-scale designs across process generations makes it worthwhile to develop design libraries and "compilers" that let designers work at a higher functional level. We hope to foster an explosion of design tool development similar to that which accompanied the development of MOSIS and scalable design rules in the VLSI community [Mead and Conway 1980]. A exciting research topic is to cross-pollinate SFF and MEMS, bringing to SFF the use of functional units typical in MEMS design and to MEMS the 3D design aspects of SFF. Preserving the scalability of representations will also be a challenge in developing higher level design tools.

III. Technical Approach

In this section we present a technical approach that supports the objectives and ideas that are outlined in the previous section. Our approach is based upon the following chain of hypotheses:

1. Layered processes build complex parts out of simple geometric elements with primarily local interaction, permitting simplified process planning and formalization of process capabilities.
2. Formalization of the process permits the development of a "clean interface" based on decomposed features between design and manufacturing, with convenient representations for each side.
3. The existence of an interface, and supporting infrastructure for design and manufacturing, will encourage designers to explore the expanded space of design possibilities that these processes enable.
4. The design interface and infrastructure will further make it practical to develop libraries of designs and design primitives to facilitate increasingly high-level design of complex systems.

These hypotheses are discussed in the following four sections.

1. Formalization of manufacturing process constraints and design rules

As mentioned in the previous section, SFF and MEMS processes both expand the range of what is manufacturable and make it easier to formalize and automate the evaluation of manufacturability. The characteristics that make these processes amenable to formalization are:

- 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).
- For each layer, *manufacturability depends primarily on local geometry, material, and accuracy requirements*. In other words, these 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.
- These layered processes also *remove traditional manufacturing constraints*, for example, fixturing requirements and tool access planning, which are often major barriers to automatic process planning and manufacturability analysis.

We note that similar characteristics are found in VLSI processes and underlie the success of scalable design rules in MOSIS. We believe that similar formalization will also be possible with other processes that have some of these three characteristics.

In the case of SFF processes, these characteristics are an intrinsic product of the manufacturing method. However, it is also possible to constrain conventional manufacturing processes with similar effect. For example, the CyberCut CNC machining facility at U.C. Berkeley[1] restricts the set of available features and the ways they can be removed from a stock part, and employs special manufacturing methods such as reference-free machining [Sarma et al. 1993] to eliminate global feature interactions and facilitate the encoding of process-related constraints [Smith and Wright 1996].

[1] URL http://kingkong.me.berkeley.edu/cybercut

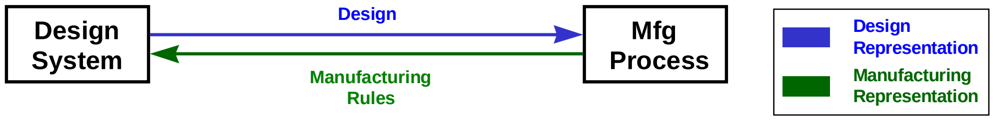


Figure 1 Existing communication between design and manufacturing. Manufacturers express process-constraints about individual layers; designers model parts as 3D solids.

Decomposed features

Although SFF and MEMS processes are amenable to formalization, little progress has been made in this direction because the processes are still in their infancy. The present mode of communication between designers and SFF fabricators is depicted in Figure 1. Manufacturers are typically concerned with detailed process-specific 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.

Our solution is to represent process-related constraints and characteristics using "decomposed features" – simple geometric elements that map straightforwardly to how parts are built with a class of 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 will restrict our attention to processes like SFF, MEMS, and CyberCut, for which a judicious choice of decomposed features will eliminate global feature interactions.

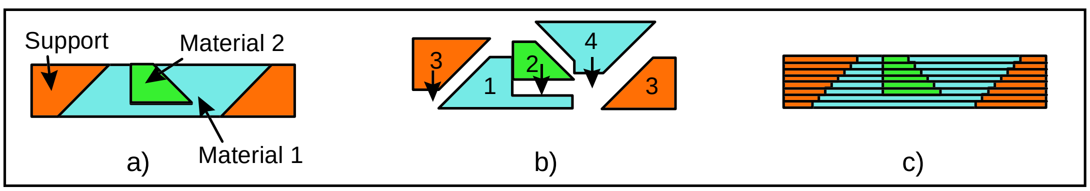


Figure 2 A two-material part embedded in support structure (a) can be represented with compacts [Merz 1994] (b) as decomposed features for SFF processes with 3D layers, or (c) as layers for processes with 2½D layers.

While most currently available SFF processes use uniform 2½D layers, processes under development, like the Shape Deposition Manufacturing (SDM) process at CMU and Stanford [Merz 1994], use 3D layers. Therefore, a 3D representation of decomposed features is required for the general SFF class. As an example, we are pursuing a description of decomposed features based on "compacts," which are single-material object segments that maintain the 3D geometric information of the outer surface of the object and have no directly-machined undercut surfaces [Merz 1994]. Figure 2a illustrates a simple two-material part (or perhaps a horizontal slice of a larger part) with support structure. Figure 2b illustrates the decomposition into SDM compacts. Figure 2c shows the decomposition into a layered representation required by current SFF processes (assuming multi-material capabilities). Constraints can be specified for each of the compacts and on local combinations of compacts to ensure manufacturability.

