SOLID FREEFORM FABRICATION RESEARCH IN ENGINEERING EDUCATION

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Milwaukee School of Engineering (MSOE) has been using Solid Freeform Fabrication technologies as a means to provide stimulating, multi-disciplinary research topics for undergraduate engineering students. SLA, LOM, and FDM have enabled undergraduate research in disciplines including *Architecture*: using SFF for preservation, archiving, and reproduction of historical features; *Microelectromechanical Systems*: producing packaging and interconnects for MEMS devices through a combination of stereolithography and photolithography; and *Biomedical Engineering*: creating forensic, research, and educational models of anatomical features and pathology development from MRI images. In addition, MSOE is currently involved in a joint program with the Milwaukee Discovery World Museum to create a SFF experiment that will fly on the Space Shuttle as a *Get Away Special* payload.

Introduction

Because Solid Freeform Fabrication (SFF) has an extremely wide range of potential applications, crossing traditional engineering and science boundaries, it is a technology that lends itself to multi-disciplinary activities and projects. SFF is an ideal mechanism to present scientific concepts including materials science and mechanics, as well as larger-scope engineering topics such as agile manufacturing. At Milwaukee School of Engineering (MSOE), we are using SFF technologies as a means to teach engineering concepts to undergraduate students through multi-disciplinary research.

MSOE was awarded a five-year grant under the NSF Research Experiences for Undergraduates Program (EEC-9619715) to facilitate student exploration in the field of Solid Freeform Fabrication. Sixty undergraduates will participate in summer and academic year programs by the year 2001. Eighteen students from around the country have participated in the program to date, bringing with them a diverse background of university experience, skill level, and interests. Working closely with a faculty advisor possessing expertise in a particular research area, they have performed research on Solid Freeform Fabrication applications in the biomedical, aerospace, architectural, manufacturing, and electronics industries.

Some of the keys to the success of this program include:

- Hands-on access to Solid Freeform Fabrication equipment through the facilities of the MSOE Rapid Prototyping Center (SLA 250, LOM 2030, and FDM 1650).
- Close partnerships of the students with faculty and industry mentors in specialized areas of expertise.
- Teaming with other educational institutions.

- Significant cross-pollination between projects; faculty from diverse departments.
- Encouraging students to publish and present results at national conferences and symposia.

Recent Research Projects

Architecture

There are potentially numerous applications for Solid Freeform Fabrication in the architectural field. One example is the restoration, archiving, and duplicating of historical architectural features such as rosettes or gargoyles -- tasks that are currently performed by labor-intensive hand operations. While architects may not talk in terms of "reverse engineering, parametric data archival, and low-volume production", these are all problems that have been addressed for the manufacturing industry using SFF techniques.

This project applies SFF to the restoration and replication of architectural pieces and artwork. This is especially challenging in that it requires the three-dimensional input of existing objects in multiple scales: from entire buildings to very small detail features. An additional challenge is in making digital input compatible with the paradigms of the architectural field, such as existing software and processes. This project analyzes the feasibility of obtaining three-dimensional data using methods of *photogrammetry*, compatible with standard photographic techniques, to quickly and easily archive and reproduce architectural features.

A set of digital photos was taken of architectural details from different angles. Commercial software (3D Builder Pro) was used to triangulate common reference points from these photos, resulting in a surface mesh which is output directly to an .stl file. A LOM part was created from this file, which served as a pattern for a silicone mold to create multiple reproductions in plaster (Figure 1). The computer surface model can remain with the architectural firm, to be retrieved and modified (size, mirror-image, negative mold, etc.) for any future client.

