Process Planning and Automation for Additive-Subtractive Solid Freeform Fabrication

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Abstract

New additive-subtractive processes promise to enhance SFF capability from prototyping to true low-volume production. However, to maintain the same degree of process automation as in currently available processes like SLA or SLS, more sophisticated planning and execution systems need to be developed.

The system we present in this paper consists of two parts. The first is an off-line planner that decomposes a CAD model into 3D manufacturable volumes called "single-step geometries", arranges these geometries into a graph representation called " adjacency graphs", and automatically generates deposition and machining codes for each single-step geometry. The second is an on-line system that handles asynchronous multi-part building, job-shop scheduling, process control and run-time execution. Communication between these two stages is through a "process description language".

The goal of this paper is to present a framework for planning and execution for additive/subtractive processes, outline the issues involved in developing such an environment, and report on the progress made in this direction at the Rapid Prototyping Laboratory of Stanford University.

1. Introduction

The demand in industry for fast, accurate renditions of designs is not new, and a whole community of specialized model makers and craftsmen has traditionally catered to this demand. This community has adopted new technology, like CNC machining, as it has become available. Nevertheless, the process of creating a model or a prototype of a design remained labor- and skill- intensive until the set of processes known collectively as Solid Free form Fabrication became feasible.

SFF processes have overcome this skill and labor requirement by simplifying the elementary geometry to be built. The simplification is achieved by decomposing any complex geometry into simple 2-dimensional slices. These processes also sacrifice tolerances, surface finish, and the use of engineering materials for the sake of automatic planning and execution of parts. This trade-off, while acceptable for "look-and-feel" prototypes, is becoming a liability for current processes. Industry is requiring functional prototypes and CNC shops are shortening their lead times, making them competitive with RP bureaus.

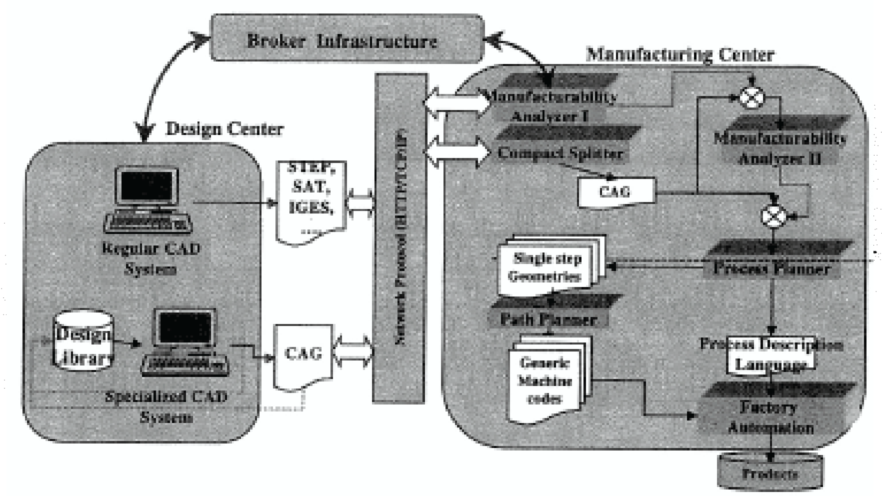
The processes currently used in the SFF industry are purely additive, where material is progressively added to the part being built in the final position and shape. Newer processes coming out of the research laboratories are using engineering materials (hard metals, ceramics), and are combining addition and subtraction of material as a way to shape more precisely the part. A comprehensive review of the available processes can be found in [Prinz, Atwood et al. 1997].

Additive/Subtractive processes improve on purely additive ones in the range of materials they handle and the accuracy they provide. They are also proving to accept more sophisticated design with multiple and graded materials in a single part [Weiss, Merz et al. 1997], as well as integrating whole assemblies in one single fabrication unit. The downside to all these improvements is that additive/subtractive processes require a substantially more sophisticated process planning and part execution control. This increased difficulty is the result of the use of CNC machining or similar material removal processes and the need to coordinate several different unit processes.

The goal of this paper is to present a planning and execution framework for additive/subtractive processes, outline the issues involved in developing such an environment, and report on the progress made in this direction at the Rapid Prototyping Laboratory at Stanford University. We take the SDM process [Merz, Prinz et al. 1994] developed at Stanford as the case study to apply the concepts developed in planning and execution for this class of additive/subtractive SFF processes.

