Prepared for the Short Communications in Manufacture and Design

Mechanical Implementation Services for Rapid Prototyping

Sung H. Ahn

School of Mechanical & Aerospace Engineering
Gyeongsang National University
Jinju, 660-701, Korea

Sara McMains

Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California, 94720, USA

Carlo H. Séquin

Department of Computer Science
University of California at Berkeley
Berkeley, California, 94720, USA

Paul K. Wright

Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California, 94720, USA

ABSTRACT

Inspired by the MOSIS project, CyberCut is an experimental fabrication testbed for an Internet-accessible, computerized prototyping and machining service. Client-designers can create mechanical components, generally using our web-based CAD system (available at http://cad.berkeley.edu), and submit appropriate files to the server at Berkeley for process planning. CyberCut then utilizes an open-architecture, CNC machine tool for fabrication. Rapid tool-path planning, novel fixturing techniques, and sensor-based precision machining techniques allow the designer to take delivery of a component machined from high-strength materials with good tolerances, e.g. +/- 0.002 inch (0.05mm).There are also instances where the component's complex geometry cannot be prototyped on our 3-axis machine tool. For these components we use Solid Freeform Fabrication (SFF) technologies such as Fused Deposition Modeling (FDM) to build a prototype of the design.

Based on our experience with this testbed, we have developed a new characterization of types of relationships, or "couplings," between design and manufacturing using the following three classifications: 1) loose, repetitive, 2) stiff, one-way, or 3) strong, bidirectional. These three couplings represent different trade-offs between "design flexibility" and "guaranteed manufacturability."

Keywords: Mechanical Implementation Service, Rapid Prototyping, CyberCut, Design for Manufacturing.

1. INTRODUCTION

During the late 1970s, Mead and Conway[1] created the groundwork for the fast prototyping of Very Large Scale Integrated circuits (VLSI). Designers were encouraged to think in terms of five 2-D patterns. These patterns defined three stacked interconnection layers on a metal-oxide-semiconductor (MOS) wafer and their mutual connections through via holes. The patterns described the actual geometry of the connection runs and via holes that one would see when looking down onto the circuit chip, regardless of the exact process and number of masking steps that were used to implement the chip. The system was called the Metal Oxide System Implementation Service (MOSIS)[2]. Today it provides students at research universities the opportunity to obtain prototype chips during semester-long CAD/CAM courses in VLSI design and fabrication. During design, students are obliged to follow the relatively conservative MOSIS-layout rules. But, by doing so, they are sure that their chips can be fabricated by a number of semiconductor companies that offer their services to the MOSIS bureau.

Inspired by the success of the "VLSI MOSIS" project, US National Science Foundation (NSF) workshops in the early1990s addressed the possibilities of a "Mechanical Implementation Service (MIS)" [3,4]. However, it was quickly evident that there was not a perfect analogy between VLSI and the mechanical domain. First, the existing MOSIS service focused on just one electrical component of a consumer electronic product, namely VLSI logic circuits. To have the same success, an MIS might need to be restricted to one mechanical component of a consumer electronic product, such as bearings, brackets, or casings, rather than complete mechanical assemblies. Second, MOSIS initially targeted just one family of manufacturing processes, namely NMOS planar fabrication. Analogically, an initial MIS might then focus on just one fabrication process such as 3-axis milling - one of the more flexible of the metal processing fabrication methods. Third, MOSIS fabricates 2.5-D VLSI chips, while mechanical processes can fabricate complex 3D shapes.

Fourth, in digital logic systems one can easily give up a factor two to four to achieve modularity and some abstraction and isolation between various sub systems. In mechanical parts, making a part 2-4 times heavier or larger than needed is out of the question. Fifth, in VLSI design concerns of device performance, circuit layout and systems architecture can be nicely separated and addressed with different representations and abstractions, e.g., the mask geometry, the "sticks" layout, and the block diagram, respectively. In mechanical systems the many different concerns, e.g., stability, aesthetic, ergonomics, sound isolation, electrical shielding in the housing of a hand drill, are much more tightly coupled and cannot be easily separated and assigned to different features.

A consensus thus emerged at these workshops, that it would be a challenge to create an integrated MIS that could truly offer the flexibility that most mechanical designers and fabricators require.