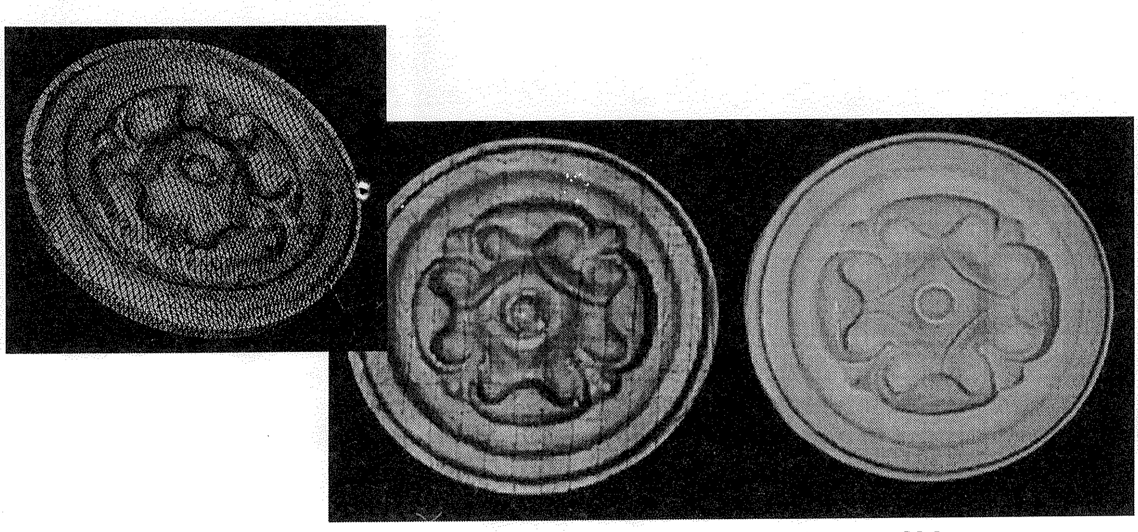

Figure 1. Computer file (inset) obtained from Photogrammetry techniques. LOM master pattern (left), original plaster item (right).

Microelectromechanical Systems

Microelectromechanical systems (MEMS) are devices containing gears, levers, and pumps etched onto a silicon wafer with features as small as 1-2 μm. Interfacing these extremely small systems with the outside world is the most costly part of a MEMS design. This project endeavors to reduce costs by using a modified stereolithography technique. Currently, stereolithography has planar resolutions on the order of 500 μm, which is not precise enough to create MEMS features. Increasing the resolution by combining stereolithography with a masking technique allows a single manufacturing system to construct not only the MEMS sensors, but also the interfaces and protective packages.

Figure 2 shows the results of initial exploration into using a micron-detail photo mask with stereolithography resin. Working with Process Technologies, Inc. of Milwaukee, multiple-layer parts were prepared by shining UV light through a mask that contained a test pattern typically used in the semiconductor industry. Features as small as 5 μm in-plane were achieved, and the creation of multiple layers was only limited by the positioning accuracy of the physical apparatus used to hold the mask. With a more precise mechanism, multiple layers at this resolution can be manufactured, creating what are in effect high-aspect-ratio MEMS devices. As aspect ratio is a key limitation in current MEMS manufacturing technology, SFF techniques can potentially offer some significant advantages.

The ultimate goal of this project is to create objects that have features spanning multiple orders of magnitude. By building larger-scale features with the scanning stereolithography laser, then inserting a photo mask in the beam path as required, this goal should be achievable. It should thus be possible to use a modified stereolithography apparatus to create 10 cm objects that contain features on the order of 1 μm.

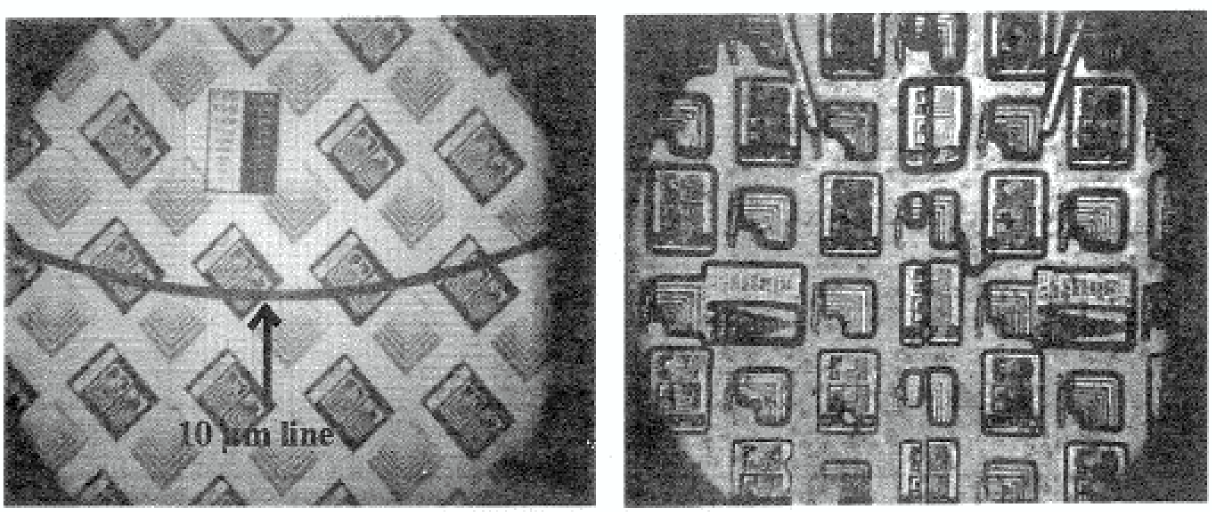

Figure 2. Mask (left). SLA model (right). Feature resolution is as small as 5 μm.