2. Design/Manufacturing interface

The first step towards automated manufacturing is to establish efficient communication between design clients and manufacturing centers. A design client can be equipped with regular CAD packages or with specialized design software [Binnard and Cutkosky 1998] where process-specific knowledge is embedded to facilitate down-stream planning tasks. On the other hand, manufacturing centers should provide manufacturability analyzers, automated process planning software and on-line execution systems. The manufacturability analyzers, for example, examine tolerance requirement of a design and verify it with their facility and process capabilities. The process planner generates sequences of process plans and associated operations and machine codes for building given parts. Execution systems read in several alternate process plans (possibly for many different parts), and determine subsequent operations and machines based on on-line job-shop configurations.



Communication between designers and manufacturers can be accomplished by Internet-based process brokers [Tan, Pinilla et al. 1998]. These brokers receive designs and check with available manufacturing centers for accessing turn-around time, material availability, facility capability, and dimensional accuracy. They then select manufacturers that best fit designers' requirements. Figure 1 shows a framework architecture that includes the concepts outlined here.

In the following sections, we will only address issues related to process planning and execution for additive/subtractive SFF processes.

3. Challenges and needs in process automation

3.1. Planning needs and challenges

The first requirement for a realistic planning and execution system for any manufacturing system is to be able to interface existing CAD systems. The supplied solid models must support free-form surfaces for the sake of geometrical reasoning and path planning required for additive/subtractive processes and for the required levels of accuracy. Further development of CAD systems to be able to represent multi-material parts and graded material parts is an active area of research that will have substantial impact on these processes [Kumar and Dutta 1997. Aug].

The required functionality for a planning system can be summarized as follows:

- Planning for finding a building orientation [Hur and Lee 1998] has to account for the fact that additive/subtractive processes can deposit and shape full 3D shapes and is not limited to thin 2D layers.
- Part shape needs to be decomposed in volumes that are readily manufacturable with the process considered. Decomposition is substantially more complex to take full advantage of the non-planar capabilities.
- Planning each of the decomposed volumes in the two phases of the process: planning the deposition of material [Kao 1998], [Farouki, Koenig et al. 1995] and the machining of the final shape for each surface. In additive/subtractive SFF, geometry simplification due to decomposition avoids most of the tool interference, and tool access problems characteristic of path planning, offering a better chance to achieve automation.

3.2. Execution needs and challenges

SDM and other additive/subtractive processes present a substantial increase in sophistication compared with pure additive ones regarding its execution environment. The main issues that should be considered are:

- SDM is a multistage process: Multistage processes require or should allow multiple processing stations and transfer of parts between stations. An industrial SDM shop needs to determine scheduling of parts and operations, floor layout, assignment of jobs to machines, etc.
- As soon as multiple machines are considered, the manufacture of several parts will want to take advantage of parallel processing in different stations to maximize equipment utilization. Each part can be built following several alternative sequences. The execution system should be able to take advantage of this flexibility to optimize cost and turn-around time.
- The execution system should coordinate activities of machines and transfer of parts, and track and balance the state of load of each machine in the shop to achieve a smooth flow.

These characteristics make the process somewhat similar to VLSI manufacturing, where an array of processes work in sequence to produce a wafer. A wafer' route travels through a variable number of machines depending on its process plan, and it is very cyclic (Lithography-Etch-

Implant). In a similar fashion to VLSI manufacturing, the execution system will have to cover the handling of partially built parts and intermediate buffers.

4. Process planning

Process planning takes full 3D geometric models as inputs and outputs process description that specifies contents and sequences of operations that are necessary to produce the input parts. The contents contain machine-understandable codes for driving designated machines to perform desired operations where as sequences specify all possible orders of operations that are valid to manufacture the input parts.

Basic planning steps involve determining building directions, decomposing a part into manufacturable volumes (called single-step geometry), representing these sub-models in a structured format for allowing optimizing building sequences, depositing materials on each single-step geometry, and shaping decomposed entities. The goals of these tasks are to generate process plans that are of low-cost, high-quality, high-precision, and fast turn-around time. We will first define the constituent of the additive/subtractive process: single-step geometry.

Single-step geometry

Additive/subtractive SFF processes involve iterative material deposition, shaping and other secondary operations. Each of such operations is associated with a part component or a decomposed geometry, which together represent a final product. The characteristics of such decomposed geometry (a set of single-step geometries) are that all supports for its undercut features are previously built, and no interference should occur in depositing or shaping processes from the top with respect to the building direction. In other words, any ray cast along the growth direction should not intersect a single-step geometry more than once.

