RPMI

RAPID PROTOTYPING AND MANUFACTURING INSTITUTE

Georgia Institute of Technology

December 2001

MANUFACTURING RESEARCH CENTER

Rapid Prototyping and Manufacturing Institute

Focusing Toward RP&M's Future

A Report on the Sixth Year of the RPMI

For more information about the Rapid Prototyping and Manufacturing Institute, contact:

Dr. David Rosen
Director, RPMI
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405
404-894-9668 phone
404-894-9342 fax

Andrew Layton
Program Manager
Rapid Prototyping & Mfg. Institute
Georgia Institute of Technology
Atlanta, GA 30332-0405
404-385-1053 phone
404-894-0957 fax

RPMI Web Site
http://rpmi.marc.gatech.edu

Table of Contents

Focusing Toward RP&M's Future

A Report on the Sixth Year of the RPMI

A Year to Build a Foundation for Impact

The RPMI started in 1995 with a small group of faculty, industry and government representatives sharing ideas for addressing specific needs in manufacturing education. From that exchange, constituents made commitments to the creation and growth of the RPMI. In our founding charter, we set down clear objectives and important guidelines for our operations and have remained true to those principles as we've grown. From the solid foundation we have established, the RPMI is making tremendous progress in leading the way into RP&M's future. Important changes are occurring within the RPMI and in the broader RP&M industry. In this report, we describe our accomplishments over the past year, and report on our plans for the future.

What We Do

Our ***vision*** of RP&M's future includes a world where layer-based, additive fabrication technologies (e.g., rapid prototyping) are recognized as production manufacturing technologies. We want to leverage the unique capabilities of these additive fabrication technologies to produce unique geometries and material structures. Our ***mission*** is to develop and deploy rapid prototyping and manufacturing technologies and applications through education, research and service. We have specific activities in each of these three categories, with a focus on the following areas:

- Applications: Rapid Tooling, Inspection, Machining
- Design for Additive Fabrication
- Stereolithography
- Laser Chemical Vapor Deposition
- RP&M Materials

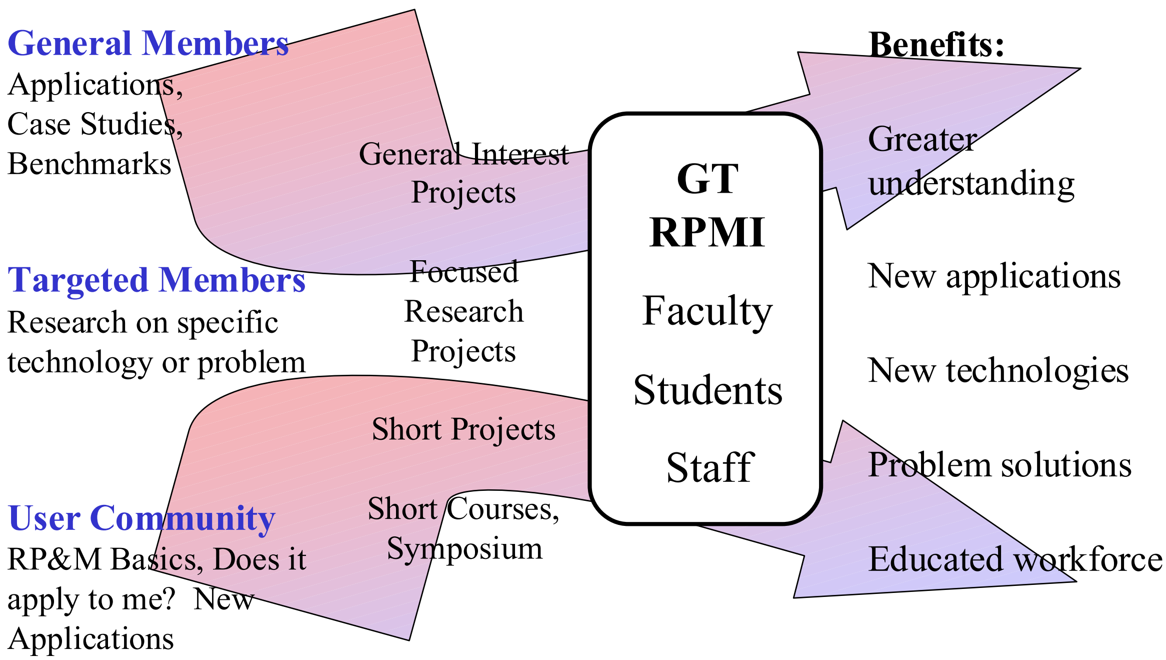
Maintaining our focus and communicating openly have been keys to our continued progress.

Who We Serve

"We" includes all of the groups listed below. The bottom line is that we serve each other within the RPMI, as well as those in industry and academia outside our group. Even as we've grown, communications among members of the group have remained open - this is the key to our success.

Our open sharing of ideas, time and capital is the foundation upon which the results of our work have grown.

Georgia Tech Students
Students in the RPMI benefit by being immersed into the real problems facing industry. Industry members provide guidance for the students as they progress through their courses, projects and research. RPMI faculty come from many disciplines; thus students are exposed to a much broader set of ideas than in a single-discipline environment.



The RPMI's lab is one of the best equipped anywhere in the world, so when combined with the other resources at Georgia Tech, opportunities for learning abound. During their time in the RPMI, many students will attend and speak at conferences, participate in member meetings, and help to organize and host our own national RP&M events. While in the RPMI, the students' intellectual capital grows – as do their lists of contacts in industry and academia. The results are extraordinarily valuable engineers, scientists and managers with unusually good employment options.

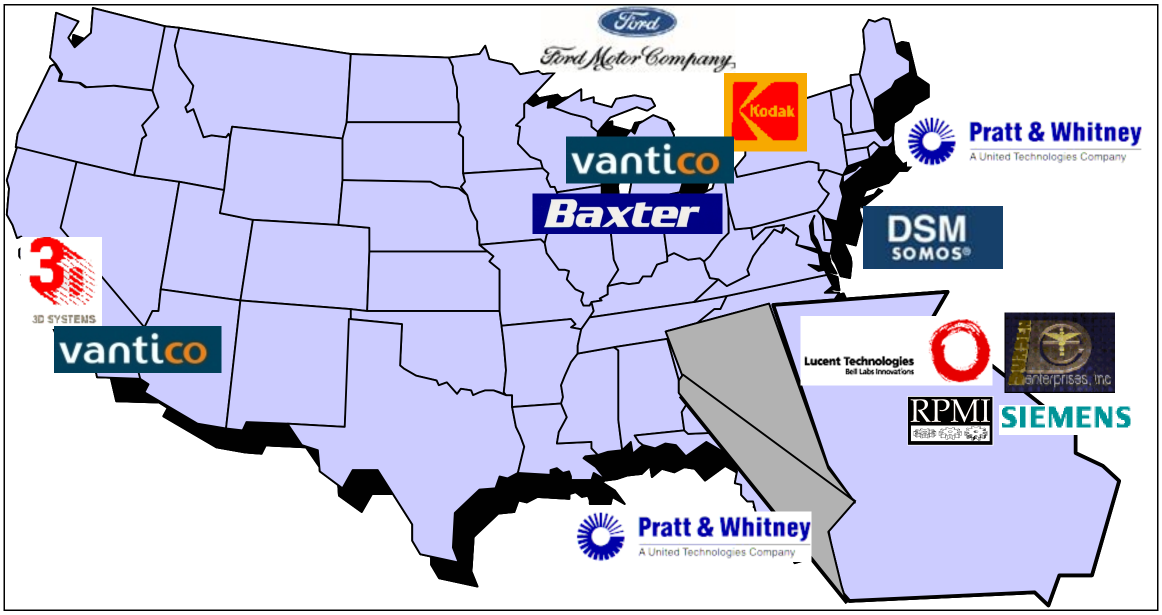
Georgia Tech Faculty
Our faculty provides the bulk of the technical know-how needed to carry out the projects. They recruit and advise the students in their individual activities. Faculty collaborate with industry representatives for a better understanding of the important issues facing the use and improvement of RP&M technologies. What they get is an improved opportunity to attract students to challenging work, access to excellent facilities, and leverage for continued scholarly accomplishment and recognition.

The RP&M Industry and Our Industry Members
Broadly speaking, any company with an interest in improved know-how in product development may reap benefits from our accomplishments in the RPMI. Scores of industry people have gained their first in-depth understanding of the capabilities of RP&M in our short course offerings (several participants have rated our symposium as the best of its kind in the nation – and the world); our technical achievements have rippled throughout the industry (at least four have been commercialized); and our students have become key

employees in design and manufacturing organizations. Fifty-seven RPMI alumni are now working in industry.

Our ten member companies serve as representatives of all manufacturers with an interest in RP&M. They provide the guidance that keeps our resources focused on the key issues, lend their specific expertise to the execution of our projects, and provide much of the capital needed to maintain our progress.

RPMI Member Companies



NSF Sponsorship

Through a Technology Reinvestment Program grant, the National Science Foundation played a crucial role in establishing the RPMI. That role expanded greatly through the Rapid Tooling Testbed initiative, a $1.35M, four-year project funded from the NSF Distributed Design and Fabrication Initiative. That project, designed to develop the technology -- and know-how -- to remove the bottleneck of tooling design and fabrication in the distributed design and manufacture of molded components, has now ended. However, new NSF grants continue to provide critical resources - and lead us in new and exciting directions!

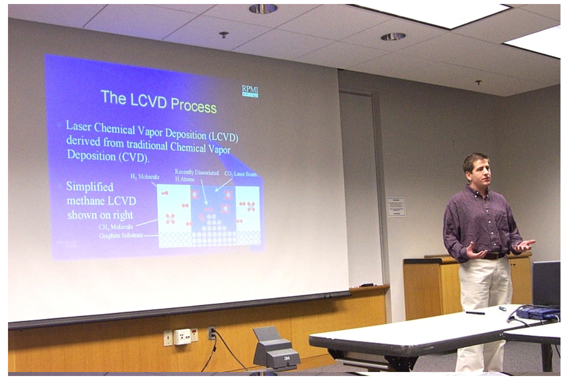
We are very pleased to report that NSF just funded a new 5-year project that we call “Digital Clay.” This is a $2M project aimed at developing a new class of user interaction devices and displays. Six Georgia Tech faculty are involved in the project, spanning three units on campus (ME, ECE, and Computing). Read more about this in the Projects section.

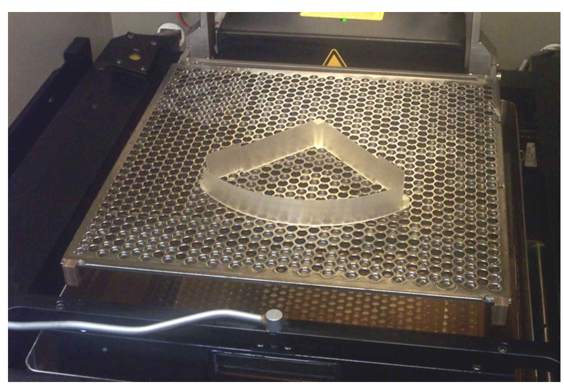
NSF continues to sponsor our LCVD work, leading to improved capability to fabricate small-scale metal and ceramic devices.

Georgia Tech Administration

We continually strive to work toward our RPMI mission of development and deployment of RP&M technologies through education, research and service. This mission directly supports Georgia Tech’s campus-wide mission of teaching, research and service. We have performed remarkably well in each of these areas: supporting education in the lab and through our projects, growing strong sponsored-research activities, and reaching out to industry and potential GT students to help them to understand and use RP&M techniques.

The Georgia Tech administration has responded by providing continued support both financially and with first-class laboratory and office space in the Manufacturing Research Center.





There Are Many Opportunities for RPMI Industry Members, Students, and Staff

Accomplishing Specific Goals

The RPMI has continued to make rapid progress in many areas since our last report in January 2001. In that report, we listed 28 goals for the year, and we've met or exceeded many of them. The list of goals is repeated here along with comments regarding our performance relative to each: (January 2001 goals are in italics and denoted by a "☐" (or "☑" for goals met).