Biomedical Engineering

The Medical College of Wisconsin has served as a partner in the exploration of a variety of Biomedical applications of Solid Freeform Fabrication. Current efforts focus on constructing solid model data from combined medical imaging modalities such as MRI and CT scans, and then using this information to create complex composites that accurately replicate the non-homogeneous mechanical properties of bone.

One student project is working on automating methods to distinguish the boundaries of anatomical structures in MRI images. Because MRI images are not homogeneous, much manual effort is required to select the desired anatomical structure using software such as MIMICS (Materialize, Inc.). Figure 3, top left shows the original MRI image of a knee. A threshold level must be set within the software to isolate desired features. As Figure 3, bottom left shows, a single threshold level is generally not sufficient to correctly identify a desired structure throughout the scan. In this picture, the bone was the target structure; most of the material meeting the threshold criteria was non-bone, thus an operator must manually isolate the structure slice-by-slice.

A computer program was developed by the student that uses a K-mean segmentation algorithm to analyze and "homogenize" pixel values associated with different structures in MRI images. This program uses data from the MIMICS format as an input, reduces the total number of pixel values from 4095 levels of gray to a user-defined, more manageable set (usually 3-20), and then re-introduces the data back into the MIMICS software for display, structure selection, and .stl

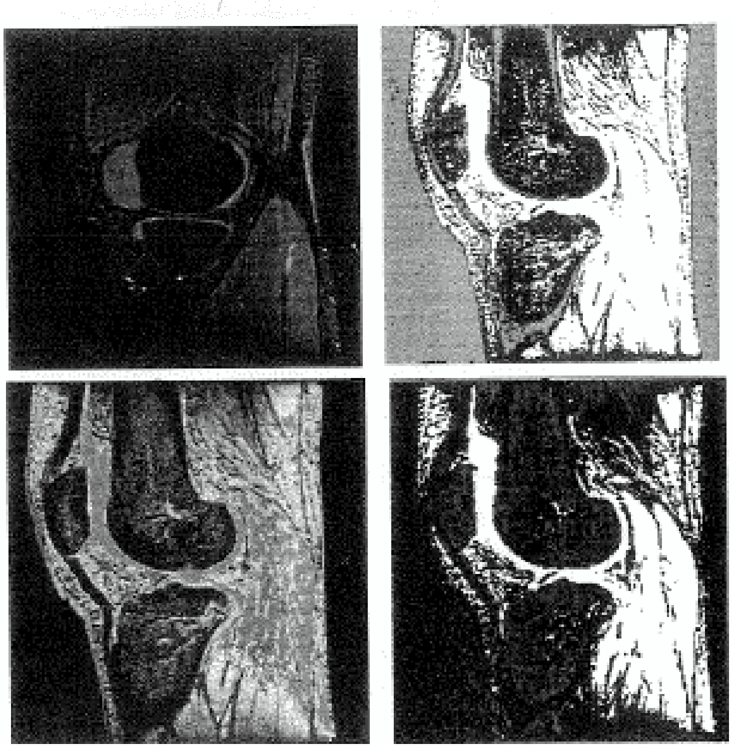

Figure 3. Top left: Original MRI image; top right: homogenized image; bottom left: thresholding on original image misses bone; bottom right: correct features are captured in homogenized image.

file construction. Figure 3 shows the results of initial efforts. The figure in the upper right is the same MRI image homogenized to 3 grayscale values. The figure in the lower right is the result after this data has been imported back into MIMICS and an appropriate threshold value has been applied. In this example, the desired bone structure has been correctly identified with minimum manual manipulation.

Whereas this project concentrates on making complex 3-D input more usable, a second undergraduate project in Biomedical applications of SFF is exploring the output side of the problem. Physical models are extremely useful in pre-surgery planning as well as the teaching of anatomy and pathology, and SFF techniques have been used in this area with great success. Human bone replicas to date show only the exterior overall structure of bone, however, and none of the minute interior tissues and structures. This project involves using SFF to build cross-sectional models of fine-detailed interior structures of bone.