Process constraints and design rules

Although the terms "rules" and "constraints" are sometimes used interchangeably, we make the following distinction. Processes are subject to *constraints* (e.g., "minimum horizontal feature size ≥ d," "available materials := {list}") and these 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 ≥ d wide” (Figure 3a) and “Keep the aspect ratio ≤ 10” (Figure 3c). The rules are expressed in terms of decomposed features and are typically conservative, to ensure manufacturability for a class of processes.

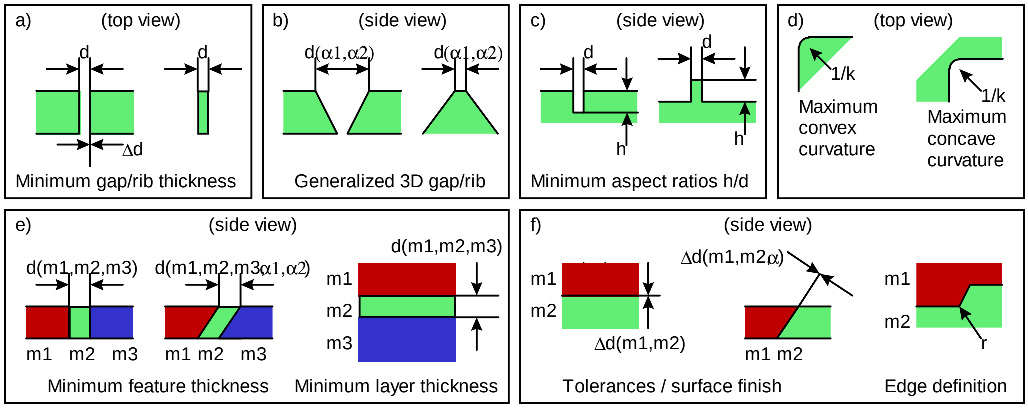


Figure 3 Design rules for SFF and MEMS, expressed at the decomposed feature level. Minimal dimensions *d* for manufacturable features depend on the cross-sectional area required for mechanical stability or cutter diameter (milling is an integral step in SDM), while achievable tolerances *Δd* depend on laser spot size or machine accuracy. For SFF processes using 3D decomposed entities (such as SDM) Figure 3b shows a more generalized model of the gap and rib features which includes the angles of the side surfaces. For multi-material processes, (e) shows the minimum thickness of an embedded material, *m2*.

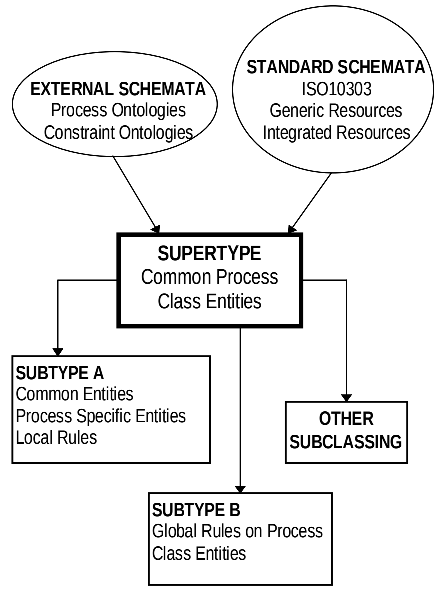
The mapping from process constraints to design rules is not easy. We will work closely with SDM and MEMS process developers at CMU and Stanford to develop both specific design rules for their processes and generic templates for encoding the design rules for their process classes. The extent to which such templates can be generalized, and the mapping automated for all SFF processes, is a research question that we will address.

To maintain compatibility with the international PDES/STEP standard, we will use the EXPRESS language to encode decomposed features and design rules. An example of some of the geometric rules in Figure 3 encoded in EXPRESS is shown in Figure 4. The schema illustrates how rules common to all SFF processes (like min. gap/rib thickness, max. aspect ratio etc.) can be identified and parametrized, and how specific services (like SDM) can specialize these rules based on other process-specific information.

While the above 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 somewhat analogous to the electrical parameter rules for VLSI. Designers need access through the interface to lists of available materials and compatibility information, and tables with important mechanical, thermal and electrical properties. In contrast to the case in VLSI design, however, material properties are not fixed *a priori*, but must be defined for each specific process within a class. Furthermore, mechanical designs require more material variety between different parts produced with the same process.