Education

- ☑ *Involve Aerospace Engineering and Industrial Design schools in the RP&M mainstream through collaborative industry research in their respective colleges.*
- ☐ *Design, produce and make available an updateable web-based RP&M course for industry outreach in conjunction with College of Engineering's continuing education.program.*
- ☑ *Increase our activities with mainstream design, CAD, and manufacturing courses at Georgia Tech.*
- ☐ *Pursue collaborations with the Packaging Research Center at Georgia Tech in the area of electronic packaging.*
- ☑ *Graduate three Ph.D. students.*

Research

- ☑ *Develop injection molding process design guidelines that maximize SLA rapid-tool life.*
- ☑ *Demonstrate a working Rapid Tooling TestBed with which designers can submit part designs and get them fabricated by RP or through rapid tooling. Make it available to external users via the Web.*
- ☐ *Disseminate widely the results of an industry survey on RP, RT, and RM usage.*
- ☑ *Benchmark 3-dimensional metrology tools and methods for RP and RT-produced parts.*
- ☑ *Demonstrate the capability to design and fabricate large, light-weight structures by adapting our "truss structure" technology on industry parts.*
- ☑ *Develop and demonstrate SLA applications that utilize embedded actuators and sensors in complex devices.*
- ☑ *Publish five papers in refereed academic journals.*
- ☑ *Submit a patent application.*

Infrastructure

- ☑ *Hire a new RPMI Program Manager to replace the Director of Operations position.*
- ☐ *Hire a new RPMI Lab Manager.*
- ☑ *Maximize Enterprise value to all members by ensuring projects are structured with business affects in mind.*
- ☑ *Acquire resources to construct a Micro-SLA device to fabricate micro-scale SLA parts.*
- ☑ *Continue to evaluate the RPMI's directions in light of the changing nature of the RP industry. Fine-tune our strategic plan.*
- ☐ *Begin a formal collaboration with at least one other university.*
- ☐ *Build our RPMI membership to 12 companies and retain nine current member companies.*
- ☐ *Structure our current "body of knowledge" in an easy to distribute "how to" format for dissemination to industry.*
- ☐ *Simplify our web site's project status by making information ever more readily available to members.*

Outreach

- ☑ *Pursue outreach initiatives that enhance RPMI relationships with the Georgia's Economic Development Initiative, and the Georgia Tech Office of Technology Licensing in technology development and deployment.*
- ☐ *Broaden faculty involvement in materials and heat transfer research.*
- ☑ *Introduce 20 Georgia-based industries to the RPMI through site visits and meeting interaction.*
- ☐ *Sell every seat in the Advanced RP&M 2002: Symposium & Expo.*
- ☐ *Teach one RP&M seminar or short course for industry.*
- ☑ *Deliver seven RP presentations at four conferences.*

Education

☑ *Involve Aerospace Engineering and Industrial Design schools in the RP & M mainstream through collaborative industry research in their respective colleges.*

⇨ Only half of a check for this one. We continued our interactions with ID through a collaborative project with Kodak. Several additional projects are pending, as well as continued interactions at the classroom level. Although we continue to work with AE, through various support of their projects, we have yet to interact with them in a research capacity.

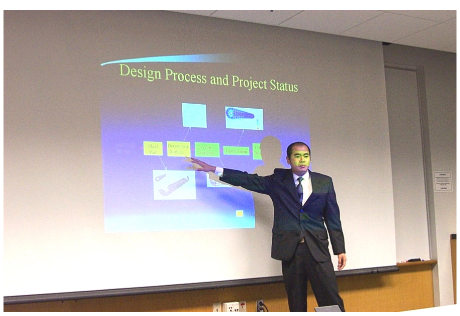
❒ *Design, produce and make available an updateable web-based RP&M course for industry outreach in conjunction with College of Engineering's component of continuing education.research.*

⇨ This has been a goal for two years, but we have not had the opportunity to pull together all of the elements to make it happen.

☑ *Increase our activities with mainstream design, CAD, and manufacturing courses at Georgia Tech.*

⇨ We are pleased to report that interactions with courses have increased. Lab tours, demonstrations, project support, and lectures have been integrated with seven courses in ME, including senior and graduate level design, CAD, and manufacturing courses.

❒ *Pursue collaborations with the Packaging Research Center at Georgia Tech in the area of electronic packaging.*



⇨ Although we have not successfully collaborated with the PRC yet, we have been working with several other groups in the MEMS and electronic areas. Our interactions with the MEMS group in Mechanical Engineering is very strong, as you will read later in this report. Also, we are working with two groups in the School of Electrical and Computer Engineering. So, we are successfully broadening the scope of our involvement and interactions across campus, but not with the groups we had planned on.

☑ *Graduate three Ph.D. students.*

⇨ For an academic perspective, the graduation of Ph.D. students is the ultimate achievement, since it indicates that we are generating new knowledge. Five Ph.D. students graduated this year, and a sixth should follow soon. Andre Claudet, Yong Chen, Chad Duty, and Dan Jean received their Ph.D.'s in Mechanical Engineering, while Kent Dawson graduated from Chemical Engineering. Congratulations to them and their advisors!

Research

☑ *Develop injection molding process design guidelines that maximize SLA rapid-tool life.*

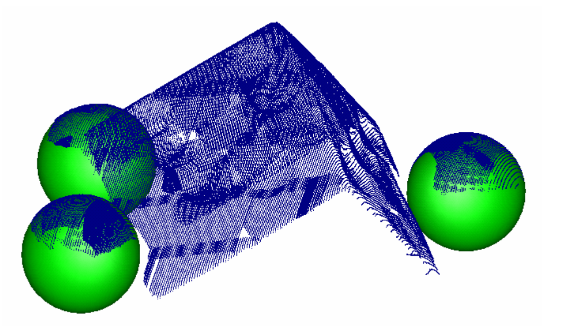
⇨ Building on our work over the past several years, we have made great progress in developing and experimentally validating models that explain AIM tool failure mechanisms. We turned this expertise into software that predicts SL mold life. And integrated that into a multiobjective optimization package that adjusts part and mold dimensions to maximize mold life. This is part of the RTTB project - see below.

☑ *Demonstrate a working Rapid Tooling TestBed (RTTB) with which designers can submit part designs and get them fabricated by RP or through rapid tooling. Make it available to external users via the Web.*

⇨ In April, we demonstrated version 3 of the RTTB distributed computing environment, with a new web-based implementation. We demonstrated robot arm and camera roller components being designed, process planned, and fabricated using SLA, as well as rapid tooling and injection molding. Everyone can access the RTTB through the site: http://rpmi.marc.gatech.edu/project/RTTB .

❒ *Disseminate widely the results of an industry survey on RP, RT, and RM usage.*

⇨ We have finished the survey and reported to the RPMI members - so that is success, but only in part. Beyond posting the survey results to the web, we have not disseminated the results widely. Look for additional presentations in the future on this topic.



☑ *Benchmark 3-dimensional metrology tools and methods for RP and RT-produced parts.*

⇨ Our metrology work has proceeded at a rapid pace, with tremendous technology transfer results! Two RPMI member companies are beta-testers for Paraform's Inspect software. We have extended our metrology study to the micro-scale, with experiments with Zygo and similar equipment.

☑ *Demonstrate the capability to design and fabricate large, light-weight structures by adapting our "truss structure" technology on industry parts.*

⇨ This is cool stuff! We demonstrated the potential of truss structures for producing parts with high stiffness-to-weight ratios. Four major experiments were performed, two on parts from Pratt & Whitney, one from a sand casting company, and one from a robot manufacturer. We are improving the technology in order to make it faster and easier to generate parts with truss structure, to optimize them, and to ensure their manufacturability.

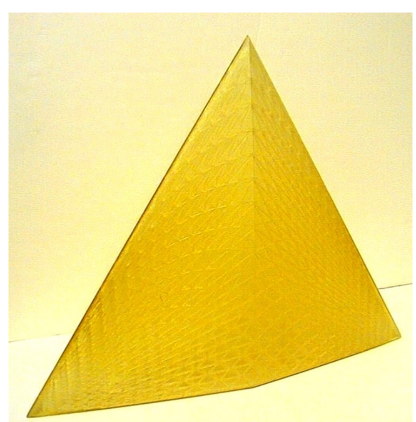
☑ *Develop and demonstrate SLA applications that utilize embedded actuators and sensors in complex devices.*

⇨ Tremendous progress has been achieved on methods for building around inserts. This past year has seen new classes of applications in MEMS devices and packages. Look for exciting developments in the coming year as we experiment with our new Viper Si2 SL machine!

☑ *Publish five papers in refereed academic journals.*

⇨ As an academic activity, scholarly publications in leading journals are critically important. In 2001, we published 6 journal papers - and submitted 10 more!

Infrastructure



☑ *Hire a new RPMI Program Manager to replace the Director of Operations position*

⇨ Andrew Layton joined the RPMI in Spring 2001. He has a multi-facetted background, with military service, industry positions, and academic experience figuring prominently. Welcome Andrew!

❒ *Hire a new RPMI Lab Manager.*

⇨ We did not hire a new Lab Manager - but we kept the "old" one! Steven Sheffield joined the RPMI on a part-time basis in Fall 2000, and has continued serving in that capacity. Since he has done a superb job in keeping the lab running, we hope he continues with us far into the future.

☑ *Maximize Enterprise value to all members by ensuring projects are structured with business affects in mind.*
- ⇨ Of course, we continue to solicit projects from RPMI members and keep them involved and updated on our progress. Delivering value remains a key goal! We have improved our procedures by incorporating specific technology transfer mechanisms in all of our projects. This enables us to build in demonstrations of research results on members' parts or tools, for example.

☑ *Acquire resources to construct a Micro-SLA device to fabricate micro-scale SLA parts.*
- ⇨ We did this … except for the "construct" part. Actually, we acquired a new Viper Si2 machine from 3D Systems in Fall 2001! This broadens our ability to fabricate much smaller features and opens up tremendous new opportunities in our MEMS research, as well as with the Digital Clay project.

☑ *Continue to evaluate the RPMI's directions in light of the changing nature of the RP industry. Fine-tune our strategic plan.*
- ⇨ Given the economic downturn and the changes occurring in the RPM industry, we must continually evaluate our operations and directions. We have refocused our efforts in our research program and restructured our membership options to increase our flexibility to work with industry. You can read more in several places in this report.

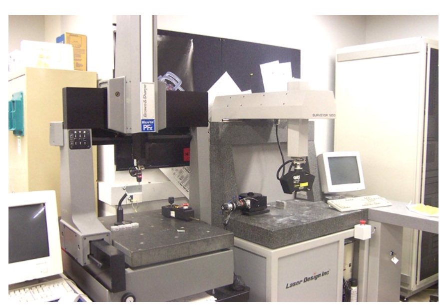
❐ *Begin a formal collaboration with at least one other university.*
- ⇨ This is an area to which we have not devoted enough energy. Several opportunities exist and we will continue to pursue them.

❐ *Build our RPMI membership to 12 companies and retain nine current member companies.*
- ⇨ With our new Program Manager, we will launch an aggressive effort to increase industry membership in the coming year. However, 2001 was disappointing since we lost members and did not gain any new ones, despite holding an Open House and recruiting aggressively in Spring 2001. Lots of interest from industry, but travel restrictions and tight budgets seemed too much to overcome.
- ⇨ As we adjust our research program and start delivering results, we believe we will improve our chances for rebuilding industry membership.

❐ *Structure our current "body of knowledge" in an easy to distribute "how to" format for dissemination to industry.*

❐ *Simplify our web site's project status by making information ever more readily available to members.*
- ⇨ We pursued both of these initiatives. In fact, we have a prototype implementation of a projects database. However, due to changes in RPMI staffing, we could not implement what we started. Both of these initiatives are very important to our long-term success and will continue to pursue them.