Operations associated with each single-step geometry may include deposition with different types of material or machines, machining operations using CNC machines, or electrical discharge machining. Or it could be simple operations such as automatic insertion of pre-fabricated components.

The following describes issues related to automatic and optimal planning for additive/subtractive processes.

Building direction

The approaches are not dissimilar with other pure-additive SFF processes in determining building directions. However, there are some more issues to be considered for additive/subtractive processes:

- The number of decomposed single-step geometries reflects time for part building. In a typical additive/subtractive process, shaping operations usually need deposited materials to be conditioned (in the case of plastics, cured/hardened; in the metal cases, cooled). The more the steps, the more the building time is consumed in the conditioning procedures.
- To facilitate machining tasks, it is preferred that a part has as many as possible flat or vertical surfaces with respect to the building direction. In the cases of free-form surface designs, an orientation that minimizes the number of undercut-nonundercut transitions is most desirable since a surface without being split can be machined in one single operation which eliminates marks resulting from the layer interfaces.

An approach that maps surface normals to a unit sphere and determines the orientation that results in the minimum number of undercut-nonundercut transitions is described in [Rajagopalan, Pinilla et al. 1998].

Part decomposition

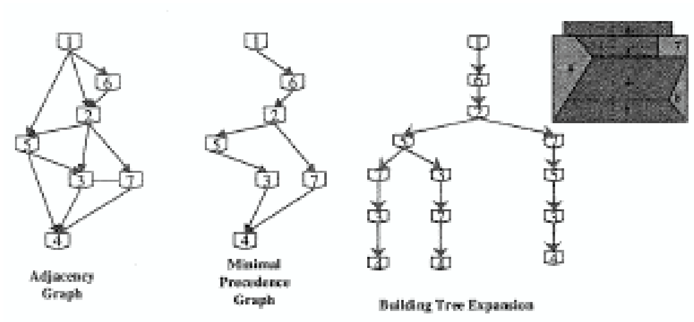


Figure 2 Adjacency graph and building tree for a sample part

An algorithm that finds a feasible solution for this decomposition is described in [Ramaswami, Yamaguchi et al. 1997]. In short, once a building direction has been determined, this approach identifies all silhouette edges that denote transitions from non-undercut surfaces to undercut features or vise versa. A collection of these silhouette edges together with existing edges form a loop, which is used to split the surfaces. Models are then decomposed and support structures are generated with the help of several extrusion operations. Although this approach gives a solution of decomposition, the following issues need to be addressed to achieve a better solution:

- Parts may be decomposed to several smaller features or may result in sharp cavities that do not exist in the original design. These features increase difficulty in machining and may require more expensive and time-consuming processes, e.g., electrical discharge machining (EDM) for metal parts.
- When a part is decomposed into several sub-volumes, their shared surfaces need not be defined exactly unless they consist of different materials. This is due to the fact that the newly introduced surfaces resulted from decomposition are internal to the part and need not be machined, since subsequent operations will deposit same types of material adjacent to these surfaces.

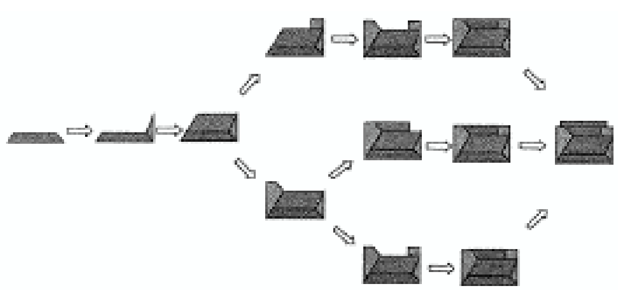


Figure 3 Alternative building sequences.

The results of decomposition are structured in an **adjacency graph** where nodes represent single-step geometries or other components to be embedded, and edges represent the adjacency relationship between connected nodes. After considering part building order, a directed graph that represents the precedence relationship among single-step geometries can be constructed. From this **precedence graph**, one can identify in what order the single-step models should be built.

With the precedence graph, a set of alternative building plans can be generated. Each plan represents a possible building sequence on the decomposed geometry and can be chosen optimally depending upon machine availability or other criteria such as minimum building time, or best possible surface finishing, etc. These building alternatives are passed to job shops for run-time job-shop scheduling. The adjacency graph, precedence graph, and the **building alternative tree** of an example part are shown in figure 3.