Although this project is in the early stages of development, the eventual goal will be to replicate not only the internal physical geometry, but also the non-homogenous mechanical properties of bone. This will require the "borrowing" of techniques developed by a previous project in the area of composites. Stereolithography patterns consisting of open cellular structures inside a surface shell are used as a host for filler materials; regions within a single object may be separated by thin barriers, allowing filling with different matrix materials to create regions of differing local properties. The internal structure can also be continually gradiated in thickness to produce composites with properties ranging from that of the filler material to that of the Stereolithography epoxy. Current fillers include epoxy matrices loaded with glass microspheres, as well as hydraulically-bonded ceramic mixtures with bulk properties matched to various bone structures. The long-term goal of this project is to create a composite spinal cord model for mechanical testing, such as automobile crash tests (Figure 4).

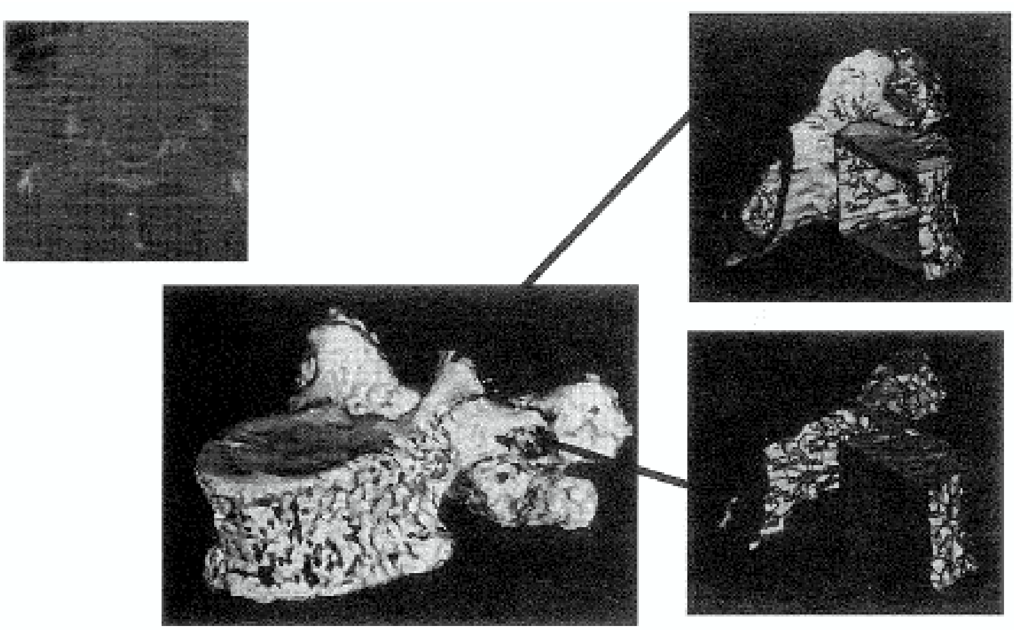

Figure 4. Inset: Original MRI image; composite model representing outside shell of dense bone and inside spongy bone. Composite model is constructed to allow filling of different materials to create non-homogeneous final product.

Space Shuttle Get Away Special Payload

The objective of this project is to demonstrate some of the key technologies required for Solid Freeform Fabrication (SFF) and other automated manufacturing processes in a microgravity environment. Because of the manufacturing flexibility offered by Solid Freeform Fabrication, these techniques have the potential to be of enormous value to continued habitation of humans in space; SFF could eventually serve the International Space Station as an on-orbit system for producing new and replacement components, as well as tools. In the absence of gravity, there is the potential for rapidly creating extremely complex shapes, as supports are not required. The absence of gravity also presents some significant challenges associated with placing a liquid to build an object, however. For example, in depositing a bead of liquid into free space (i.e. without a substrate), interfacial tension will tend to cause the bead to break apart and ball up before it can solidify into a layer. Placing a liquid with a slow solidification rate in a planar arrangement thus becomes a significant challenge.

Two students have prepared a preliminary design for a Get Away Special (GAS) payload to be flown on the Space Shuttle in September 1999 (Figure 5). This payload has been donated to MSOE by the Gammex Corporation through the Discovery World Museum of Milwaukee, WI. This set of GAS experiments will explore a number of the core scientific principles behind the deposition, material flow, and solidification of fluids absent of a gravitational field.