Outreach



☑ *Pursue outreach initiatives that enhance RPMI relationships with the Georgia's Economic Development Initiative, and the Georgia Tech Office of Technology Licensing in technology development and deployment.*

⇨ We have had good interactions with EDI, including helping a Georgia company achieving a deadline to exhibit at a major show. There is a major effort to expand OTL and the technology transfer infrastructure at Georgia Tech - and we are involved.

❒ *Broaden faculty involvement in materials and heat transfer research.*

⇨ We did not broaden faculty involvement in these areas, but we did maintain interactions. Look for additional activities in the coming year.

☑ *Introduce 20 Georgia-based industries to the RPMI through site visits and meeting interaction..*

⇨ We visited with and introduced over 20 Georgia industry representatives to the RPMI through lab tours, recruitment contacts, and the Symposium. Among these were CibaVision, Gulfstream, MicroCoating Technologies, ARRK, Morris Technologies, Razzi Corp., and Elan Motorsports.

❒ *Sell every seat in the Advanced RP&M 2002: Symposium & Expo.*

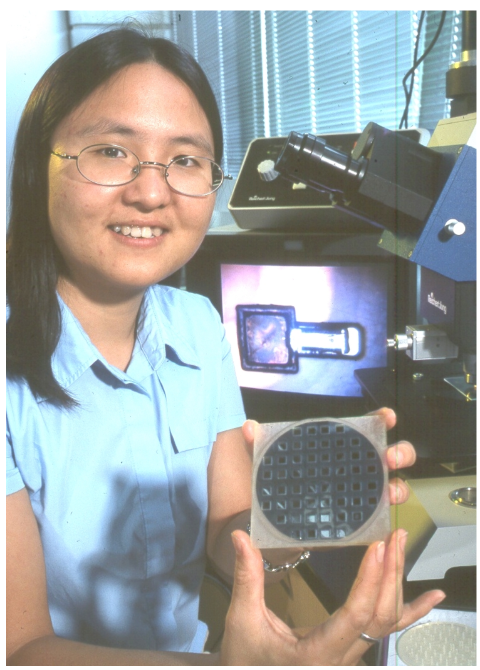
⇨ Too early to tell. We have postponed this event until October 2002 due to the poor business climate and travel restrictions. Look for a very strong program in October.

❒ *Teach one RP&M seminar or short course for industry.*

⇨ This was not a priority area in the past year and we did not pursue it. With expanded interactions with other groups at Georgia Tech, we are confident of holding at least one new short course, with a unique twist, in the coming year.

☑ *Deliver seven RP presentations at four conferences.*

⇨ This has been another banner year for presentations at conferences, universities, and industry. Ten conference and workshop papers were presented at seven different conferences, including the 3D Systems NASUG Conference, the SME RPA Conference, ASME Design Technical Conferences, Solid Freeform Fabrication Symposium, CIRP General Assembly (Nancy, France), and workshops in Hong Kong and Korea. All of these conferences have significant RP&M content and we are making an impact!



Angela Demonstrates a MEMS-Stereolithography Application

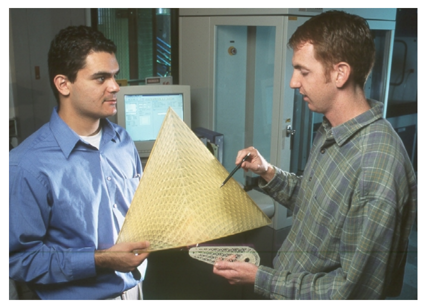
Leverage

As we embark on the future trends of RP&M, our industrial applications, multidisciplinary research and deployment of educational solutions contribute to future industry advancement. Now that we are into our sixth year, many have heard of our accomplishments and more have come to us with their ideas and resources looking to get involved. We are clearly known throughout the RP&M community both nationally and internationally. As more people get involved in our community, more opportunities for synergy and leverage arise. And we take advantage of them. We are visited from inside Georgia Tech, from industry, from professional societies, from national research laboratories, from government bodies and key RP&M players in Europe and Asia. Those who have come and those whom we have visited have made good things happen. Here are some examples:

Driving Industrial Applications

Many companies now utilize RP parts, patterns, and tools as part of their every-day product development processes. As we have progressed, the RPMI is no longer just solving problems, we are now well poised as **drivers**, helping to identify new applications and make them a reality. Following are some examples of RPMI projects that have made an impact.

The truss structure research that we reported on last year has made a real impact at Pratt & Whitney. Visitors to Pratt & Whitney's facilities (from suppliers and customers including the Defense Department) were very impressed with the truss structure samples that the West Palm Beach, Florida folks built. Based on that interest, we developed truss structure models for two Pratt applications. The capability to build strong, stiff, light-weight structures has many applications, and gets people's attention. Through this collaboration, we have impressed many visitors and internal P&W personnel, making a positive impact on them and the RPMI.



With no in-house RP equipment, Lucent Technologies is continually challenged to quickly fabricate prototypes of new designs of injection molded parts. By interacting with the RPMI, John Malluck was able to investigate alternative rapid tooling methods and vendors, compare them, and help lower Lucent's product development budget, impacting their bottom line.

Product development at Baxter Healthcare requires rapid inspection of production and prototype parts. Through interactions with the RPMI, Marc Bellotti learned about inspection and metrology hardware and software. He was able to integrate rapid inspection methods, particularly Paraform's Inspect software that is based on Dr. Tom Kurfess' Georgia Tech research, into his product development processes, significantly impacting his bottom-line too.

A small, local Atlanta company, Razzi, Corp., manufactures ground-effect components for the automotive after-market. They needed to quickly generate a CAD model of a new spoiler that their craftsmen had constructed. By leveraging the RPMI's expertise in reverse engineering, we were able to quickly scan and reverse engineer their design, enabling them to meet a critical deadline. Leverage!

Multidisciplinary Research

Faculty and students from five disciplines are involved in the RPMI. Combining our understanding from more than one area of expertise allows us to tackle the tough problems that cross traditional disciplinary boundaries.

One area of critical importance to Georgia Tech is MEMS, Micro-Electro-Mechanical Systems. During the past year, tremendous progress has been made in demonstrating the synergy among traditional silicon micromachining and stereolithography. Collaborations among Peter Hesketh (ME), James Gole (Physics), and David Rosen have enabled new applications to be demonstrated. Gas chromatography devices, interdigitated electrodes, and atomic force microscope cantilever package are three types of devices that have been demonstrated. One particularly useful result has been to show that SL devices that are built on silicon wafers can be subject to many silicon micromachining operations. SL provides tremendous opportunities for building 3-D structures on top of MEMS devices.

A new NSF grant was received in Fall 2001 that provides breakthrough opportunities. A collaboration of seven Georgia Tech faculty from Mechanical and Electrical Engineering, College of Computing, and the Center for Rehabilitation Technology resulted in a major grant to develop new types of human-computer interaction devices. We call these devices "digital clay," evoking the image of interacting with a lump of physical clay to shape it … and having the clay integrated with a computer, so that shape changes can be captured electronically, represented in CAD, communicated to others, etc. We have an ambitious research agenda that involves new MEMS fabrication technologies for hydraulic control of the "clay," new SL structures that can serve as the "body" of the clay, and new controls methods for controlling the massively parallel clay structure. We will be reporting results periodically throughout the 5-year project, so look for new examples of multidisciplinary leverage.

The RPMI served as a focal point for an investigation into the automated manufacture of dental crowns and other restorations. Working with local orthodontists and GTRI personnel, we helped evaluate candidate processes to scan teeth and anatomy, fabricate patterns, and ultimately fabricate crowns and restorations. Look for some announcements in 2002 along these lines.

Outreach to Secondary Education and Exposure to the Community at Large

In November 2001, the RPMI was pleased to show our laboratory facility to the high school teachers being recognized in the Siemens-Westinghouse Science Fair that was held on campus. Their curiosity and continuing desire to learn was made apparent by the vast number of questions, the depth of the questions, and the perceptive follow-up questions. These teachers are an important part of the scientific education community, and guide the development of talented young minds. Hopefully, these teachers were impressed sufficiently to guide some of those talented young minds to Georgia Tech.

Another high school group visited the RPMI this Fall. The Georgia Academy of Mathematics, Engineering and Science (GAMES) brought their students on campus for a tour of the Georgia Tech facilities and the research centers in the MARC building. Upon graduation from GAMES, the student is awarded a high school diploma and Associates of Science degree. If the student has taken an appropriate course of study in pursuing the A.S., the student is guaranteed admission to Georgia Tech upon satisfactory completion. Andrew Layton is certain that he will see some of those same faces in the RPMI lab in the future.

The Georgia Public Broadcast System, through its PeachStar organization, produces video documentaries for use in high schools throughout the state of Georgia. The RPMI supported PeachStar in the production of a documentary entitled "SmARTistic." The RPMI is proud to have provided them with an Actua 2100 rendering of a sculpture created by Cheryl Goldsleger, one of the featured artists. We also hosted a film crew in our laboratory, so they could film the Actua as it built the sculpture. Steven Sheffield's wristwatch has been memorialized on film for posterity!

The "SmARTistic" documentary, which is hosted by the First Lady of Georgia Marie Barnes, features Georgia-based artists and discusses how they use math, science and technology in their artwork. The PeachStar project was funded through a grant from the state of Georgia. Governor Barnes attended the premier and spoke briefly. By supporting these types of projects, the RPMI is working to create a network of friends, colleagues, and supporters in high places.

We continue to work with artist Cheryl Goldsleger, an Assistant Professor from Georgia State University, in support of an upcoming exhibit. Her works will be part of a show that will be traversing Georgia during the course of 2002. Our support is being recognized prominently in her program literature, and on the wall text which describes the various works. She has spoken highly of us to friends in the art community, many of whom have funding through a variety of sources and are eager to explore the capabilities of additive fabrication in realizing their works.

The Museum of Contemporary Art (MOCA), in Atlanta, will be opening sometime in the spring of 2002. Cheryl Goldsleger's works will be on display. She has contacted the curator to arrange for a videotape loop of her work being built in our SLA to be filmed. This is to be included as part of the display. Andrew Layton will be writing a description of the SLA process to be included as an "information crawl" on the tape loop, and will mention the RPMI as many times as he can.

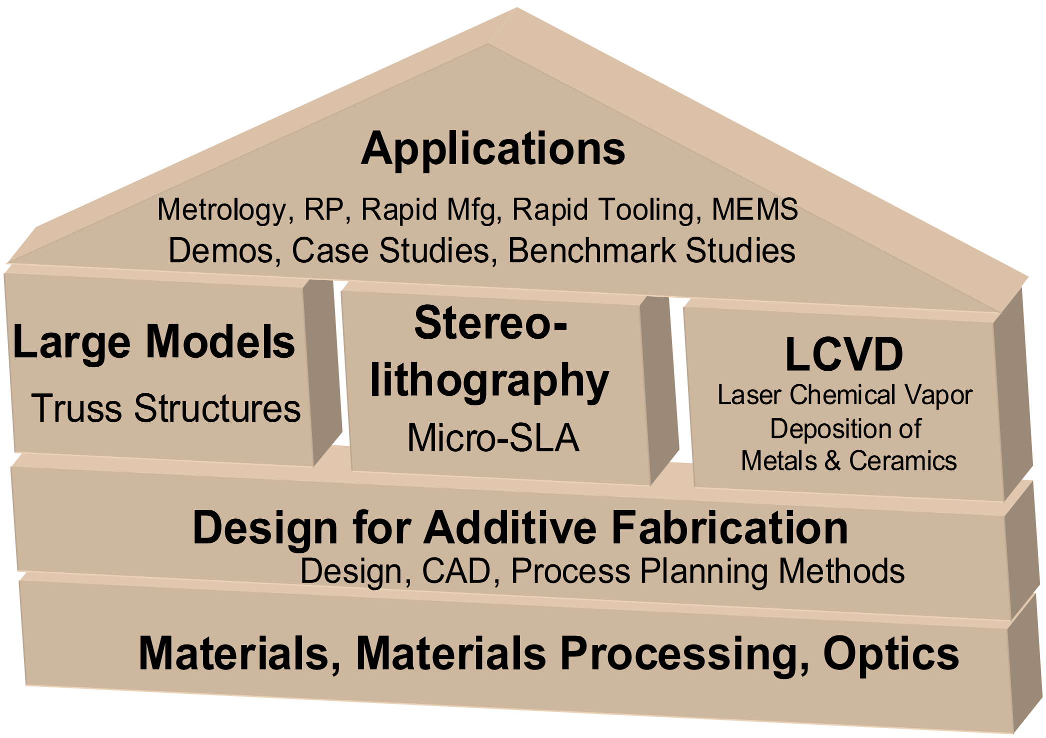
We have expressed our willingness to support a small project at Louisiana State University. Professor David Baird, from the LSU School of Architecture, is working to secure funding to explore the use of RP and the World Wide Web in Architectural design and modeling. Ultimately, he would like to add Interior Planning and Design, Construction and Structural design, and modeling – basically RTTB for buildings.