2. "DESIGN FLEXIBILITY" VERSUS "GUARANTEED MANUFACTURABILITY"

This short communication reviews some recent progress for both machining and SFF processing that allows the introduction of an MIS in the spirit of the original MOSIS. In comparison with VLSI MOSIS, the mechanical domain brings much more complexity to the link between design and manufacturing, thus demanding a variety of approaches to the idea of a fully automated implementation service. The philosophical dilemma that continues to engage us is to balance the following two opposing factors:

- the designer's demand for a flexible and extensible CAD environment;
- the inherent limitations of any given manufacturing process.

To address this dilemma we have found it practical to think in terms of three models of coupling the CAD tools and the fabrication process: 1) the traditional, loose, repetitive, style, 2)the stiff, one-way, mode of VLSI MOSIS, or 3) an emerging strong, bidirectional coupling.

In the loosely coupled, repetitive mode, no commitment to a particular manufacturer need be made in the early phases of design. The designer initially works in a wide open design space, and eventually transmits design information to one or more potential manufacturers. At this point an intense interaction ensues, and the design is modified repeatedly based on critique and suggestions from the chosen manufacturer.

In the stiffly coupled, one-way mode, the designer works in a restricted design space that allows manufacturing rule-checkers based on a particular manufacturer's capabilities to be easily integrated. Design information, typically in electronic form, is transferred to the manufacturer only once, with no need for feedback and iterative improvements.

In the strongly coupled, bidirectional mode, the designer also starts out working in a large design space, but is guided away from infeasible designs through repeated automatic feedback from manufacturability process planners. The designer commits to a particular manufacturer or even a particular machine early on to gain access to very specific feedback. (Table 1 shows a brief comparison of the three coupling modes.) In the following three sections, we describe further each mode of linking designers and fabricators, using illustrative examples.

Table 1: Comparison of the three coupling modes.

Coupling Mode	Pros	Cons
Loose/repetitive	Flexible design	Cost and delay for redesign
Stiff/oneway	Guaranteed manufacturability	Less design freedom
Strong/bidirectional	Moderately flexible design Guaranteed manufacturability	Some loss of design freedom

3. THE TRADITIONAL "LOOSELY-COUPLED" CAD/CAM ENVIRONMENT

Colloquially speaking this corresponds to "over-the-wall" manufacturing typical of today's mechanical CAD/CAM community. The "client" for this looser model of CAD/CAM is a designer who uses a flexible CAD tool, who may be only marginally aware of any manufacturing limitations, and who is willing to pay (in both cost and delays) for the machine shop to redesign the part so that it can be manufactured.

In industry, such clients might work in an aerospace company or a national laboratory, where the "voice" of the design community usually dominates over that of the manufacturing community. It should nevertheless be emphasized that this mode requires many phone calls or face-to-face meetings between the designer and the fabricators. These are needed to resolve design ambiguities and/or manufacturing procedures that will demand special tooling.

Even within a university-like prototyping environment, more complex mechanical designs with multiple sub-components also demand the flexibility of commercial CAD systems and the capabilities of a conventional machine shop with experienced craftspeople. For example, injection molds and many types of mechanical parts exhibit the free-form surfaces shown in Figure 1. This figure shows an aluminum mold, at the rear of the photograph, that was used during an injection molding process to form the plastic casings for the fingerprint recognition devices shown in the foreground. Figure 2 shows an artistically driven part with toroidal and spherical surfaces. In our laboratories we have routinely created and then fabricated such parts that have been designed by conventional CAD methods that use Constructive Solid Geometry (CSG)[5] and parametric [6] and/or constraint-based design[7]. We have used commercial packages such as PTC's ProEngineer, SDRC's I-DEAS environment, SolidWorks, AutoCAD, and ACIS for the design phase. For example, tools built on top of ACIS were used to design the parts in Figures 1 and 2. The use of such packages then demands the skill of a downstream craftsperson (usually a senior graduate student) on the manufacturing side to carry out several crucial steps: a) analyze the part and break it down into millable features; b) decide on the feasible fixturing methods; c) create tool-paths; d) select milling conditions. Despite our integrated capabilities in this area, with the design and manufacturing engineers working more closely than in a standard machine shop, the intense hands-on aspects of manufacturing and the many discussions with the original designer move the activity out of the realm of a MOSIS-like MIS.