In summary, we propose to establish a set of low-level design rules for SFF and MEMS technology similar to, but more extensive than, the “spare Mead-Conway rule-set” [Mukherjee and Hilibrand 1994] originally used in MOSIS for VLSI manufacturing. The rule set will consist of parametric descriptions of low-level decomposed features and will be common for classes of SFF and MEMS processes. Distinctions between individual processes, or the use of different materials, will be handled by allowing process- and material-dependent parameter settings. Furthermore, a mechanism to allow sub-classing of any given design rule depending on process-specific aspects of local geometry will be established to handle local feature interactions.

```
SCHEMA process_characterization_example_schema;

(*reference an external schema which defines the entities for parameterizing
geometric rules, similar to the minimum feature size in VLSI rules.
Terminology borrowed from ISO10303-41 specific_measures_schema.*)
REFERENCE FROM feature_measures_schema
    (  length_unit,
       plane_angle_unit,
       unitless);

(*design rules for the general class of SFF processes.   Individual processes
can implement additional rules by sub-typing this entity and defining local
variables and constraints.*)
ENTITY sff_geometric_rules SUPERTYPE OF (ONEOF
    (sdm_geom_rules, sls_geom_rules, stl_geom_rules));

    minimum_gap_thickness:      length_unit;
    minimum_rib_thickness:      length_unit;
    maximum_aspect_ratio:       unitless;
    maximum_convex_curv:        length_unit;
    maximum_concave_curv:       length_unit;
    maximum_surface_finish:     length_unit;
END_ENTITY;

(*Shape Deposition can sub-type the SFF class rule definition, and define
additional variables specific to SDM (like undercut and non-undercut faces).
The function compute_sdm_rule() returns a minimum feature size, given the
face relief angles.*)
ENTITY sdm_geom_rules SUBTYPE OF (sff_geometric_rules);

    left_face_relief_angle:         plane_angle_unit;
    right_face_relief_angle:        plane_angle_unit;
    minimum_gap_thickness:
            compute_sdm_rule (left_face_relief_angle,
                              right_face_relief_angle);
END_ENTITY;
END_SCHEMA;
```



Building a new Application Protocol

Figure 4 Example geometric design rules encoded as an EXPRESS schema

2. Development of a “clean interface”

The centerpiece of this proposal – and of the companion SU/CMU proposal on “A Manufacturing Interface for 3D Design” – is the development of an interface between design and manufacturing. As shown in Figure 5, this interface allows the translation of process constraints into simplified design rules that designers can use, and decomposes design information into a representation suitable for manufacturers, thereby allowing design and manufacturing engineers to communicate on their own terms. 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 manufacturing facilities for the associated class of processes must be able to evaluate manufacturability unambiguously, and to manufacture the part if appropriate. Additionally, we will define hierarchical representations of process capabilities and decomposed features that can be specialized for particular processes within a class. The decomposed feature definitions for the class will be intentionally broad (e.g., generalized cylinders [Binford 1971; Ponce 1990] or B-rep surfaces bounded by upper and lower planes). As discussed below, specific facilities may issue conservative specializations of these generic features to ensure manufacturability.

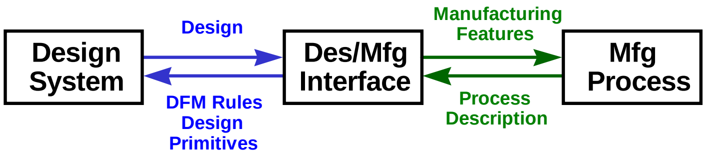


Figure 5 An interface allows designers and manufacturers to represent all information in a format they prefer.

The basic concept is illustrated in Figure 6 and is similar to the object-oriented process hierarchy originally proposed by [Ray 1987]. The representation of process capabilities will draw upon ongoing work in the ISO STEP community [ISO 1993] and at NIST[2]. However, in contrast to these efforts, which are focused on unambiguously representing processes so that they can be planned and duplicated with repeatable results, our emphasis will be on capturing process characteristics as they map to, and constrain, design features.

Interaction with the interface

Designers will interact primarily with three types of programs:

- *Decomposers* that convert design specifications into decomposed features which are acceptable to manufacturers.[3]
- *Process brokers* that help designers select a process or process class, and provide process-specific information to designers on request.
- *Manufacturability analyzers* that evaluate decomposed designs to provide feedback to the designer.[4]

Design sessions will typically involve several interactions. For example, a designer might first submit a part with a blind conical hole. A decomposer breaks the CAD model into decomposed features (layers or compacts for SFF or SDM, respectively). The analysis agent can then perform a manufacturability analysis on the decomposed features. The layer which contains the tip of the cone would be recognized as invalid, because it does not meet the minimum size constraint (Figure 3, a or b). This feature is modified (automatically, or manually by the designer) to conform with the design rules. Finally, the constrained decomposed features are re-assembled to provide a manufacturing preview, allowing the designer to see a blunt bottom on the conical hole. At this point, the designer will be able to accept the modification, adjust the original design, or directly modify the decomposed representation.

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[2] NIST Process Specification Language project: http://elib.cme.nist.gov/msid/projs/sima/psl.html

[3] Decomposition 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. For SFF, the decomposed features are sufficiently simple that automated decomposition appears feasible. Decomposers are analogous to the software used to generate tooling (MEBES tapes) for VLSI manufacturing.

[4] Analogous to the design rule-checkers used by VLSI designers.