Material deposition

Material is usually deposited in consecutive 2D layers until a single-step geometry is completely built. The advantages of additive/subtractive processes are that deposition may not need to be net-shaped since material removal processes are involved. This helps reduce stress concentration and warpage problems and improve deposition path optimality that could reduce voids during deposition. An algorithm that describes a method of relaxing 2D-layer geometry based on its medial axis transform can be found in [Kao 1998]. With this approach, original 2D-layer geometry is "fixed" to reduce sharp corners and narrow passages, and to optimize the deposition path for smoothness.

Machining

In additive/subtractive SFF processes, there exist no tool accessibility problems if appropriate machine tools are selected. This is because any supports for undercut features of a single-step geometry have been built in earlier stages and parts can be further decomposed according to machining constraints. Therefore, planning for machining operations need not consider interference problems.

In additive/subtractive processes, automatic machining path generation is crucial due to the number of machining operations involved. These tasks include determining surfaces to be machined, selecting appropriate cutter sizes, retrieving corresponding cutting parameters from database, using the best cutting strategies for given surfaces, and generating tool paths for target machines.

5. Execution system

We take the SDM process as a case study for the more general case of SFF additive/subtractive processes. SDM has two levels of operation at the shop level: executing each individual operation and building complete parts.

Operations

SDM relies on a limited set of primitive operations to build the parts. The execution system dedicated to machine operations must provide such primitives. These primitives are **load/unload**, **mill/shape**, **deposit**, **cure**, **preheat**, and **cool**. Other auxiliary operations may be needed that act as a bridge between primary operations. These may include **wash**, **sandblast**, **shot-peen**, or special operations such as **embed** components, **inspect**, etc.

Part building and process description language (PDL)

Parts are built by a sequence of operations. Each part to be built is characterized by a process plan that is built in terms of the primitive operations presented above. Required operations are described allowing flexibility in the allocation of its execution to a particular machine as late as possible. No specific machine characteristics are built into the part plan description.

The process plan determines sequences of operations to build the part only to the extent necessary for correct completion of the part. The plan should leave as much flexibility as possible to the execution system for possible build-time optimizations. As an example of this, in figure 2 single step geometries 3 and 7 do not require any special ordering between them to build a correct part. The process plan should reflect this flexibility and not over constrain the execution system by imposing an artificial order between them. A process description language has been designed to accommodate this requirement.

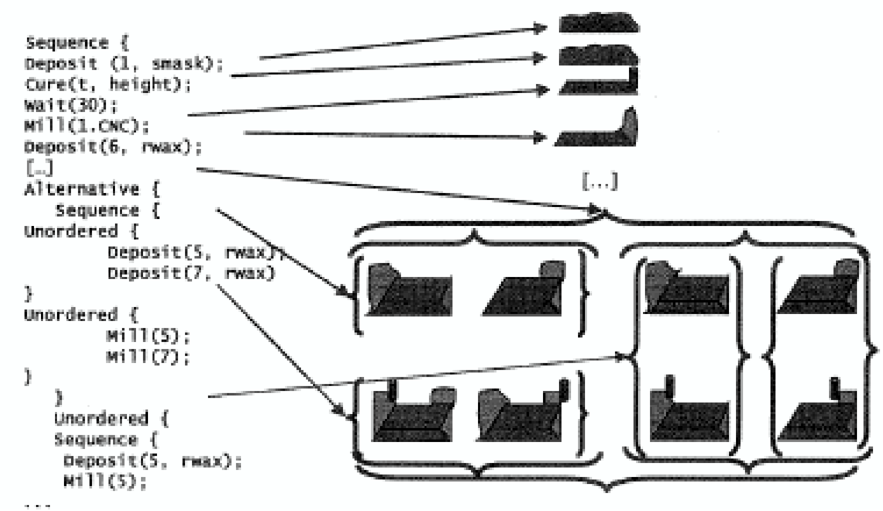


Figure 4 Process Description Language

The language in its current implementation has the operations described above as primitives, and provides three higher level constructs to group them:

- Sequence: Describes a set of operations that need to be executed in sequence.
- Unordered: Describes a set of operations that can be executed in any order and still yield a valid part.
- Alternative: Contains a set of operations such that executing one of them is enough to complete this step.

These constructs can be arbitrarily nested to express the full range of possibilities that result from expanding the building tree. In figure 4 a portion of such process description is given to show how this language can be used to express the building options for a sample part.