4. AN EXPERIMENTAL "STIFF" CAD/CAM ENVIRONMENT

This environment is modeled after the MOSIS style of doing VLSI circuit design. The "client" for this model of CAD/CAM is a designer who is willing to give up a lot of design freedom for the benefit of guaranteed manufacturability, low cost, and fast delivery. Such a client might be interested in quickly obtaining the Fused Deposition Modeling (FDM) part shown in Figure 3 (a) and (b), or the machined metal bracket in Figure 4 that will be used in a piece of experimental equipment. A testbed, called CyberCut [8], for this "stiff" service has been created at Berkeley and is now being used by students in our engineering and CS classes, by colleagues in related research laboratories, and by a limited number of students in collaborating campuses such as Carnegie Mellon University. FDM and machining are the two processes currently being offered to these clients. In this “stiff service mode” the client is obliged to accept the following MOSIS-like limitations:

For FDM parts that are made on our Stratasys 1650 machine:

1. We accept files in STL [9] or SIF [10, 11] format.
2. Build-size is limited to parts that are 10x10x10 inches in size.
3. Although Stratasys’ Quickslice software can handle much larger files, we prefer in our student class projects to limit the number of triangles to about 40,000.
4. ABS plastic is the work material. Since it is layered, the part strength is less than that of full-strength ABS: on average only 70% in the best orientation or as poor as 10% in the worst orientation.
5. Accuracy of a mid-size (5 inch) part is only +/- 0.03 inches.

The FDM process builds a part layer by layer. Thus accessibility during fabrication is not an issue, allowing virtually any complex 3D geometry to be deposited in a layer-by-layer fashion. Thus there are not too many design rules concerning the basic geometry of the part, other than observing a minimum feature size of about 0.02 inches. However, the selection of the build orientation, and the possible modification of the default overhang angle under which some supporting scaffolding has to be built, needs some considerations.

Build rules for planning a successful FDM fabrication (for example, orienting the largest face down on the machine table) are available from [12, 13]. For faster FDM builds of large solid parts, we use the technique described in [14]. Optimizing builds for SFF technologies in general is discussed in [15-18].

For machined parts that are made on our Haas VF0 3-axis CNC milling machine, the following limitations apply:

1. Build-size is limited to parts that are 36x15x12 inches in size but for student class projects we

typically set a 12x4x4 inch limitation.

2. Steel, aluminum, and ABS plastic are the available work materials.
3. The accuracy of the resulting part is as good as +/- 0.002 inches.

For the fully automated, MIS testbed for milling, the client designer must use our WebCAD [19] front-end as the design software. In addition to enforcing the limitations on build size and material, this software imposes a strict Destructive Solid Geometry (DSG) design philosophy and checks machining rules [8]. To guarantee manufacturability, the designer begins with a cuboid stock and removes features that can be milled or drilled. Limits on the corner radii of inside corners and limitations on feature placement are shown to the designer during the graphical editing process. Part designs are output from this environment in SIF-DSG format [20] and submitted to our server, where they are processed automatically to produce G-code tool-paths for the milling machine.

Consequently, at the time of writing, the components being made in this fully automated but "stiff" machining testbed are single sub-components that exhibit relatively simple 2.5D geometries composed of milled pockets and drilled holes (Figure 4). Turner and Anderson describe such a machining feature based approach to design [21]; Cutkosky and Tenenbaum described the implementation of another such stiff environment which supported concurrent process planning [22]. The designer must use a special purpose CAD environment that only allows design features that can be automatically mapped onto machining features. Such an environment also makes it feasible to add the built-in rule checking capabilities we provide.

The evidence so far is that a fully constrained, or stiff, design environment, in which MOSIS-like rules and limitations are strictly imposed, is acceptable to only a small subset of all designers.

5. AN EMERGING “STRONGLY-COUPLED-BIDIRECTIONAL” CAD/CAM ENVIRONMENT

At the time of writing, we are focusing on an alternative model, offering the best of the two previous models. This third approach is *bidirectionally coupled*. From his or her local workstation, the CAD designer can access, over the Internet, certain software agents that: a) describe the limitations of downstream manufacturing, and b) allow process planning routines to be run on an emerging part design. The goal is to urge the designer to consider manufacturability limitations (CAM) at critical junctures during design (CAD), thereby insuring that manufacturing can more readily take place on a specific machine at a chosen sub-contractor.