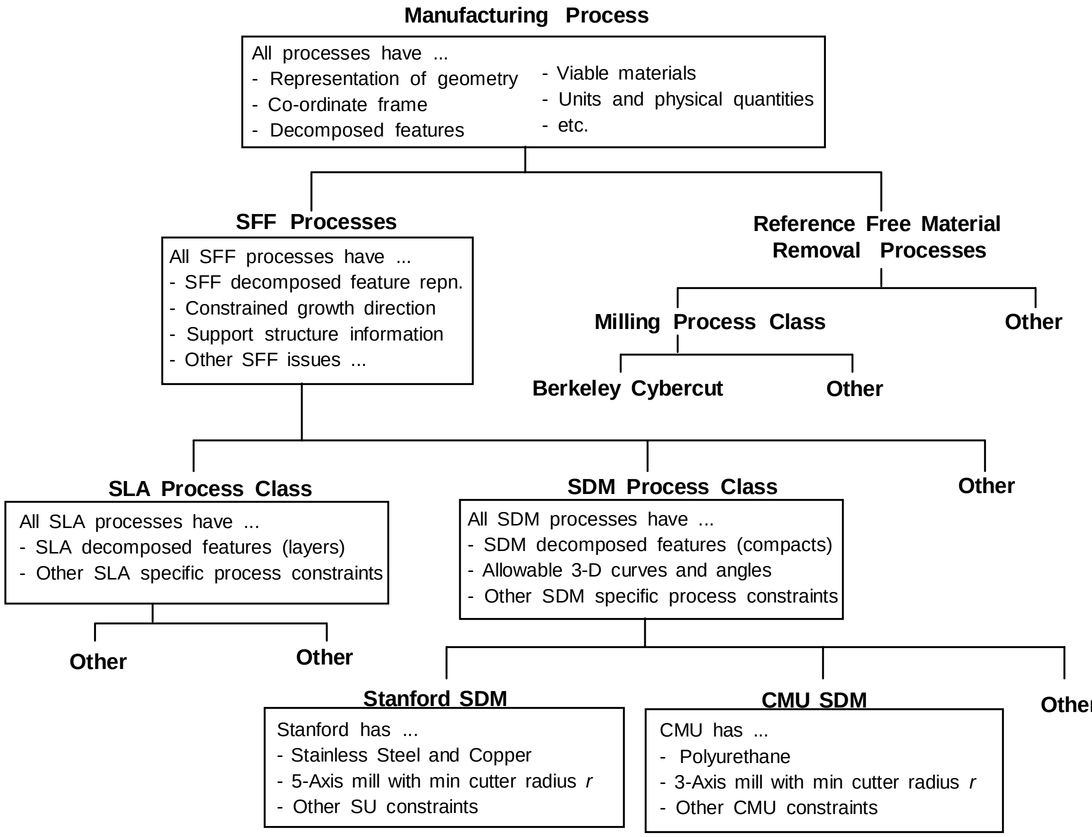

Figure 6 Hierarchical process capability model: each process class possesses a set of capability models. In general, each capability model includes a combination of declarative design rules and constraints, process simulation procedures and documentation.

On the manufacturing side, each facility will be responsible for characterizing their process capabilities, according to the template established by the process class they belong to. The descriptions 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 process descriptions, including available material properties, achievable accuracy, and maximum part size, expressed within the framework established by the process class.
- Optional libraries of design building blocks represented in terms of decomposed features.

Manufacturers will be assisted with this process of "plugging-in" to the interface by means of illustrative examples, templates, and possibly the partial automation of translation from process constraints to simple design rules.

Infrastructure

Establishing the interface between design and manufacturing requires formal representations of design and manufacturing data, formal communication protocols, and an infrastructure for information exchange. Our approach builds upon recent developments in the application of agent-based software to engineering, including communication protocols and representations for agent communication over the Internet [McGuire et al. 1993; Olsen et al. 1995[5]; Pancerella et al. 1995]. As indicated in Figure 7 we will create design, process capability, and interface agents.

To make this system work, we must develop, in collaboration with designers and SDM and MEMS providers:

- Ontologies (i.e., formal agreements on terms and definitions [Gruber 1993]) for general process capabilities, process-neutral geometric representations, and process-specific geometric capabilities
- Design decomposition and manufacturability analysis methods
- A library of manufacturable components and parts to demonstrate process capabilities to designers.
- A language for the exchange of design information. The "SDM and MEMS Unified Exchange Language" will be developed in close cooperation with SDM and MEMS process experts at Stanford and CMU.