Two types of liquids will be deposited in test patterns that evaluate the relationship between the liquid and the surface onto which it is deposited. In one set of experiments, beads of a rapidly solidifying thermoplastic (ABS) will be deposited onto a rigid substrate, into free space, and onto previously deposited, unsupported beads. In another set of experiments using the same apparatus, a low viscosity photopolymer will be deposited onto a fiber mesh to create a planar

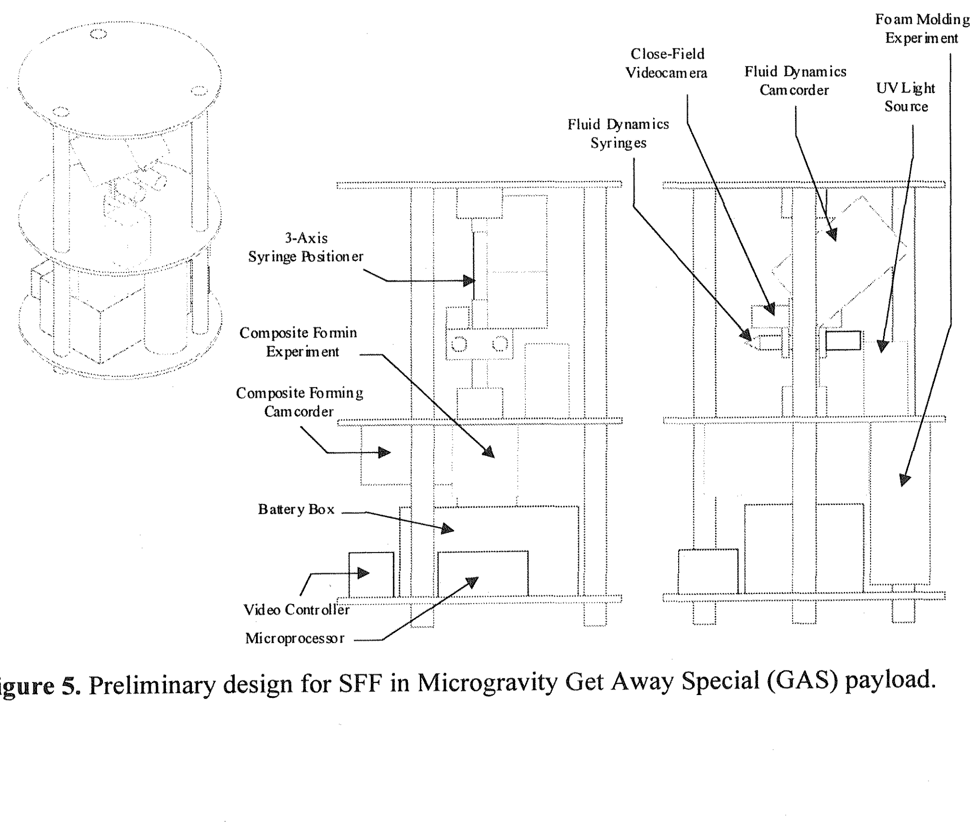

Figure 5. Preliminary design for SFF in Microgravity Get Away Special (GAS) payload.

sheet of liquid. This liquid will be cured by ultraviolet light after deposition.

In a separate experimental apparatus, carbon-fiber composite tubes of varying diameter will be constructed from prepreg material without any support structure. Two heated pinch rollers will feed a prepreg strip past a guide roller, which will change the trajectory of the strip such that it feeds back through the pinch rollers after circling through a set diameter. A composite tube with multiple (3-5) layers will be produced during this experiment.

The final experimental apparatus will create and mold a polymer foam. This apparatus consists of a double syringe: Part A is polymeric diphienylmethane diisocyanate and part B is a polyether type of a polypropolene glycol mixture. Parts A and B will be mixed mechanically at the end of the syringe and expand into a mold where the foam will set.

Benefits of SFF Research in Engineering Education

Whereas textbooks have traditionally defined the *boundaries* between engineering principles, modern engineering education requires packages that *integrate* diverse concepts – "containers" providing the resources for student-initiated, project-based learning. These containers must be constructed around a topic that captures the imagination of students and encourages them to view technology in a holistic perspective. They must enable mentor relationships between educators and students, whereby the learning process is a non-linear, joint exploration that includes collaboration with colleagues and industry. Few technologies offer a scope of applications as broad as Solid Freeform Fabrication. Because of this, SFF is a topic that can become the ideal tool for modern engineering education; an education container built around SFF can provide the foundation for an entirely new engineering education paradigm.

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