The intended "client" for this coupled model of CAD/CAM is a designer who wants to use a flexible, commercially oriented design system but who is willing to check its manufacturability, from time to time, as the design emerges on the CAD screen. This requires extra effort and some compromises on the part of the designer. However, we anticipate that it will be a useful mode of attack that avoid many (but not all) of the "downstream" manufacturability problems.

Our current experimental environment for this third type of implementation service for milling begins with any CAD system such as SolidWorks, ProEngineer, or SDRC I-DEAS. After some initial design work has been done to create a new component, the user outputs the CAD file in a neutral format (currently we use STEP [23] or the ACIS .sat format [24]). The neutral part file is then ftp-ed to the remote server at the manufacturing site, where we convert it to ACIS .sat if necessary, so that we can use it as input to our suite of automated process planning and analysis tools. Our current modules include: a) feature recognition b) feature sequencing and fixture planning routines, c) feature decomposition and tool path planning routines, d) special-purpose tool path routines to minimize deleterious burrs on a part, and e) cost estimations for producing the features so far specified. Once the analysis has been completed, the designer is informed whether a suitable process plan was found and what the incremental costs are. Because we have produced a detailed process plan, we can make a reliable estimate of the cost without relying on heuristics. A CNC file can also be generated and sent back on request, if the part is indeed manufacturable.

As an alternative implementation, we have also configured such software agents as direct "plug-ins" to the CAD designer's desktop. This configuration allows the designer to immediately run "virtual process plans" on the emerging part design on their local workstation for faster feedback.

Implementing multiple plug-ins in a research lab is generally not feasible however, as they must be configured to the specific APIs of each individual commercial CAD system, a time consuming and non-platform independent task[25].

Our process planning work in these system builds on many years of related research in feature recognition. Popular approaches include graph matching, rule-based, volume decomposition, and knowledge-based techniques [26, 27]. Surveys of feature recognition and automatic manufacturability analysis can be found in [28, 29]. Analyzing manufacturability and evaluating process plans are discussed in [30, 31]. Recent work of Han et al. uses feature recognition for cost estimation [32].

6. DISCUSSION

As a final note, it is worth posing the question: What factors might encourage an industrial designer to give up the familiarity and flexibility of one of the well known commercial CAD systems in favor of the ”stiff, one-way” mode of a MOSIS-like MIS? In today’s industrial settings the answer to this question is usually driven by cost considerations. If there is a major cost saving that can be obtained as a result of the ”guaranteed manufacturability and fast turnaround” of the CyberCut MIS, then an industrial designer will be obliged to consider it more seriously and forego some of the creative shapes that are possible on a CAD system. Of course, if we can continue to expand the domain of parts that can be designed with WebCAD and still maintain ”guaranteed manufacturability” then so much the better.

Also recall that mechanical devices usually consist of many sub-components. Do all of these sub-components need to exhibit graceful complex curves? Probably not: sub-components that are destined to be buried deep inside a washing machine or an automobile can more readily be designed and fabricated with the ”stiff” mode of CyberCut. By contrast, the outer bodies of a car or a consumer product – those needing ”eye-catching” graceful lines – might be the sub-components that need to be designed with the full flexibility of a mature CAD system, where full design creativity is desirable and potential manufacturing difficulties are tolerated. This can be achieved in either the traditional loosely-coupled mode or in the newer strongly-coupled bidirectional mode; but the latter is expected to lead to much shorter completion times, in most cases.

A valuable insight gained in the CyberCut and MOSIS++ projects was the identification of these three existing modes of interaction between designers and fabricators, and realizing that all three of them may have their advantages for some particular design situation. We have implemented all three different types of test-beds, and let our students and clients explore them.

7. CONCLUSIONS

1. Inspired by VLSI MOSIS, an experimental Mechanical Implementation Service (MIS) has been developed that employs prototyping by layered manufacturing (FDM) and 3-axis milling.
2. Each manufacturing process plays a vital role at different points in a product-development cycle. Layered manufacturing will be more important at the start of a product-development cycle, while machining becomes most appropriate at a later stage to create highly accurate molds. Finally plastic injection molding will dominate in the final, high-volume production phase of a consumer product.
3. New interchange formats for SFF processes (SIF) and for machining (SIF-DSG) have been developed which are designed to serve as the link between designers and fabricators in an MIS.
4. We can characterize the coupling between design and manufacturing as either 1) loose, repetitive, 2) stiff, one-way, or 3) strong, bidirectional, choosing different points in the trade-off between "design flexibility" and "guaranteed manufacturability." The decision of which approach to use depends on the designer's preference, on cost considerations, and on the type of parts to be fabricated.