Shop scheduling

For an industrial setting, SDM shops will be composed of differentiated machines to perform each operation. For each part and for each operation, it needs to be decided which machine to use. A first step is to match the operation requirements to the machine capabilities. In the system being built at Stanford, machine capabilities are described parametrically by

- Type of operation they support from the list of operations needed by SDM.
- Some general characteristics like maximum part size or weight.

- Operation specific parameters: materials available for deposition, tools available in a CNC mill tool magazine, achievable accuracy, 3 or 5 axis, etc.

With this information, the pool of machines available for a particular operation is identified. The selection of which machine to use within this pool will be determined by the cost and speed of the machine and by the operating conditions of the machine and the shop.

Information system

Shop scheduling activities and the manufacturing operation implementation at the machine level are implemented in a shop information system with on line access to the status and control of the machines, and can be accessed on-line to submit parts for construction.

SFF shop operation is likely to work with lot sizes of one or very few parts. The execution system has to support a very high part mix, where each part has its own process plan. The shop control system

- Keeps track of the state of construction of each part. In our current implementation, the state of construction is represented by a sort of "program counter" in the process description language.
- Knows the state of load of the shop and each machine. Dynamic dispatching of operations to machines is not possible otherwise. The architecture of the system keeps most of this information distributed in the agents that control each of the machines.
- Can compute an estimate of cost and processing time. This will be used to determine which machine, among the available ones, is the best fit to perform an operation.

Current research in manufacturing executions systems [Motavalli 1995; Gowan 1996] point to information system architectures using a distributed computing system [Whiteside, Pancerella et al. ; No-author 1997]. This type of system supports a multiplicity of agents that collaborate to control production [Maturana and Norrie 1995; Ramos 1996; Gong 1997]. The approach that we will be taking in building a SDM shop control will comprise a network of agents that will use bidding to coordinate estimates and bid for the next operation to be performed.

Bidding among a set of competing agents has already been explored as a way for scheduling and assigning production resources to jobs or making design resources in [Baker 1996; Tilley 1996; Parunak 1997]. This framework is adaptable to SDM given the parametrization of building operations and machine capabilities outlined above.

Currently at Stanford's RPL, a first prototype of such system is being built using a CNC mill as the basis for an integrated SDM machine tool. The overall shop control will be tested on a simulated set of such machines. A web-based interface is being built on top of the execution software to provide access to the fabrication of parts from other sites than the RPL at Stanford and to provide a design/manufacturing interface.

6. Implementation for Shape Deposition Manufacturing

6.1. *Planning*

The current process planner being developed at Stanford Rapid Prototyping Laboratory is based on the Unigraphics system and its API's. Models are imported in STEP format and are decomposed into single-step models. These sub-models are structured in the adjacency graph, precedence graph and building alternative tree, which are implemented in C++.Deposition and machining codes are generated automatically within UG/Open API and UG/Open GRIP programming environment.

6.2. Execution system

The current execution system is implemented on a single real machine. A simulated multi-machine shop is being built to test the scheduling and information support systems.

The SDM machine is based on a Haas CNC mill with additional equipment to enable it to perform the deposition of three different materials, curing, preheating, and cooling. A detailed description of the machine hardware is given in [Cooper, Kang et al. 1998]. The controlling software is written in Java and controls the machine through two serial ports, one to interface the Haas CNC controller and another to control the digital and analog I/O boards.

The software has three main parts: The machine control in charge of hardware interface, an interpreter/scheduler of the process description language, and an interface towards the network that will allow for job submission remotely over the network to facilitate the design and manufacturing scenario described in [Rajagopalan, Pinilla et al. 1998; Tan, Pinilla et al. 1998].