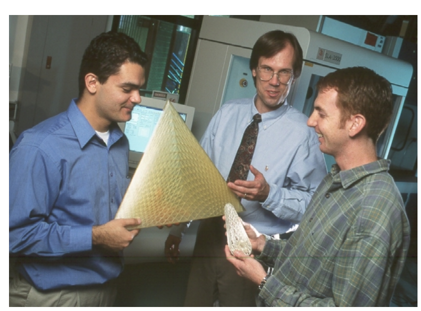
The RPMI has been approached by, and worked with, several entrepreneurs who were in the process of developing new products. They have approached the RPMI for two reasons: Because they trust the "brand name" Georgia Tech; and, because they didn't know where else to turn. We have created an avenue to work with these entrepreneurs. We will do this to stay abreast of the desires and needs of potential RP consumers. This serves as a reality check for our research efforts. It also gives us the opportunity to "learn by doing," and to cross-pollinate with others and the ideas that they have.

Example of Cheryl Goldsleger's Geometric Art

RPMI Projects

Rapid prototyping and manufacturing is an incredibly varied and exciting area. Opportunities abound. During the past year, we reorganized our research portfolio into categories that correspond to the figure below. Rapid Tooling, Rapid Inspection and Computer-Aided Verification (CAV), and machining have been grouped into the category of Applications. Design for Additive Fabrication work includes efforts to develop technologies for large models, as well as the Digital Clay project. Three projects are grouped under the SL Research category. The area of RPM within Product Realization is useful, but reflects the previous project organization. Both projects in this area have finished. The LCVD and Materials areas continue to be of key interest.





Project Overview Table

Current RPMI Projects	Students	Faculty	Industry/Govt
Applications			
Effect of RP Tooling on Final Product Properties	Kent Dawson	John Muzzy	G Beldue, C. Hull, B. Durden, S. Jayanthi
Experimental Methodology for Rapid Tooling . Failure Mechanisms for AIM Tools	Vincent Rodet, Giang Pham	Jon Colton	N Enke, G. Beldue, J. Malluck
Point-To-Surface Assignment During Registration	Andre Claudet	Tom Kurfess	G. Beldue, B. Delisle
Metrology and Reverse Engineering Capabilities	James Nichols	Tom Kurfess	G. Beldue, M. Bellotti
Characterization & Calibration of SLA Products and Processes	Brian Davis	Janet Allen	C. Hull, S. Jayanthi
Machining of Ceramic-Filled Tooling Board	Tosin Tomori	Shreyes Melkote	M. Kotnis
Large Models/Design for Additive Fabrication			
Truss Structure Design	Vincent Wang	David Rosen	N. Enke, M. Bellotti, R Pressley, D Kalisz
Compliant Structures	Jacob Diez	I. Ebert-Uphoff	M. Bellotti, D. Kalisz, M Kotnis
Digital Clay	Austina Nguyen, Paul Bosscher, Haihong Zhu	David Rosen, Imme Ebert-Uphoff	NSF, D Kalisz, M Kotnis, N Enke
Stereolithography Research			
Micro-SLA and SL Resolution	Benay Sager	David Rosen	J Malluck, D Kalisz
SL Cure Modeling	Yanyan Tang	John Muzzy	D Kalisz, M Kotnis
MEMS Applications	Angela Tse	Peter Hesketh	D Kalisz, J Malluck
RPM Within Product Realization			
Best Practices Survey	Atul Mandal	Nagesh Murthy	M Bellotti, J. Malluck
Rapid Tooling Testbed Material & Process Selection RP Process Planning, Tool Design Ejection Mechanism Design Tool Design Rules Point-To-Surface Assignment During Registration Distributed Computing Environment	 Marco Fernandez Yong Chen, Shiva Prasad Sunji Jangha Joe Crawford Andre Claudet R Kulkarni, A. Xiao, Yuan Chen	 Janet Allen David Rosen David Rosen Jon Colton Tom Kurfess Farrokh Mistree, Karsten Schwan	NSF
Laser Chemical Vapor Dep.:			
Machine and Process Development	C. Duty, D. Jean, S Bondi, T. Elkhatib, R Johnson	Jack Lackey	GT & NSF
Process Planning	Jae-Hyoung Park	David Rosen	GT & NSF
Materials			
RP Materials Characterization	Andrew Layton	David Rosen	M Kotnis, R. Pressley, Baxter

Applications

In the Applications area, we group together rapid tooling, metrology, and machining projects. Rapid tooling was the first focus area for the RPMI and continues to generate considerable interest in industry. Our projects this year include fundamental studies of molding and material behavior in rapid tools made in SL and tooling board. Metrology covers research in various aspects of scanning parts, manipulating point clouds, inspection, reverse engineering, and characterizing manufacturing accuracy.

Effect of RP Tooling on Final Part Properties

The development of a plastic part frequently involves several prototype iterations. Production of these prototypes with conventional metal tooling often results in high costs and long lead-times. A group of materials and processes known as rapid tooling can produce a limited number of prototypes faster and more economically than conventional tooling. However, the material property differences of these types of tooling result in mechanical property differences in the final plastic parts.

In order to understand the reasons underlying this phenomenon, the tensile and flexural properties of atactic and syndiotactic polystyrene molded in H13 steel, T6061 aluminum, aluminum filled epoxy, ceramic filled epoxy, carbon fiber composite, and backfilled stereolithography (SL) tools were compared. The properties of polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), and polypropylene (PP) were also studied. Kent Dawson, a Ph.D. student in Chemical Engineering, led this investigation, supervised by John Muzzy. When molded in the rapid tools, both polystyrene isomers exhibited lower ultimate tensile stress, similar Young's modulus, and lower ultimate elongation than parts produced from steel and aluminum molds. Birefringence observations were used to analyze these results. The differences in the ultimate tensile stress and ultimate elongation were attributed predominately to the degree of polymer orientation within the part. The stress-strain data for both isomers were found to be correlated. In flexural testing, both isomers produced in the rapid tools exhibited higher flexural strength, higher flexural modulus, and lower ultimate flexural elongation than parts produced in the steel and aluminum tools. Unlike the tensile tests, these differences were attributed to the thickness of the frozen skin on the surface of the part.

In order to understand how different mold materials and construction techniques affected the heat transfer characteristics of the part and mold, a one-dimensional heat transfer model for composite injection molds was developed to predict the heating and cooling rates of the injected polymer and mold material. The model provided a very accurate prediction of experimental data for the first 100 seconds. Additionally, the model indicated that SL shell thickness (1.02 - 2.54 mm), backfill material (Aluminum filled epoxy, low melting point alloy, and solid SL), and cooling distance (2.79 - 6.35 mm) exerted negligible effects on the surface temperature of the mold over a single molding cycle. The model was adapted for multiple cycles in order to quantify any long-term heating or cooling of the mold. C-Mold simulations were performed to help validate the experimental work. As a result, we can predict the mechanical properties of certain injection-molded materials as a function of the mold material and molding conditions. Kent graduated with his Ph.D. in Spring 2001.

Experimental Methodology for Rapid Tooling

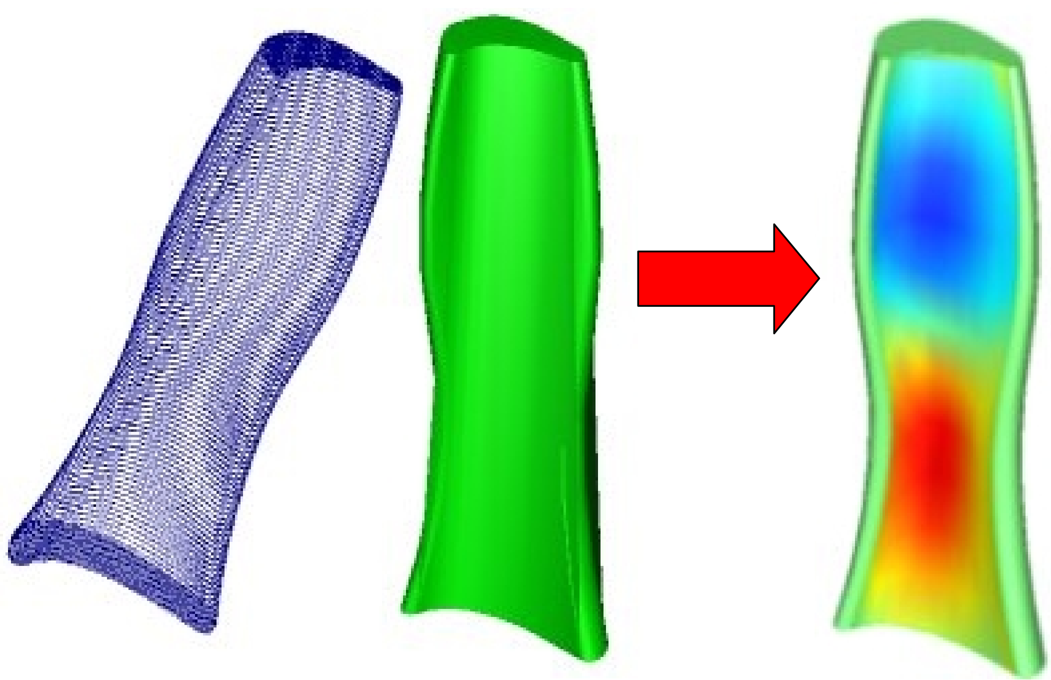
Predicting the number of parts that can be molded in a SLA tool is very difficult due to the complexity of the molding process and the nature of SLA resins. The goal of this project is to reliably mold 50 parts in SLA tools. To do so, we must understand the failure mechanisms of SLA tools and relate these failures to molding process variables, mold material properties, part geometries, and the polymer being molded. Due to our research over the past 4 years, we have identified the predominant failure mechanisms of SLA tools: flow failures during injection, fatigue failures due to thermal and mechanical cycling of the tool.

Jon Colton is leading this project. Three Masters students worked on various aspects of the project. Joe Crawford focused on flow failures and quantifying their causes. Giang Pham and Vincent Rodet concentrated on different aspects of fatigue failures. Joe performed an extensive set of computational simulations using ANSYS for determining temperature and stress distributions over a series of shots. Using C-Mold, the pressure distribution on mold features was also determined. A variety of feature height and aspect ratios were tested. Physical experiments were performed in order to compare with the computational predictions. Again, higher aspect ratio features failed earlier. Giang developed an improved ejection force model based on part geometry and SL process variables, including feature sizes, draft angle, Young's modulus and Poisson's ratio of the mold material, layer thickness, line width compensation, and border overcure. A series of physical experiments were performed to test the analytical model. This is the first time that an ejection force model based solely on material properties and geometry has included both the mold core and the part being molded. This allows the ejection force for any arbitrary combination of mold and part materials to be determined. Vincent developed correlations between measured properties of SL molds and the injection molding processing conditions so that we have a better understanding of failures and can predict mold failure. The correlation identified testing procedures for new materials. Also, these results help to minimize the effects of fatigue and maximize tool life. Specific factors and properties investigated included: mold build orientation in the SL machine, physical aging of the material during molding, tensile fatigue tests at elevated temperatures to test macroscopic fatigue failure due to ejection, fracture tests at different temperature and thermal aging levels to address crack initiation, and the effect of additional curing processes. All three students graduated in Spring 2001.