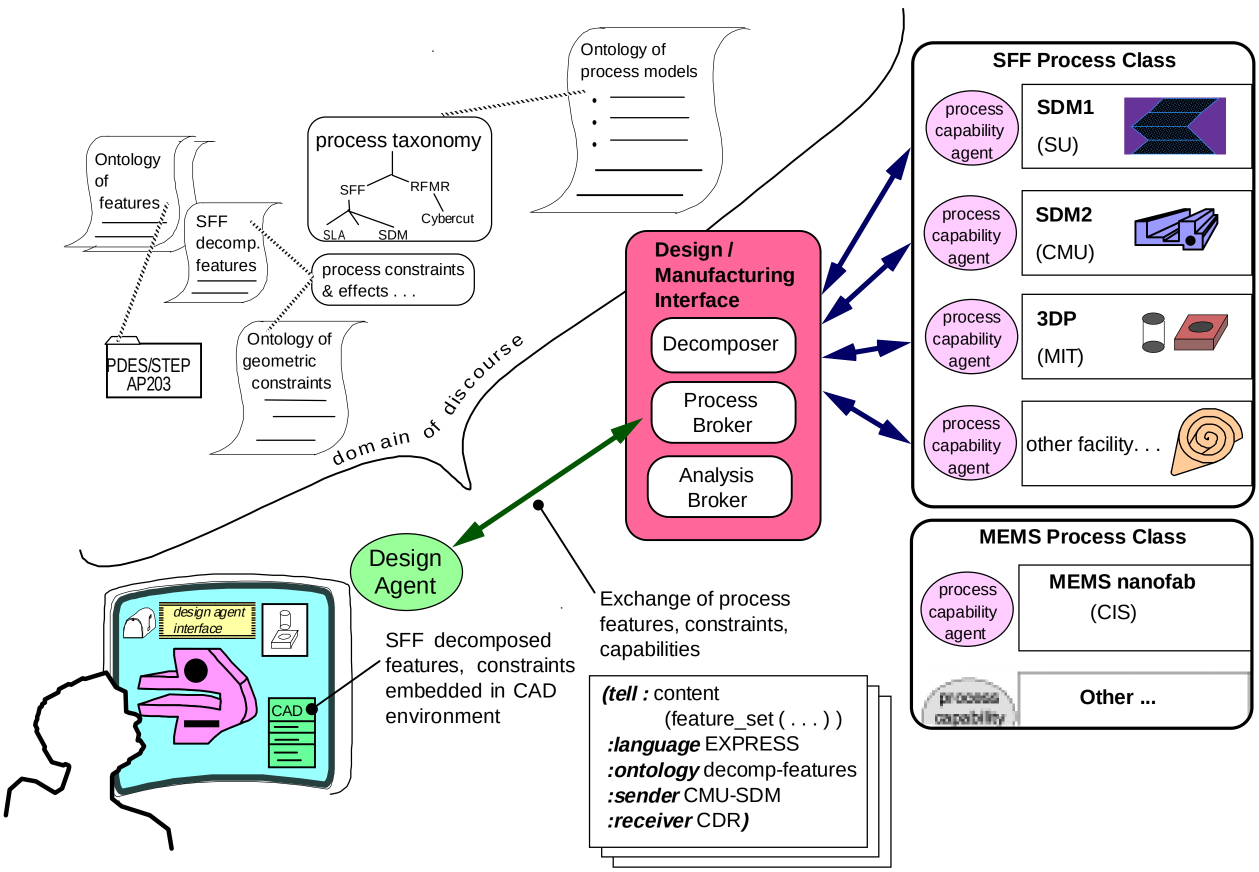

Figure 7 An interaction between a designer and the design/manufacturing interface – at the instant shown the designer is obtaining a description of the decomposed features for SDM at Carnegie Mellon. The information is sent as a KQML [Finin et al. 1994] message to the designer's agent. The message content is in EXPRESS and refers to ontologies of features and constraints which, in turn, refer to applicable standards such as STEP AP203 [ISO 1993].

[5] An introduction to this technology can be found at http://piano.stanford.edu/concur/

For the underlying implementation we intend to build upon our previous work with Java-based agents [Frost and Cutkosky 1996] that use KQML [Finin et al. 1994] for exchanging design information. The agents can exchange not only declarative information such as design rules, but also procedures using CORBA or Java applets. Using this infrastructure we recently collaborated with researchers at U.C. Berkeley to create an interface between the ProEngineer™ CAD system and the U.C. Berkeley CyberCut prototyping service in which CyberCut features and basic constraints are automatically loaded into the CAD environment as design building blocks.[6]

3. Maintaining flexibility to foster innovation

Providing a clean interface will increase accessibility to new processes and allow formalized communication between design and manufacturing. To fully encourage innovative uses of the new capabilities, however, the system should allow maximum flexibility for designers. As indicated in Figure 8, different types of process information (design rules, manufacturable primitives, or lists of feasible processes) are made available to designers. Our interface can also give designers access to a variety of individual processes or general process classes. By providing designers with the options illustrated in Figure 9, our system lets novice users of a process experiment with new ideas while simultaneously allowing experienced designers the option of exploring the limits of the processes.