REFERENCES

1. Mead, C. and Conway, L. The Caltech Intermediate Form for LSI Layout Description, in Introduction to VLSI Systems. Addison Wesley, 1980, 115-127.

2. University of Southern California’s Information Sciences Institute -- The MOSIS VLSI Fabrication Service, http://www.isi.edu/mosis/, 2000.

3. National Science Foundation, Solid Freeform Fabrication Workshop I, New Paradigms For

Manufacturing. Arlington VA, May 2-4, 1994.

4. National Science Foundation, Solid Freeform Fabrication Workshop II, Design Methodologies for Solid Freeform Fabrication. Pittsburgh, PA, June 5-6, 1995.

5. Requicha, A. A. G. Representations for Rigid Solids: Theory, Methods, and Systems. *ACM Computing Surveys*, December, 1980, 437–464.

6. Shapiro, V. and Vossler, D.L. What is a Parametric Family of Solids? *Proceedings of the 3rd ACM/IEEE Symposium on Solid Modeling and Applications*, Salt Lake City, Utah, May 1995.

7. Bouma,W., Fudos, I., Hoffmann, C., Cai, J. and Paige, R. Geometric constraint solver. *Computer Aided Design*, June 1995, 27(6), 487–501.

8. Ahn, S. H., Sundararajan, V., Smith, C., Kannan, B., D'Souza, R., Sun, G., Mohole, A., Wright, P. K., Kim, J., McMains, S., Smith, J. and Séquin, C. H. CyberCut: An Internet Based CAD/CAM System. *ASME Journal of Computing and Information Science in Engineering*, 2001, 1 (1), 52-59.

9. 3D Systems, Inc. Stereolithography Interface Specification. Company literature, 1988.

10. McMains, S., Séquin, C. H. and Smith, J. SIF: A Solid Interchange Format for Rapid Prototyping. *Proceedings of the 31st CIRP International Seminar on Manufacturing Systems*, CIRP, May 1998, 40–45.

11. McMains, S. The SIF SFF Page. http://www.cs.berkeley.edu/˜ug/sif 2 0/ SIF SFF.shtml, 1999.

12. Stratasys, Inc., Eden Prairie, MN. *FDM System Documentation*, 1999.

13. Ahn, S. H., Montero, M., Odell, D., Roundy, S. and Wright, P. K. Anisotropic Material Properties of Fused Deposition Modeling (FDM) ABS. *Rapid Prototyping Journal, 2002* (submitted).

14. McMains, S., Smith, J., Wang, J. and Séquin, C. H. Layered Manufacturing of Thin-Walled Parts. *Proceedings of ASME Design Engineering Technical Conferences 2000, 26th Design Automation Conference*, Baltimore, MD, September 2000.

15 Alexander, P., Allen, S. and Dutta, D. Part Orientation and Build Cost Determination in Layered Manufacturing. *Computer Aided Design*, 1998, 30(5), 343–356.

16. Arni, R.K. and Gupta,S.K. Manufacturability Analysis for Solid Freeform Fabrication. *Proceedings of ASME Design Engineering Technical Conferences 1999*, Las Vegas, NV, Septem-

ber 1999.

17. Bablani, M. and Bagchi, A. Quantification of Errors in Rapid Prototyping Processes and Determination of Preferred Orientation of Parts. *Transactions of the North American Manufacturing Research Institution of the SME*, May 1995, 23, 319–324.

18. Thompson, D. and Crawford, R. Computational Quality Measures for Evaluation of Part Orientation in Freeform Fabrication. *Journal of Manufacturing Systems*, 1997, 16(4), 273–289.

19. Kim, J. H., Wang, F. C., Séquin, C. H. and Wright, P. K. Design for Machining Over Internet. *Proceedings of ASME Design Engineering Technical Conferences* 1999/CIE-9082, Las Vegas, September. 1999.