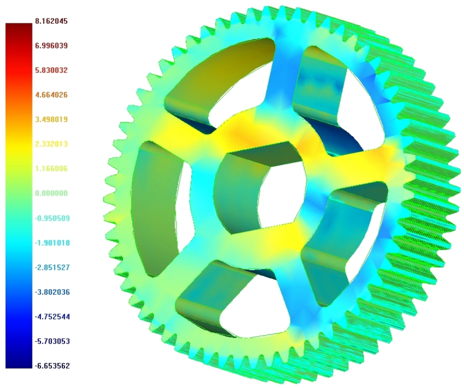
As a result, we can conclude that SL molds fail during either injection of the molten polymer or ejection of the molded part. We developed models of SL mold failure under both conditions that correspond well to physical experiments. As a result, we have identified the significant factors in the SL and injection molding processes that influence mold life (the number of parts that can be molded before mold breakage). Furthermore, these models can be used to predict mold life. These results aid designers and molders who are considering the usage of SL molding by providing guidance in: assessing the suitability of SL molds for molding specific parts, fine-tuning part and mold designs to facilitate SL molding, setting process variables for the SL and molding processes

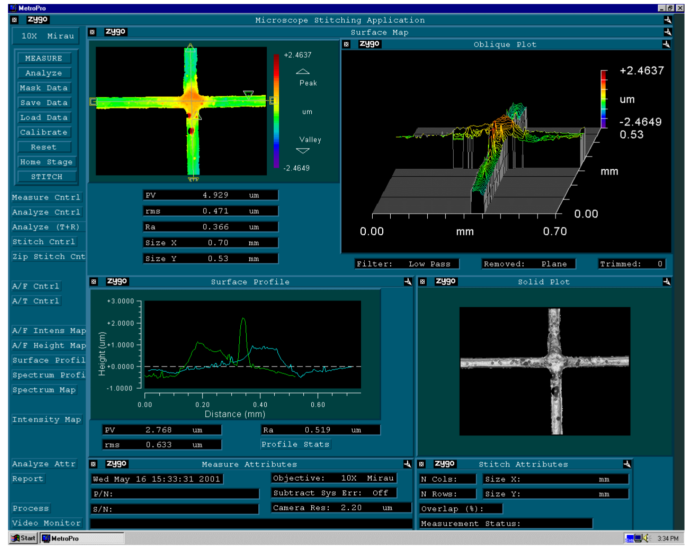
Point-to-Surface Assignment During Registration

As part of our continuing metrology research program, we have a significant effort underway to develop better and faster ways to measure what we produce, and then to explain those measurements in terms of the fabrication processes that produced the measured parts. There are many technical challenges when developing algorithms to register and analyze three dimensional measurement data. New technologies have become available for quickly generating large data sets, including laser scanners and other optical systems. These technologies provide very dense data sets that can easily contain millions of points. Therefore, these algorithms must be efficient and the computational complexity of the algorithms must be kept low. This is a shift from algorithms that were previously developed to analyze data from touch probe Coordinate Measuring Machines (CMMs) where data sets contain only tens or hundreds of points.



The research problem, then, is: How can these large data sets be compared to complex CAD models to yield, in a practical amount of time, information that



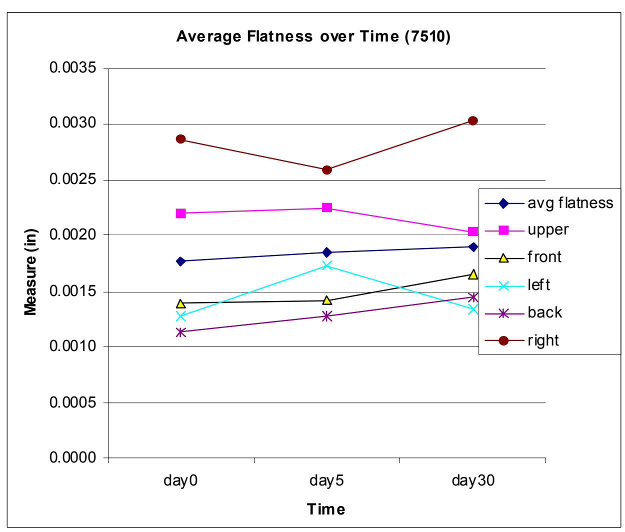


is useful to manufacturers? This research addresses the analysis problem and contributes to the theoretical body of knowledge for the area. Andre Claudet was the graduate student working on this project, supervised by Tom Kurfess. Generally speaking, we seek to develop algorithms and procedures for extracting artifact quality information from the combination of a set of three-dimensional coordinates with the design CAD model. The specific focus in this project was to solve the problem: Given a point cloud that represents more than one part surface, it is first necessary to determine to which surface each point corresponds. At worst, it is necessary to test each point against each surface in the part. Our research focused on first reducing the number of points to be tested, then on improved methods for eliminating point-surface comparisons and on more efficient point-to-surface deviation calculations.

This project has resulted in faster methods for analysis of three dimensional measurement data. Algorithms have been developed and implemented to achieve a reduction in the computational complexity methods currently used at Georgia Tech. The modular framework for the transform allows any first order continuous transform to be included (*i.e.,* fit) in the localization process.

Characterization and Calibration of SLA Products and Processes

When building parts in an SLA machine, the user is faced with many decisions regarding how the part will be built. The user can control the quality of the build by changing numerous SLA process variables, such as layer thickness, by reorienting the part, or even by changing resins. A user will probably have preferences for the part build (i.e., accuracy or speed), but may not understand how to vary the process variables to produce the desired results. To complicate matters, new resins are being developed and new SLA technologies are periodically updated. The overall goal of this project is to design an experimental system to characterize and calibrate SLA products and processes. This proposed system should be applicable to new resins and SLA technologies as they are introduced.



Brian Davis graduated in Fall 2001 after working on this project, supervised by Janet Allen. This project continued the research of Charity Lynn-Charney and Joel McClurkin, who conducted extensive accuracy studies of our SLA-250. Brian had the task of verifying past work and, more importantly, of developing a general experimental methodology for SLA accuracy assessment. Research results provide input to many different projects, including our rapid tooling work, our other metrology work, and the Rapid Tooling Testbed project. Specifically, this work provided the empirical models of SL capability that were needed for SL process planning for the RTTB project. More importantly, a characterization and calibration procedure was developed, based on ASME and ISO standards for CNC machines. This procedure is an important contribution to the eventual development of characterization standards for SFF machines, as well as all manufacturing machine tools.

Machining of Ceramic-Filled Tooling Board

In contrast to SL based rapid tooling approaches, high speed machining is an alternative process for manufacturing intricate prototype parts using injection molding. This project will investigate the machinability characteristics of Vantico (Ciba-Geigy) tooling board materials, specifically the CIBA-Express ceramic-filled epoxy tooling board materials. In past work, aluminum filled materials were investigated for their machining characteristics. Since these materials can machine faster than aluminum, they hold tremendous promise for rapid tooling applications where speed is critical.

Prof. Shreyes Melkote is leading this project, supervising graduate student Tosin Tomori. Broadly speaking, the goal of the project is to develop a fundamental understanding of the surface integrity of machined ceramic-filled epoxy tooling board and the impact on injection mold performance. Experimental objectives include the investigation of the effects of filler material and concentration on machinability, machining conditions on surface integrity as a function of filler material, and surface integrity on mold performance. To date, much of the experimentation has been completed. Results indicate the following: machining forces increase with increasing % filler, surface roughness increases with increasing % filler, and machining reduces the material's ultimate compressive strength. Most results were expected, but had not been as thoroughly quantified. A tool wear study and an evaluation of machined mold performance must still be completed.

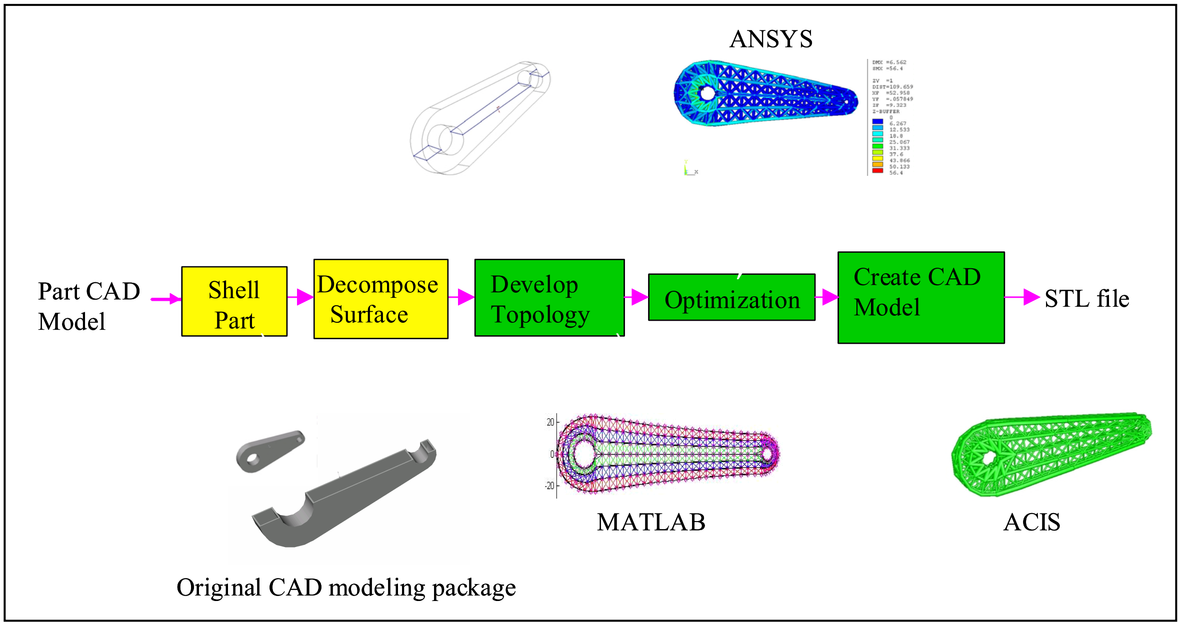
Large Models and Design for Additive Fabrication

We envision the future of additive fabrication – layer-based fabrication processes – is for applications that take advantage of the unique capability of these layer-based technologies. Our focus is on extending the suite of applications of SLA machines, particularly in the fabrication of functional assemblies and mechanisms. In short, it is our contribution to the emergence of rapid manufacturing. Applications for which manufacture is difficult, expensive, or impossible using conventional manufacturing processes are potential candidates for "rapid manufacturing." We seek to define what rapid manufacturing may look like in the future.

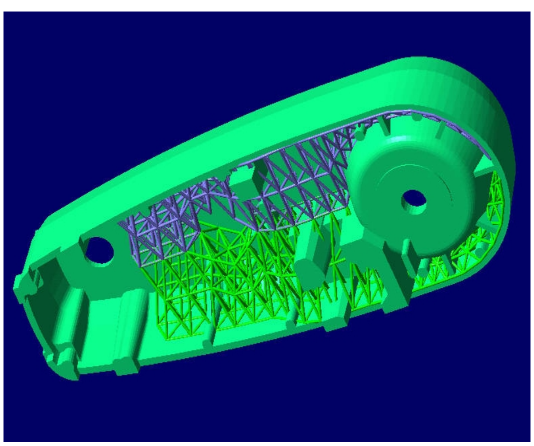
Truss Structure Design

We are identifying the unique capabilities of layer-based, additive fabrication technologies and identifying fundamental design principles and primitives that can be used to design products that take advantage of these unique capabilities. Ultimately, we want to have leading design methods and tools for products manufactured on additive fabrication machines, such as our "5-Axis SLA Machine" that we reported on last year.