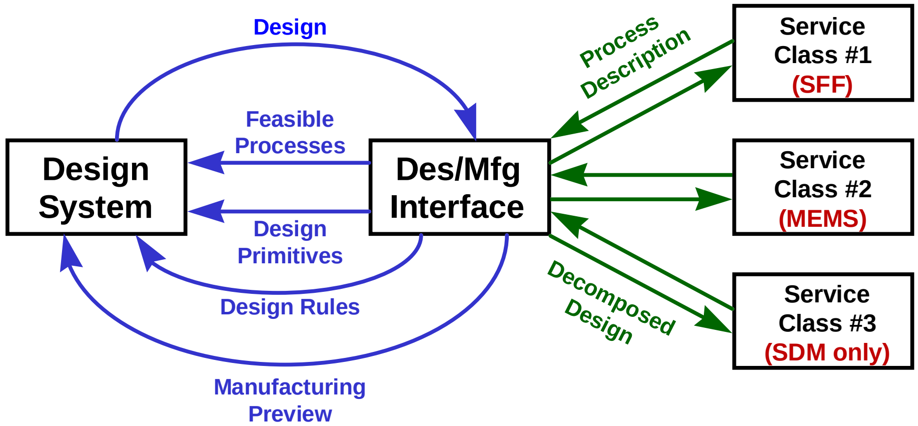

Figure 8 The proposed architecture for our system. Designers have access to different process classes, and can access process information at different levels of detail.

Part of the reason for the combination of hierarchical process capability models, formal descriptions of features and constraints, and agent-based communication protocols (as described in the previous section) is to allow designers as much flexibility as possible when interacting with the system.

[6] ACORN demo URL http://kingkong.me.berkeley.edu/amii.demo.html

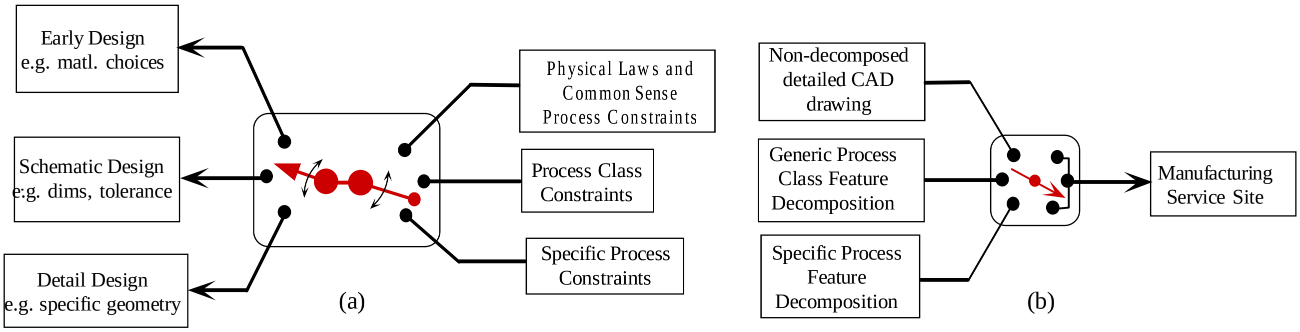

Figure 9 Two ways we provide flexibility to designers – (a) making process information optionally available at various levels of design abstraction and (b) delivering designs at various levels of decomposition to the manufacturing site (via an interface)

The goal is to allow designers to "buy-in" to a manufacturing process whenever it is most appropriate, and to the degree needed. Designers will be able to design parts without knowing anything about decomposed features and process constraints; or they can download design rules and build parts at the decomposed level. For example, our system will permit the following different scenarios:

- During preliminary design, the size of a part, strength to weight ratio, and surface finish requirements can transmitted to the process broker which uses this information as a filter to select a candidate process or process class.
- Having found a process or process class, designers can load class-specific design rules into their CAD systems to ensure manufacturability.
- A library of manufacturable primitives can also be loaded into the CAD system (as illustrated in Figure 7), allowing designers to "build" parts that are guaranteed to be manufacturable.
- Alternatively, designers who do not want to know process details can submit complete designs to a decomposer, which will convert it to a decomposed representation that can be used by the process broker to solicit manufacturing cost estimates, and by analysis agents to assess manufacturability.

4. Providing support for designing at a higher level

Better design systems

We expect that creating a clean separation between design and manufacturing will encourage creation of new design tools that allow designers to work at a higher functional level – as occurred in the VLSI community. A big advantage of VLSI design methods is the ability to design circuits at the block-diagram level. This capability allows designers to quickly construct complex circuits, and facilitates re-using parts of one design in another product. As mechatronic devices grow more complex, similar systems will be needed for designers to cope with mechanical complexity.

The trade-off that must be made to design at a functional level is that the final designs are not optimized for size or power consumption. In mechanical systems, minimizing size, weight, and power consumption are often primary concerns [Voelcker 1994; Sequin 1994]. Restricting mechanical engineers to building parts out of pre-defined building blocks will eliminate their ability to perform these optimizations. New CAD systems must allow access to low-level details so designers can optimize critical part features.

Designing integrated components

To build exceptional mechatronic machines, engineers need to integrate sensors, actuators, and electronics with structural components. A typical approach to building a robot is to design a mechanical structure, then attach off-the-shelf actuators, sensors, and electronics, and finally to route wires and cables. Using this technique, designers spend most of their time dealing with the limitations of the off-the-shelf components and designing connections between them.

SFF processes are capable of building parts with multiple materials and embedded components. These capabilities will allow a new class of integrated mechatronic devices where electronics, MEMS sensors, and micro-actuators are embedded in SFF parts. Our proposed system will help designers explore these possibilities, and will manage manufacturability analysis, reducing the complexity of the design task.