20. Smith, J. The SIF DSG Page. http://www.cs.berkeley.edu/˜ug/sif 1 0/ SIF DSG.shtml, 1999.

21. Turner, G. and Anderson, D. C. An object oriented approach to interactive, feature based design for quick turnaround manufacturing. *ASME Computers in Engineering Conference*, San Francisco, July 1988.

22. Cutkosky, M. R. and Tenenbaum, J. M. A methodology and computational framework for concurrent product and process design. *Mechanism and Machine Theory*, April 1990, 25(3), 365–381.

23 Dunn, M. (ed.) Industrial Automation Systems and Integration -Product Data Representation and Exchange-Part 48: Integrated Generic Resources: Form Features. ISO/ WD 10303-48, 1992.

24. Spatial Technology, Inc, Boulder, CO. *ACIS Save File Format Manual*, 1996.

25. Smith, C. and Wright, P. K. CyberCut: A World Wide Web Based Design to Fabrication Tool. *Journal of Manufacturing Systems*, 1996, 15(6), 432–442.

26. Jami J., Mäntylä, M. and Nau, D. S. *Advances in Feature Based Manufacturing*. Elsevier, Amsterdam, 1994.

27. Jami J. and Mäntylä, M. *Parametric and Feature-Based CAD/CAM: Concepts, Techniques, and Applications*. John Wiley & Sons, Inc., New York, 1995.

28. Han, J. H., Pratt, M. and Regli, W. C. Manufacturing feature recognition from solid models: a status report. *IEEE Transactions on Robotics and Automation*, December 2000, 16(6), 782–796.

29. Gupta, S. K., Regli, W. C., Das, D. and Nau, D. S. Automated manufacturability analysis: a survey. *Research in Engineering Design*, 1997, 9(3), 168–190.

30. Gupta, S. K. and Nau, D. S. A Systematic Approach for Analyzing the Manufacturability of Machined Parts. *Computer-Aided Design*, 1995, 27(5), 323–342.

31. Hirode, K. and Shah, J. J. Metrics for Evaluating Machining Process Plans. *Proceedings of ASME Design Engineering Technical Conferences*, Las Vegas, NV, September 1999.

32. Han, J. H., Kang, M. and Choi, H. STEP-based feature recognition for manufacturing cost optimization. *Computer Aided Design*, August 2001, 33(9), 671–686.

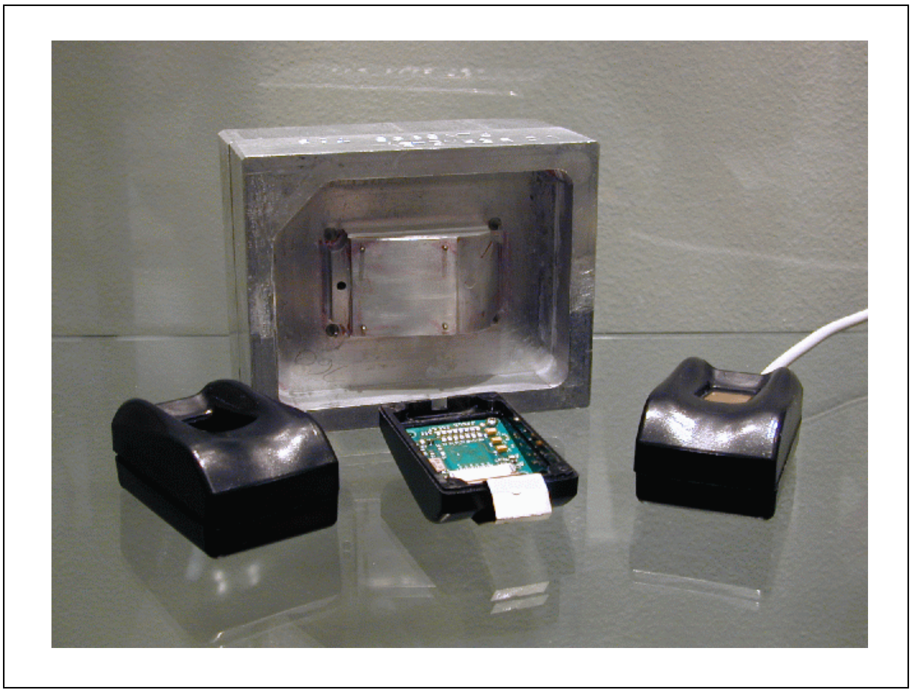


Figure 1. Machined part - aluminum mold (back) for STMicroelectronics' finger print sensor. ABS plastic parts were made from the mold (front left) then assembled with a printed circuit board.