Work over the past two years has focused on the application of regular patterns of truss elements throughout parts and structures – where it is the truss elements that serve as design primitives. By arraying these primitives throughout the interior of a part, it is possible to generate many types of truss and honeycomb-like structures. In this manner, we can replace solid blocks of material in a part design with a honeycomb-like truss structure as a means of reducing its mass. The key uniqueness of our approach is our ability to generate conformal truss structure – where the truss elements deform to conform to the parts shape. That is, the part can better distribute stresses through the conformal truss structure than a uniform structure. This idea can be seen in the various figures throughout this report. Hongqing Vincent Wang is the student working on this project, supervised by David Rosen. Vincent graduated with his Masters degree in Fall 2001 and will continue to pursue a Ph.D.



In the past year, we have applied the truss structure approach to several industry structures and parts. Additionally, we have explored the application to light-weight robot arms to make them as stiff, strong, and light as possible. For example, the figure shown here is demonstrates an application to an industrial robot, the Cobra 600 from Adept Technology. Based upon this work, we believe that there are four application areas for this technology: **craftsmanship models**, that is, visual models used to assess the aesthetic characteristics of CAD models, **large models** where stiffness and light weight are critical, **high speed machinery**, where high stiffness-to-weight ratios are necessary to lower the inertia of moving parts, and **tooling**, where the capability to tailor strength and cooling characteristics with physical paths through truss elements may offer unique advantages.

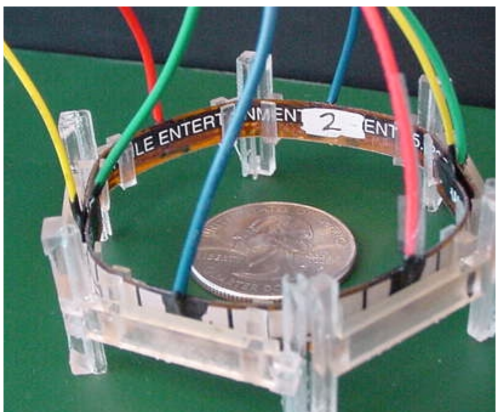


These application areas have tremendous potential in the aerospace and automotive industries, as well as others such as Industrial Design. Basically, we want to replace thick sections or thick skins of parts with a thinner skin that is backed-up with truss structure. At present, we have software that generates conformal truss structures in CAD models of virtually any shape. We are working to make the software easier and faster to use. Earlier this year, we submitted an invention disclosure and provisional patent application on this technology.

Compliant Structures

Instead of distributing stiff material throughout a structure, this work is focused on methods of distributing compliance selectively within a structure to enable it to move. Jacob Diez finished his Master's Thesis research under the advisement of Imme Ebert-Uphoff on their project "Design for Additive Fabrication: Building Miniature Robotic Mechanisms." This project addresses the potential to build robotic systems (composed of rigid links, joints, actuators, and sensors) utilizing the strengths of Additive Fabrication. Miniature robotic systems are well suited for manufacture with additive fabrication techniques because these techniques have the capabilities to build both fine geometries (used for joint designs) and internal geometries (used to hold actuators and sensors).

Jacob demonstrated a series of impressive devices. First, he developed different types of compliant joints. These joints demonstrate compliance only along the intended axis of rotation, and have achieved rotations up to +/- 200°. Shape Memory Alloy (SMA) actuators were utilized to successfully create motion in the robotic systems as well. These achievements led to the creation of a miniature robotic device as well as a model of the human hand. The miniature robot has 2 DOF and the hand has 9 DOF, 9 SMA actuators, 13 compliant joints, and the fingers can achieve approximately 50° of cumulative motion. Both of these devices show the clear potential for a non-assembly robotic mechanism that is able to achieve motion.

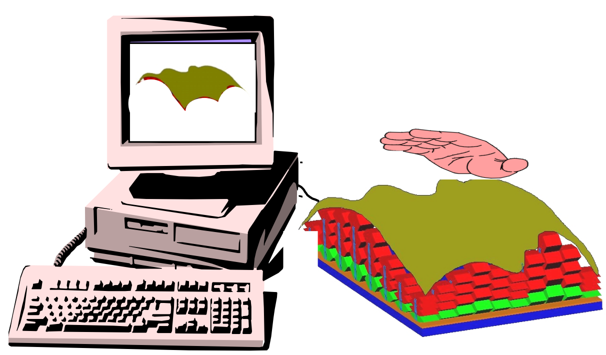


In addition to compliant joints and actuators, it is also important to integrate sensors into these devices. After a review of suitable sensing technologies, a simple type of sensor, called a strip sensor, was selected for further study. Basically, strip sensors change resistance (electrical) as a result of bending them. By placing these sensors across a compliant joint, the deflection of the joint can be directly measured. Jacob demonstrated the use of 6 strip sensors in a hexagon-shaped ring of 6 compliant joints. By deforming this ring, the sensors communicate with a host computer to sense the deformation and display a model of the deformed ring on the computer screen. These demonstrations helped lead to the key ideas behind the Digital Clay project, described next.

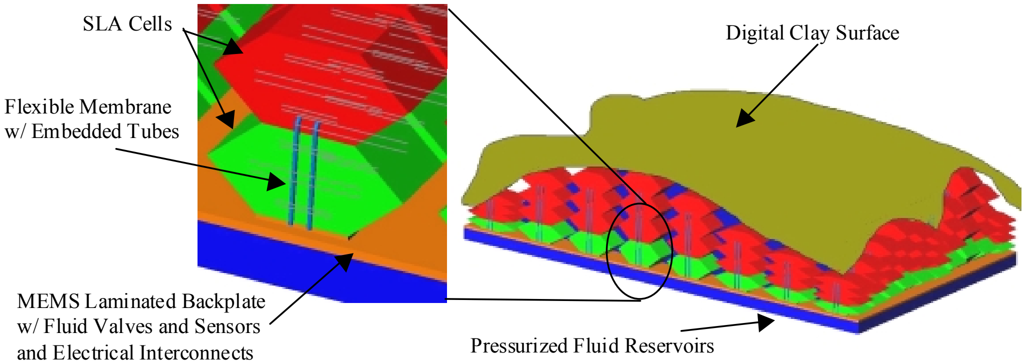
Digital Clay

As mentioned in the Leverage section, a new five-year NSF grant was received in Fall 2001 to pursue new types of human-computer interaction devices. This grant was funded through the Information Technology Research (ITR) Initiative within NSF, a very competitive program. A collaboration of seven Georgia Tech faculty from Mechanical and Electrical Engineering, College of Computing, and the Center for Rehabilitation Technology resulted in a major grant to develop new types of human-computer interaction devices. We call these devices "digital clay," evoking the image of interacting with a lump of physical clay to shape it … and having the clay integrated with a computer, so that shape changes can be captured electronically, represented in CAD, communicated to others, etc. The figure on this page shows one clay configuration with stacking hexagonal prisms built on top of a MEMS-fabricated backplane.

The design, analysis, fabrication, and usage of digital clay are all multidisciplinary activities. Austina Nguyen, supervised by David Rosen, is working on the design and fabrication of SL scaffolds (the clay's structure). Her background in Industrial Design will provide an important usability perspective to the work. Paul Bosscher is working on the kinematics of the clay's interior structure, supervised by Imme Ebert-Uphoff. Haihong Zhu has a strong background working with parallel robots and their controls. He will apply this background, supervised by Wayne Book. Ari Glezer is another PI who will be supervising work in the micro-scale fluidics that are important for controlling the clay. All of these people are in Mechanical Engineering. In Electrical and Computer Engineering, Professor Mark Allen is applying a MEMS fabrication technology for producing polymer laminates to the clay's backplane. In the College of Computing, Professor Jarek Rossignac is exploring applications for digital clay and simulating the behavior of various clay designs. In the Center of



Rehabilitation Technologies, John Goldthwaite is an expert on assistive devices for blind people, an application area for digital clay.



This is an exciting project that will be pushing the envelope of technology, as well as human-computer usability. To achieve high resolution displays, it is important to construct small "cells" with which to compose the clay's structure. We will push our new Viper SL machine to construct such small cells. We will also push SL resin suppliers to develop materials with improved material properties, such as flexibility and fatigue strength to serve this application area. Look for updates on this project.

Stereolithography Research

Many of our research efforts focus on applications of RP technologies, and SL in particular. It is also necessary to better understand the focal technologies of our program – in this case stereolithography. Certainly, we do not want to duplicate the efforts of 3D Systems, we want to have a complementary focus, so we work with them to ensure that what we do is relevant. Our overall goal of this work is to gain a thorough understanding of the SL technology at Georgia Tech so that we are in a position to help the entire industry to push the additive fabrication envelope. Our current projects share a theme of investigating the SL process at small size scales.

Micro-SLA and SL Resolution

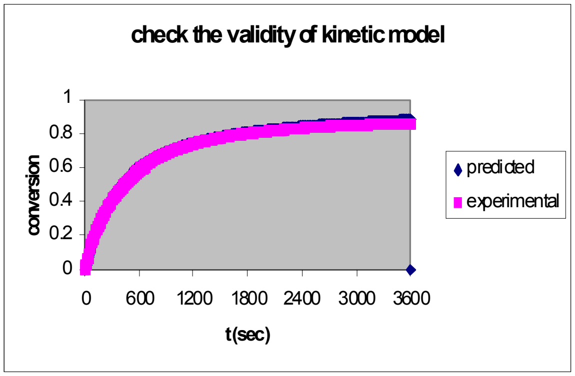
As the title of this project states, there are two parts to this project: developing specifications for a micro-SL machine, and studying the resolution of the SL process. Essentially, we want to answer "How small is small?" That is, given that we want to fabricate a part with certain small features, we want to know how well a given SLA machine could build it. Or, viewed the other way around, how small should the laser spot size and layers be in order to accurately produce the features.

Benay Sager is the graduate student working on this project, supervised by David Rosen. In the past year, Benay surveyed patents and 3D Systems' literature to better understand SLA machines, their optics systems, and resins. Several other research groups in the world have developed micro-SLA machines that are capable of fabricating features of a couple of microns in size. One Japanese group developed a two-photon SL technology and claims sub-micron resolution. With this understanding, Benay has developed designs for micro-SLA machines with laser spot sizes of 2 to 10 microns. He has also developed specifications for stages and resins.

In the area of SL resolution, we have begun by studying how resolution is controlled in 3D Systems' machine. Resolution affects the size and shape of features that can be built accurately, and is a function of laser beam spot size, laser spot focus depth, layer thickness, line width compensation, and the SL grid slice point spacing (internal to Lightyear and Buildstation). Experiments were performed to determine the effect of line width compensation on feature size. Also, we have begun developing methods for predicting the "as-built" shape of 2-D cross-sections, given the nominal slice geometry. For 3-D resolution, we are developing an analytical model of cure depth as a function of laser beam, optics system, and resin properties. Accomplishments should enable entire new fields of applications in MEMS, electronic packaging, opto-electronics, etc.

SL Cure Modeling

The curing of SL resin is a complex process, to say the least. Despite decades of research in the photo-polymer field, specifics of the chemical reactions that occur in SL resins, and other photo-polymers, can be difficult to predict and explain. Average cure rates are easy to predict and measure, but do not explain phenomena at the micro-scale, nor the how and why of variations from the average. The goal of this project is to develop a quantitative model of SL cure process that includes a kinetic (rate) model for photopolymerization and a heat transfer model to predict temperature distributions in the vat.

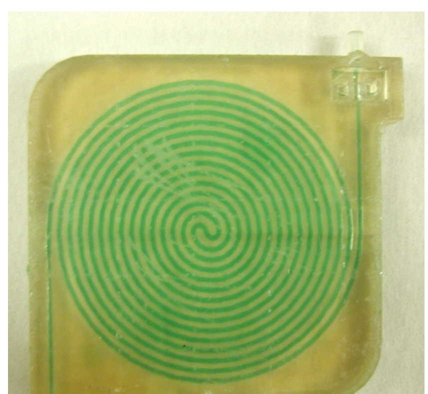


This challenging project is led by John Muzzy in Chemical Engineering, who is supervising graduate student Yanyan Tang. Good progress has been made in studying reaction kinetics using differential scanning calorimetry (DSC) as well as differential photo calorimetry. A simulation model has also been developed in order to validate the physical experiments. Very good correlation was achieved. This kinetics model also predicts the heat of reaction – which causes heating of the local cure region. This heat generation can cause problems, as evidenced by usage of SLA-7000 machines. To better understand the effects of heat generation, a finite element heat transfer model will be developed to predict temperature distributions and degree of cure profiles.