New product possibilities

We are particularly interested in the development of libraries of mini-actuator modules that combine motors with sensors and low-level controllers for applications in miniature robotics, haptic displays, and other small mechatronic systems. The modules will be described in terms of decomposed features and scalable design rules associated with a class of SFF processes. As process tolerance and feature size capabilities improve, the size of the smallest possible actuator modules decreases correspondingly. These actuators will be useful in miniature robotic systems for several application areas of current interest:

- **Minimally Invasive Surgery**. Research in this area includes master-slave manipulators for laproscopic surgery as well as micro-robots which can maneuver within the intestines.
- **Haptic/Tactile Interfaces**. To provide realistic simulations, virtual reality and teleoperation systems need displays that match the sensitivity of human tactile perception. These devices will require arrays of small, high-performance actuators.
- **Planetary Exploration**. A thousand 1 Kg robots can do a better job exploring Mars than one 1000 Kg robot. Small size, light weight, and the ability to operate in rugged environments are the principal requirements for this task.
- **Explosive Ordinance (Mine) Disposal**. There is increasing interest in developing inexpensive robots that can be used to detect and destroy mines buried underground and in surf zones.

IV. Work Plan

1. Time Line

Figure 10 shows a timeline for our proposed activities, along with the corresponding activities of process providers.[7] The work falls into two general categories: Interface Development and Design/Manufacture Exercises. The interface requires development of software systems for formalization, communication, and translation of design and manufacturing concerns. The Design/Manufacture Exercises will demonstrate and test the capabilities of the developing interface. The tasks are as follows:

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[7] described in a companion SU/CMU proposal "A Manufacturing Interface for 3D Design"

Interface Development

- Formalization of decomposed features and design rules: Work closely with SDM process researchers at CMU and Stanford to develop 3D decomposed features and design rules to reflect process constraints. In years 2,3 extend to MEMS and general SFF processes.
- Interface language: Assist SDM process researchers at CMU and Stanford to develop an SDM And MEMS Unified Exchange Language (SAMUEL).
- Design Knowledge: Develop representation to allow the specification of design requirements regarding materials, dimensions, finishes.
- Protocol: Develop communication protocol for the interface's software agents (brokers, decomposers, analyzers, design agents).
- Process taxonomy and ontologies: Develop hierarchical process taxonomy and associated ontologies.
- Software: Develop Process Brokers for SDM and MEMS. Collaborate with SDM process researchers at CMU and Stanford to develop Decomposer and DFM analyzer for SDM and MEMS. Establish template to support development of Brokers, Decomposers and Analyzers for other SFF processes.

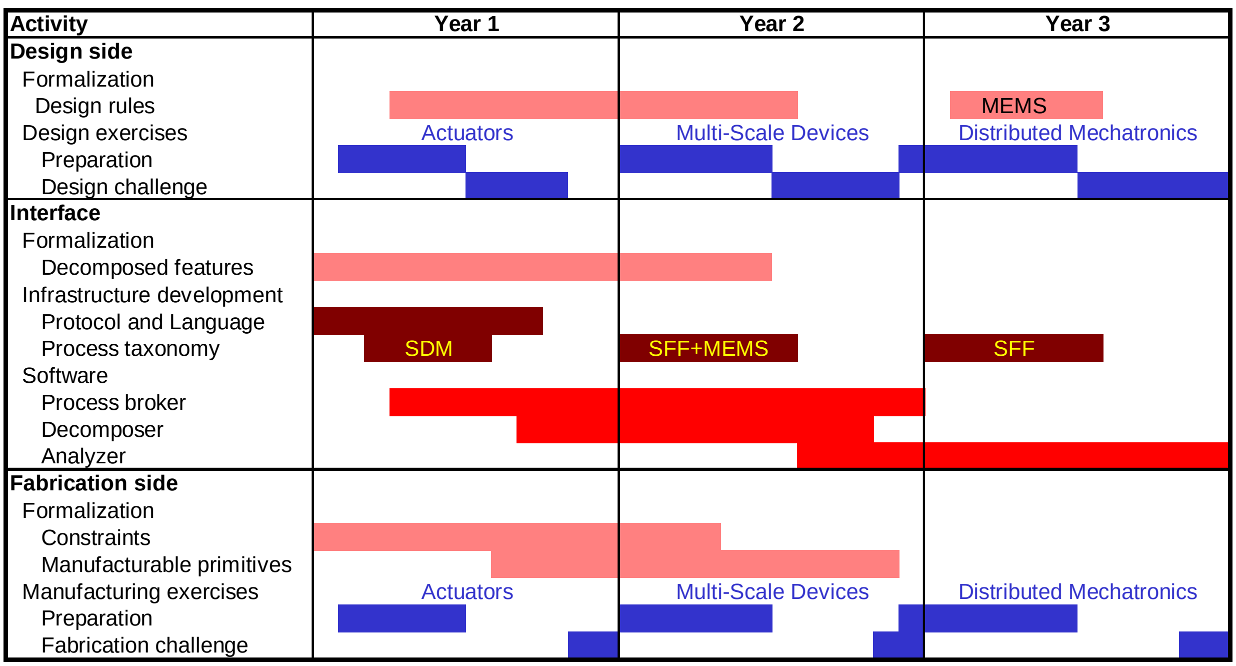

Figure 10 Project Gantt chart. (Design side tasks are described in this proposal, fabrication side tasks in a companion proposal on "A Manufacturing Interface for 3D Design," interface tasks are in both proposals)