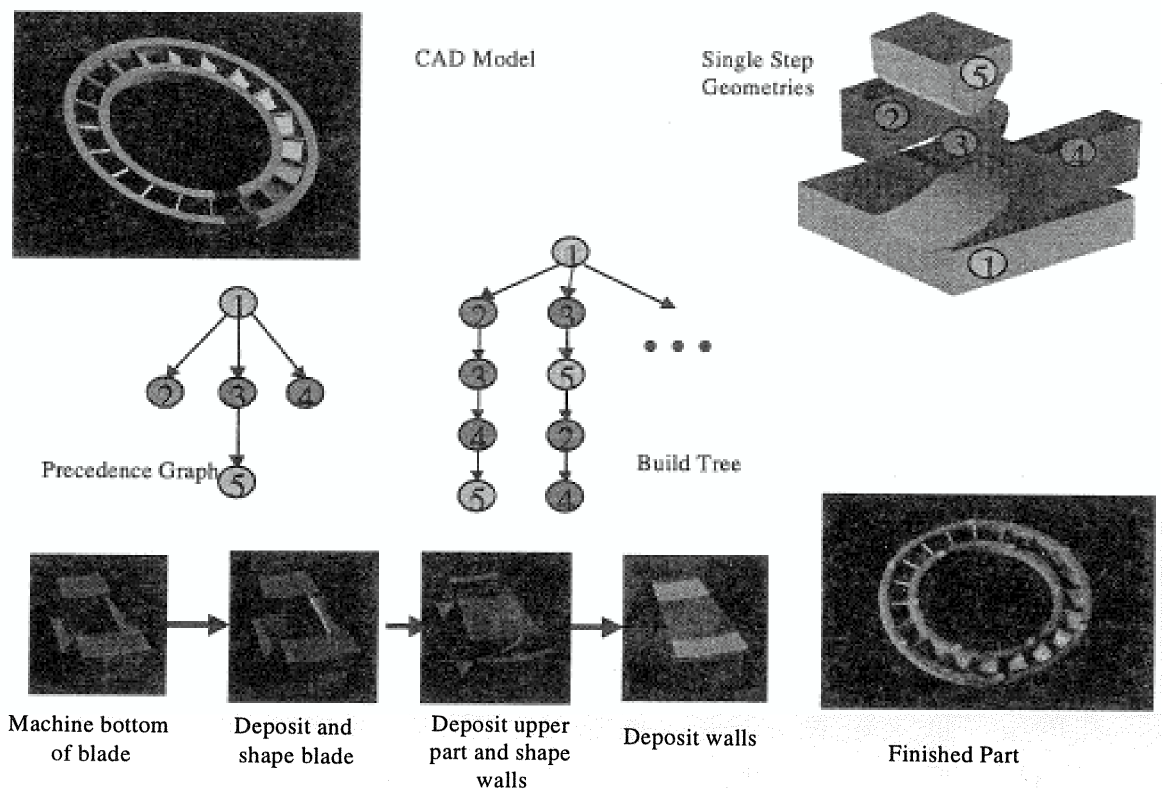


Figure 5 Construction of a shrouded fan from a CAD model

6.3. CAD to Part process

Figure 5 shows an example of a part building plan of a shrouded fan. The CAD model is decomposed into five single-step geometries. These geometries hold precedence relationships that are represented in a precedence graph. This graph completely represents their building constraints. Deposition and machining code is then generated for each single-step geometry. This process code is used to directly drive machine tools.

The overall part plan is codified in the Process Description Language that encodes all possible building sequences derived from the building tree and their associated manufacturing information.

The encoded process description is interpreted by the execution system that controls and monitors all the part building activities. A building sequence is then chosen in real time depending on machine availability, job-shop scheduling, and other criteria. Figure 5 shows the steps of a particular building sequence that completes the part, and the finished part.

7. Conclusions.

We have presented the main issues that need to be solved to make additive/subtractive SFF processes amenable to industrialization. While the basic technology for these processes is well developed, the supporting planning and execution aspects are not well understood.

Planning defines how to achieve a feasible plan to build a design from its geometrical representation. The main tasks are to decompose the model into manufacturable elements, plan the deposition of material and its shaping. Algorithms are being developed to address each of these tasks, and a representation formalism to support them has been presented.

Execution is a somewhat looser term that comprises aspects from shop organization to control of machines looking into commercial use of the technology. In this framework a flexible shop is envisioned supported by an information system to track each part and to dynamically assign tasks to the different machines.

This set of technologies are being explored at Stanford's Rapid Prototyping Laboratory, building prototypes of both a planner and an execution environment as a test bed for pre-industrial deployment of SDM opening the facilities to part submission over the network.

8. Acknowledgements

This work was supported by Air Force Research Laboratory AFRL/MLKT under contract F33615-95-C-5560-P00004 and the Future Professors of Manufacturing program at Stanford University. The authors thank the contributions of their colleagues at the Rapid Prototyping Laboratory for providing experimental support and critique to the ideas presented here, and especially to Falk Kaehny, Jianpeng Dong and Yu-Chi Chang for their contribution to the software implementation, and their thorough knowledge of Unigraphics environment.

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