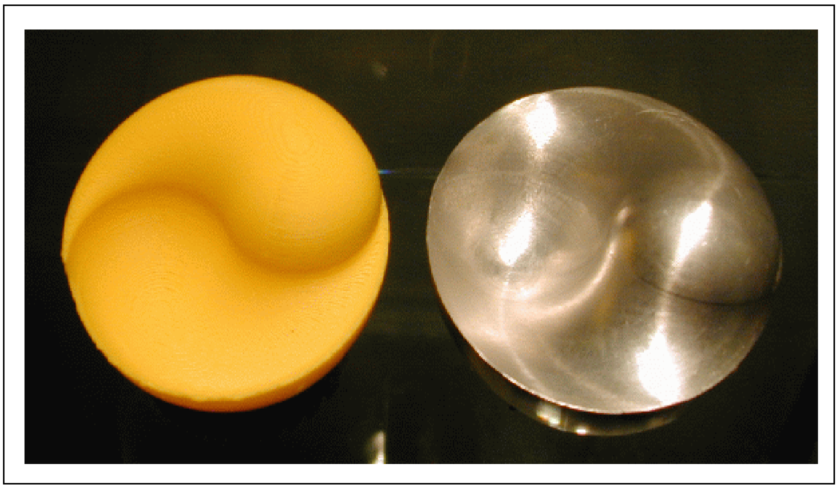
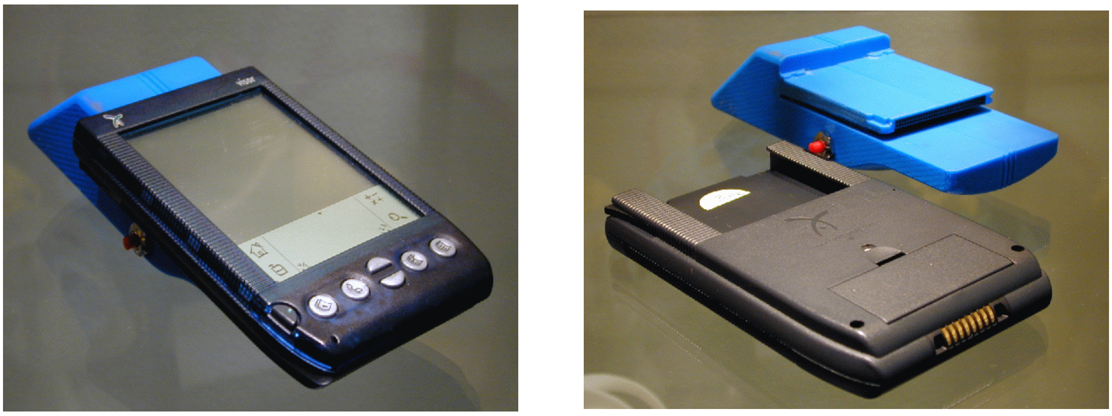


Figure 2. FDM and machined parts - three dimensional Yin-Yangs were fabricated by both the FDM process (left) and in aluminum with CyberCut machining (right).



(a) Front view

(b) Back view

Figure 3. FDM part - Package of GPS module for PDA device.

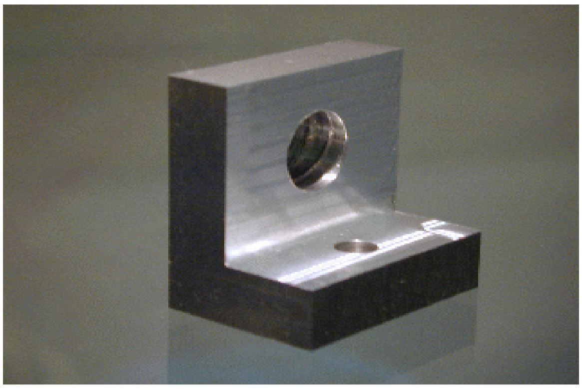


Figure 4. L-Bracket machined by the CyberCut system.