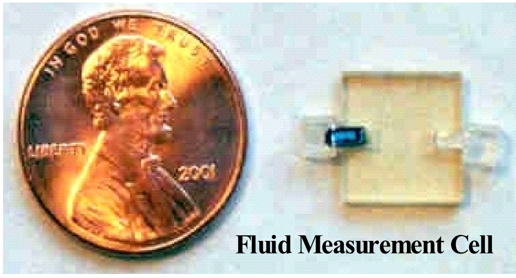
Challenges remain. The kinetics model is complicated by the presence of dark reactions – that is, SL resin continues to cure after the laser passes by. Heating of the resin by curing can cause additional thermally-based curing. Also, temperature distributions will be difficult to validate experimentally. Despite these complications, we expect that the quantitative cure model will help us predict the benefits of materials and process modifications. Additionally, success will enable us to demonstrate improvements in SL precision and processing speed. Results should lend insight into the resolution issues that Benay is investigating.

MEMS Applications

Although not strictly a SL technology project, our work on MEMS packaging and devices pushes the limits of present SLA machines and help identify requirements for future capabilities. Angela Tse is the graduate student performing this work, along with her adviser, Peter Hesketh. The project objective is to investigate the ability to build functional MEMS devices and packages in stereolithography. Materials capability, compatibility with silicon micromachining processes, resolution, and device durability and functionality are being investigated. We want to identify the capabilities and limitations of current SL technologies regarding MEMS applications.


Gas Chromatograph

A series of devices and packages have been investigated to date. Reaction chambers and packages for gas sensors have been developed. Gas chromatography (GC) columns and packages have also been fabricated and tested. We have built directly on silicon wafers, then subjected them to standard silicon micromachining processes, including cleaning and dicing operations. Specifically, a set of interdigitated electrodes were fabricated and cleaned on a large silicon wafer, then diced into individual electrodes for use as biochemical sensors. Additionally, we have experimented with fabricating a fluid measurement cell - by building around an atomic force microscope cantilever beam with a nano-probe. That is, the nano-probe is to measure a fluid surface. The cell that holds



Fluid Measurement Cell

the probe and the fluid sample was fabricated using SL. The sensor was tested and shown to be functional.

These applications indicate the tremendous potential of combining SL and MEMS technologies. We have just scratched the surface so far. Look for new developments in the areas of micro-fluidic systems and MEMS mechanical systems (gear trains, etc.) in the next year.

RP&M within Product Realization

As use of RP&M technologies is becoming more widespread, the issue of how to effectively use the tools has become more important. Specifically, we are interested in helping users to better understand when and how to use these tools and when it is better not to use them.

Best Practices Survey

Today, many firms are faced with a high rate of technological change, shrinking product life cycles, and intense competition in global, dynamic, and fragmented markets comprised of discerning customers. There is overwhelming evidence in the business world to show that a majority of technology-based initiatives, in spite of scoring high marks on technical performance metrics, fall short of achieving their intended business objectives. A lack of understanding of the fundamental drivers of successful implementation results in their failure to accomplish the established business goals.

Under the guidance of Nagesh Murthy, we are identifying best practices in the development and implementation of RP technology. Bill Griffin and Atul Mandal were the graduate students researching different RP and RT methods through a literature search and site visits to RPMI member companies. But the major effort was a comprehensive survey of RP and RT technology usage in Fortune 500 companies and selected smaller companies. Surveys for both engineers and managers were mailed in early 2000, with surveys returned through Spring. A particularly noteworthy accomplishment is the cooperation and endorsement of SME in this survey. The report is available on our web site and additional dissemination opportunities will be pursued.

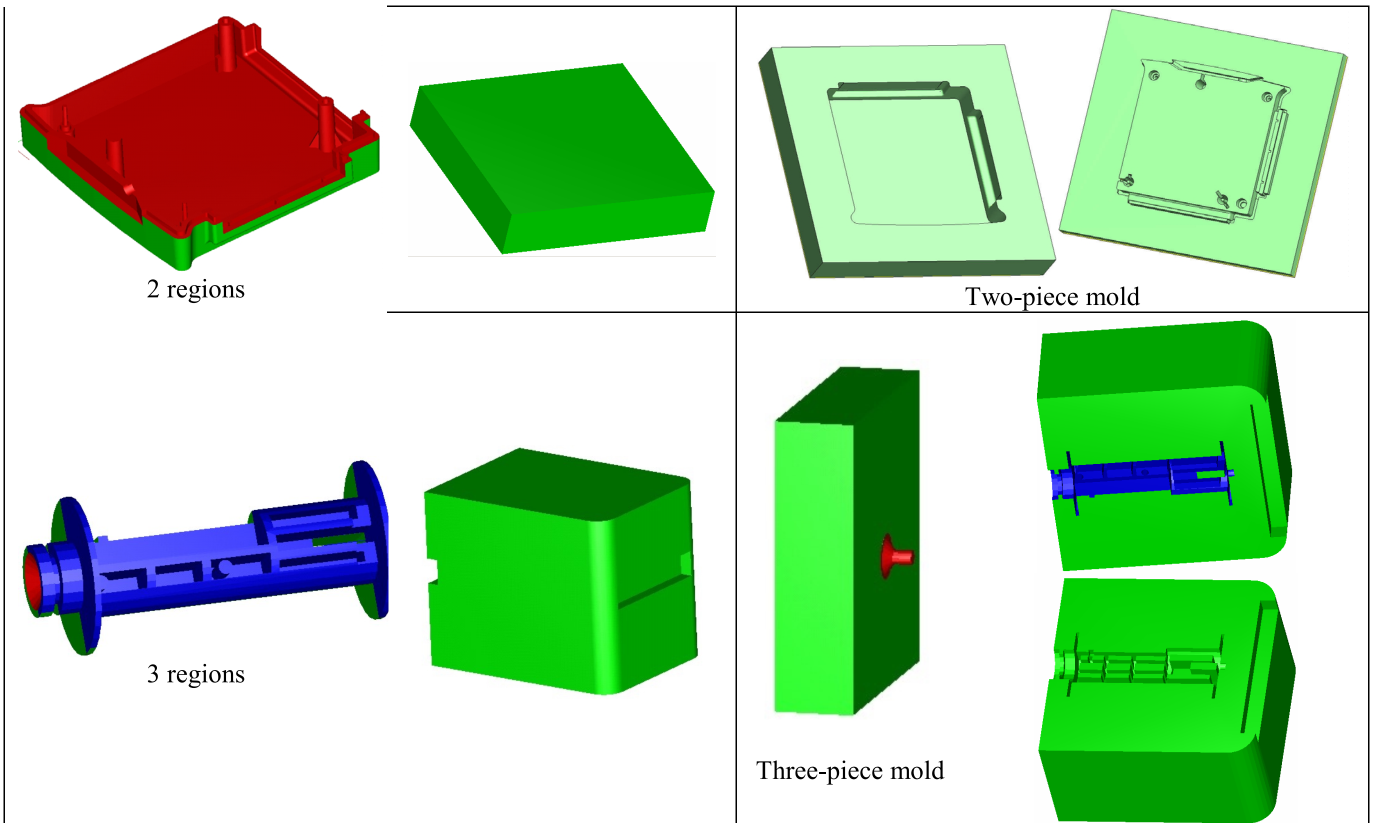
Rapid Tooling Testbed

The product realization process, driven by market factors, is changing dramatically. Increased competition is forcing product realization to become faster, enabling shorter time to market. At the same time, globalization, core-competencies, outsourcing, etc. are changing the structure of the product realization process; it is becoming distributed, both organizationally and geographically. Rapid prototyping has the potential to dramatically reduce time to market by shortening the time required to produce tooling. Realizing this potential, however, requires creating a technological infrastructure for both rapid tooling and distributed product realization. In response, a **R**apid **T**ooling **T**est**B**ed (**RTTB**) is proposed in order to focus on injection-molded products and processes. A team of eight Georgia Tech faculty from three units on campus has been funded by a four-year NSF Distributed Design and Fabrication Initiative grant to develop the RTTB. As of Fall 2001, the project has been completed – and we have tremendous accomplishments to show for it! See the web site: http://rpmi.marc.gatech.edu/project/RTTB for the complete report and other on-line material.

Product and Mold Design Methods

Janet Allen, Farrokh Mistree, and David Rosen led this thrust area. The goal is to translate a product design description into fabrication process plans, including process plans for polymer or powder injection mold tooling. A series of activities are required to perform this translation. Given a preliminary part design as input, our testbed will select the appropriate component material and fabrication process, tailor the design to that material and process, design molding tools for the parts, design the tool fabrication process, fabricate those tools, design the molding process, and mold the part.

By taking a decision-based design approach, we can model key design activity as either selection or compromise decisions. Most work focused on three primary decisions, resource selection, mold design, and fabrication process design, plus, on information modeling to support those decisions. Our new selection decision formulation has been integrated with a database of rapid prototyping and tooling processes and material information. A new model of designer preferences was developed based in utility and decision theory. Marco Fernandez performed this work, under the supervision of Janet Allen. Jitesh Panschal ported this software to the web and a generic utility theory-based system is available on-line at http://www.utilityselection.com .



SLA rapid tools act differently from conventional steel tools and must be designed somewhat differently. Based on our rapid tooling research over the past 4 years, a set of mold design rules was developed to enable tailoring SLA mold designs. Yong Chen and Shiva Sambu were the graduate students investigating mold design. Additionally, Sunji Jangha developed an ejection system design tool for use with SLA rapid tools and our standard mold bases. Tremendous accomplishments have been made in this area over the past year. Yong made significant contributions to the geometric construction methods for mold design. The mold figures on this page were automatically generated by his software, based on a CAD model of the part. Shiva and Yong developed geometric tailoring methods to enable the "tweaking" of part and mold geometry so that prototype parts better match the characteristics of production parts of most interest to the designer. This maximizes mold life, while endowing production-representative properties to prototype parts.

Tool Design Rules

Jon Colton led this research thrust. The goal is to characterize polymer injection molding in support of the molding process design activity. We utilized this knowledge to develop a set of rules that designers can use when designing SLA mold inserts, to assure that they will produce a specific number of quality parts (e.g.,

50) without damage to the mold. The key activities, personnel, and results were reported in the Applications section earlier. That work was, of course, part of the RTTB project as well.

Metal Powder Injection Molding

Tom Starr led this research area with a focus on processing of stainless steel materials. Compared to materials used in plastic injection molding, the powder/binder mix used in PIM has low cohesive strength and is susceptible to damage during removal from the mold. In addition, this mix adheres more strongly to the SLA epoxy mold material as compared to metal molds. Our measurements of part/mold adhesion show that this adherence is only weakly dependent on surface roughness and molding conditions and is not eliminated by use of mold release or mold surface treatments. Part/mold adhesion for ceramic powder "green" parts was usually not much of a problem. However, for stainless steel powders, part removal from the mold is more difficult. Often, a thin layer of mix remains on the mold surface, indicating cohesive failure within the part near the surface as it cools and hardens. While it is easier to remove a part from the mold this damage adversely affects the surface quality of molded parts. *In-situ* temperature measurements and modeling of mold/mix cooling indicate that transient thermal stresses in the part depend on molding temperature, on mold thermal conductivity, on thickness of the part and on the shrinkage of the mix during cooling and solidification. The influence of part thickness is the key to incorporating this effect into the mold design algorithm. Michael Pearson received his Masters degree at the University of Louisville for this work.