Design/Manufacture Exercises

To be successful, this project must take place in an environment of ongoing design activity. We have identified three stages of development for the interface: formalizing a single process - SDM, formalizing a general class of processes - SFF, and finally incorporating MEMS processes. These stages are matched by a series of three design exercises. Preparation for these design challenges (working with process providers to identify feasible goals) will be done by our research team.

The first exercise will be performed by mechatronics designers from Stanford and CMU. The goal will be to develop electromechanical actuators which can be incorporated into future designs. Actuator design was selected to study the purported advantages of SFF processes: constructing moving parts without assembly, and producing complex internal passages within solid objects. The actuators will test the tolerance and material qualities of SDM and the corresponding design rules.

We will explore issues of scale in the second exercise. Complexity and power density of the actuators can be increased and size reduced by incorporating MEMS components into SDM parts. At the same time, we will begin to explore a common methodology between the two, bringing to MEMS 3D design concepts from SDM while attempting to create cross-process scalable part libraries typical of current MEMS design.

The third exercise builds upon the first two, extending the system to the general class of SFF processes, and assembling components built at different facilities. This exercise will use the library of actuators to build complex mechatronic assemblies. The challenge of integrating processes and representations from multiple facilities will hone the expression of both design rules and design specifications.

All three design exercises will occur in a networked environment with human intermediaries giving way to software agents to formalize the communication path between design and manufacturing. By limiting communication in this way can we hope to develop the clean break between design and manufacturing that holds such promise toward moving the success of the MOSIS project into mechanical system design.

V. Results From Prior NSF Support

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

TITLE: Rapid Design through Virtual and Physical Prototyping

NSF Award Number: MIP-9420396

This research initiative provided us with the opportunity to expand the design and analysis capabilities of a 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 are 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 this, and related projects funded by DARPA, have created a demand for a design and manufacturing interface for layered processes from students and industrial partners. It is precisely the time consuming communication between design and manufacturing that prevents us from creating and realizing complex artifacts in a timely fashion.

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FACILITIES, EQUIPMENT & OTHER RESOURCES

The development of this infrastructure clearly requires close interaction between SFF fabricators, mechanical designers, and the interface developers. Stanford and Carnegie Mellon Universities offer a unique combination of design research and SFF facilities.

1. Center for Design Research (Stanford)

The Center for Design Research is a 10,000 sq.ft. research institute within the Department of Mechanical Engineering at Stanford University. Its goals are to contribute to the development of cost-effective, quality products, to develop new design tools, and to develop a deeper understanding of the technical culture that produces new products. Our past efforts in formalizing knowledge for cable harness design and other projects [McGuire et al. 1993], [Cutkosky et al. 1993] have used KQML and ontologies to exchange and express design/manufacturing knowledge in a networked environment. Ongoing efforts at integrating traditional manufacturing methods [Sarma et al. 1993] in a networked design environment, and developing the Java Agent Template [Frost and Cutkosky 1996], provide additional perspective towards developing open infrastructures.

The Center houses 19 high-performance computer workstations as well as specialized systems for graphics, computer-controlled machine tools and robotics, digital controls and virtual-reality user interfaces. All of the above systems are connected to SUNet, the campus network, which provides access to the Internet. The Center also houses a multimedia authoring system. A wide array of design and program development software is used, including SDRC IDEAS, Wisdom Systems Concept Modeler, PATRAN and ANSYS.

2. Rapid Prototyping Laboratory (Stanford) and Shape Deposition Laboratory (CMU)

SDM has been implemented in testbed facilities at both the Shape Deposition Laboratory of Carnegie Mellon University and the Rapid Prototyping Laboratory (RPL) at Stanford University. To allow for easy addition and exploration of alternative processes, both facilities currently use flexible robotic automation where parts are built on pallets, and robotic transport systems transfer the pallets between individual processing stations.

3. Stanford Nanofabrication Facility

The Stanford Nanofabrication Facility (SNF) provides extensive facilities for state-of-the-art VLSI and MEMS processing. The facility encompasses a class 100 clean room with a large selection of deposition, material removal and processing stations, and a variety of measurement tools. A wide range of materials, including semiconductors, metals, and insulators can be processed for the fabrication of structures at dimensions ranging from 100 nanometers to 100 micrometers. Process runs at SNF include standard VLSI and MEMS processing, such as the MOSIS compatible CMOS and BiCMOS processes, as well as process sequences specific for individual user requirements. The facility is automated using computer systems which are used for laboratory management and to control process equipment.

The RPL and SNF are described in more detail in the companion SU/CMU proposal – “A Manufacturing Interface for 3D Design”.