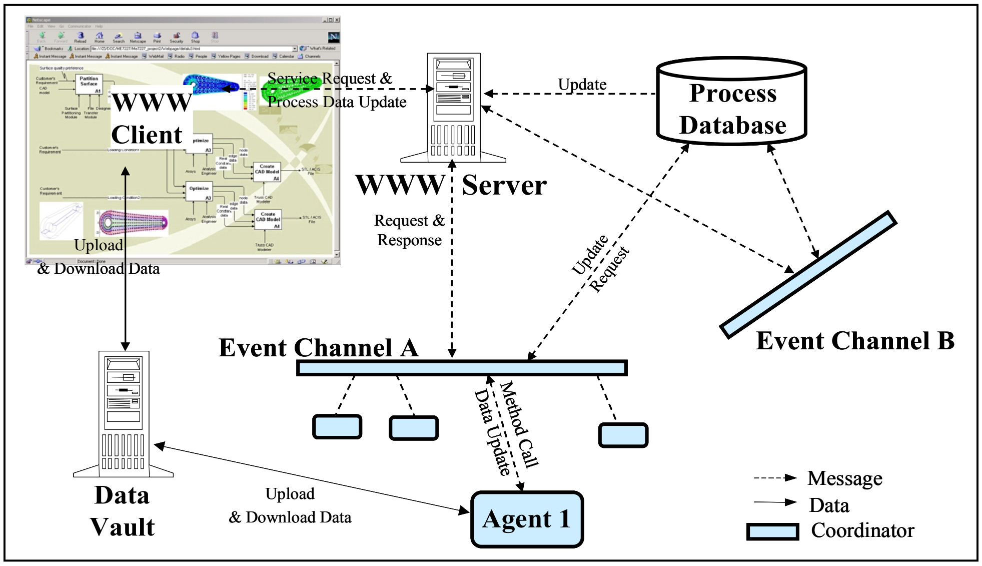
RP Error Characterization

Tom Kurfess led this thrust from the perspective of three-dimensional metrology. The objective is to characterize rapid prototyping processes and encode their characteristics for use in the SLA process design. To do this, we need effective and efficient metrology methods. The other aspect of this research being investigated is SLA tolerance capability and repeatability characterization. Optical metrology systems typically generate hundreds of thousands to millions of points. The research emphasized point-to-surface assignment methods that drastically reduce the complexity of the least-squares best-fit registration methods, as reported in the Applications section earlier. Janet Allen's work in this area was also reported in that section, with an emphasis on developing an experimental procedure for characterizing the accuracy and repeatability of SL machines.

Distributed Computing Environment

The goal is to develop the distributed computing environment that enables the RTTB to function across the web. As required by the NSF Initiative, the RTTB must support distributed design and fabrication. It should be possible to search for materials and manufacturing processes on the web. Designers in one geographic location should be able to collaborate with manufacturers in other locations. Mold-filling simulations and mold design optimization runs should be observable and controllable from remote locations. These challenges call for a new approach to developing distributed computing environments. Our approach to this environment involves a two-prong effort: applying the Distributed Laboratories work in the College of Computing to focus on *parallel computations*, and applying ideas from the Sandia PRE system to *distribute* computations. In the latter effort, we developed a series of three new distributed computing frameworks to provide platform and operating system independent communications frameworks for enterprise integration and product realization. The latest version is web-based, enabling usage of the framework through conventional web browsers. The system is called Web-DPR, for web-based Distributed Product Realization system. Web-DPR was coded in Java and made use of the JAVA-RMI messaging system. Instead of encapsulating message, control, and information within an Event as in previous environments, Events contained only message/control information, while application content was routed through a separate data flow. The Web-DPR framework is shown in the following figure. Note the separation of message flows (through Event Channels) and data flows (through the Data Vault). Haejin Choi and Rahul Kulkarni were the students leading the development, supervised by Farrokh Mistree.

Another addition to Web-DPR was the capability to identify suitable distributed computing resources (agents) throughout the web. An information model of **capability descriptors** was developed to represent the capabilities of agents, and implemented in XML. Agents were broadly classified as Analysis, Selection, or Synthesis resources. Capability descriptors contain information regarding input and output parameters required and the design freedom associated with them, a brief description of their solution strategy, estimates of cost and time involved in the usage of the resource, and information about who will execute the resource. A utility theory based selection procedure was incorporated into Web-DPR to perform the selection of agents for a particular usage scenario.



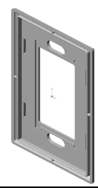
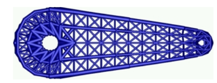
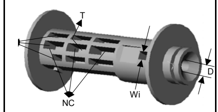
To better utilize the distributed computing environment in engineering product realization, it is necessary to tailor the environment to the particular realization process, the organizations involved, and the tools available. This is where Angran Xiao's work comes in. He is a senior Ph.D. student also supervised by Farrokh Mistree.

In the College of Computing Distributed Labs work, led by Richard Fujimoto and Karsten Schwan, the focus is on high performance parallel and distributed computations. They are developing technologies that enable large computations to be parallelized, distributed, and "steered" by people observing the progress of the computations. Their primary development of the past several years is JMOSS, the Java implementation of their Mirror Object Steering System. We have implemented a gear train example using JMOSS to parallelize finite-element analysis computations during the design process. But what is really interesting about their work is their ability to migrate the observation of computations across several computers… What this means is, for example, the gear design engineer could leave his office to meet with his supervisor, and bring up his view of the computing environment for his manager's input. Then, the engineer could travel to visit a supplier, all the while monitoring the progress of his analyses on his tablet computer, PDA, or even a cell-phone! JMOSS takes care of switching from one computer to another (or another computing appliance), even taking into account the variations in computing ability of the computers. We demonstrated this with a Sun workstation communicating with a iPAQ H3650 handheld computer running Linux through a wireless network. Yuan Chen is the Ph.D. student developing JMOSS.

RTTB System Experiments
It is important to synthesize the results of the research thrusts to achieve the overall project objectives and to answer the research question. The motivation for the NSF-DARPA Initiative on Distributed Design and Fabrication was to investigate the nature of a "digital interface" between design and manufacturing. What types of information should cross that interface and what should their form be? To begin answering these questions, we investigated the hierarchy of information types that are related to design-to-manufacture transfer and classified them. Most "digital interface" research is focused at the level of transferring

geometric information, possibly as solid models. In contrast, our focus is at a level that includes design parameters, requirements, tolerances, and surface finish requirements, in addition to geometric information.

RTTB Major Examples and Experiments.

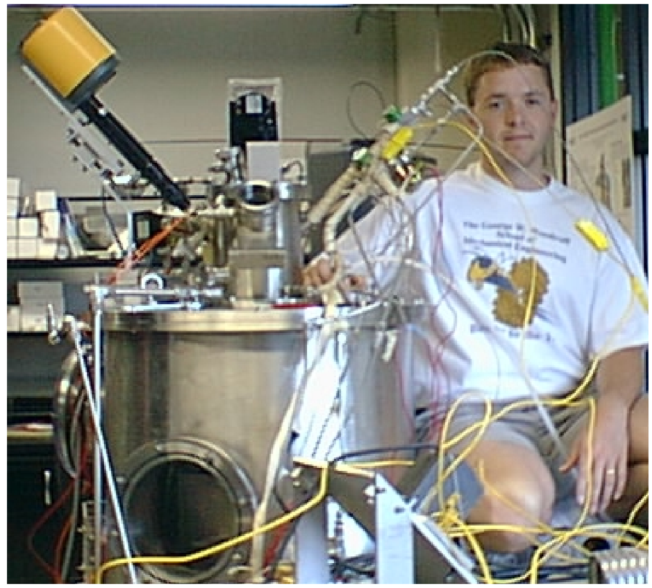
	Gear Train 	**Light Switch** 	**Simple Robot Arm** 	**Truss Robot Arm** 	**Camera Roller** 
Date	5/99	5/00	5/01	5/01	7/01
Transfer Time	Late	Late	Early, Late	Early	Early, Late
Process Selection	Early	Early	Early	Late	Late
Distribution Extent	V1 of DCE	V2 of DCE	V3 of DCE	V3	V3
RP Part	Yes	Yes	Yes	Yes	Yes
Molded Part	No	No	Yes	No	Yes

These experiments allowed us to explore different design-manufacture contexts for the transfer of design and information between product development organizations. Five examples were used, ranging from a gear in a planetary gear train, to a film roller for a single-use camera. The examples are listed in chronological order. The first example, the gear, was completed in May 1999. For this example, the fabrication process and material were selected early, and the product model was transferred late. Correspondingly, no geometric tailoring was performed, but it was assumed that the designer took into account the prototyping process and material as he/she was developing the design. The purpose of the experiment was to test the first version of the distributed computing environment. Design, FEA, CAD, and process planning for SL were performed, each by a distributed agent. Only part prototyping was performed. Separately, both polymer and metal powder injection molding were performed on various gear designs, enabling some testing of the rapid tooling and molding processes. Based on these experiments, we can make the following conclusions:

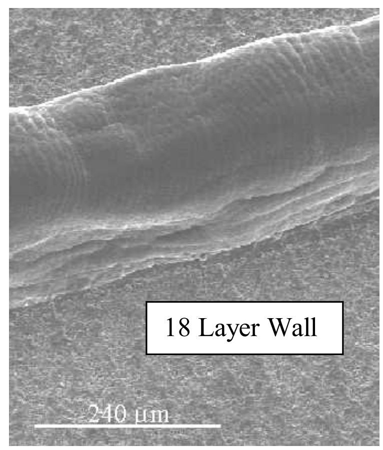
- Communicating only a part's nominal geometry was insufficient to enable the manufacturer to design the RP process plan to meet designer requirements.
- By communicating tolerance and surface finish requirements, the manufacturer can design a RP process plan to attempt to meet as many of these requirements as possible. By communicating designer preferences among time, cost, accuracy, and surface finish, the manufacturer can better meet designer requirements by exploring trade-offs among various process plans.
- Geometric tailoring can be effectively performed, provided that the designer provides sufficient design freedom to the manufacturer. This applies to both geometric tailoring for RP as well as for Rapid Tooling.
- The compromise Decision Support Problem (DSP) is effective at integrating design requirements, design freedom, design models, and manufacturing capabilities and constraints into a comprehensive decision model. This integration enables the exchange of functional requirements and the transfer of design-for-manufacture responsibility to the manufacturing organization. As a result, we can conclude that the compromise DSP can serve as a **digital interface** between design and manufacturing, effectively enabling the separation of design and manufacturing organizations.

Laser Chemical Vapor Deposition

Machine and Process Development



Laser CVD rapid prototyping systems (LCVD-RP) are capable of fabricating complex net-shaped metallic and ceramic structures. In contrast to most metal and ceramic RP systems, LCVD bonding occurs at the atomic level, having the potential to produce a material that is fully dense, ultra-pure, and mechanically sound. Since LCVD can also produce fibers or layers in any given direction, the LCVD-RP system will be capable of producing parts of complex geometry, multiple materials, and possessing unique material properties. Furthermore, this capacity for multiple materials permits composite structures and functionally graded materials and alleviates traditional material restrictions imposed by a given prototyping technique. This project extends the size dimension of RPMI activities into the micro- and meso-scales.The team of Dr. Jack Lackey and students Chad Duty, Dan Jean, Scott Bondi, Tarek Elkatib, and Ryan Johnson have successfully designed, constructed, and improved the LCVD-RP machine.



Since the machine became operation in September 1999, most research has focused on understanding the basics of LCVD and identifying process windows in which deposits can be made. More recently, Chad and Dan (both graduated with their Ph.D.'s in 2001) have made great strides in developing heat and mass transfer models of the process, and using those models to fine-tune the operation of the machine. Success this summer is evidenced by the fabrication of a wall composed of 18 layers of carbon. While a single wall may not sound like much, to our knowledge no one has ever constructed any structure with that many layers in LCVD. Several materials are also under study, in addition to carbon, including molybdenum, boron nitride, and a silicon-silicon carbide composite.

At present, work is under way to add an additional stage to the machine, to give it 4 degrees-of-freedom. Also, a second laser is being added, with a spot size of 10 microns, to enable much smaller structures to be fabricated. In the next year, look for the successful fabrication of complete structures and devices.

LCVD Process Planning

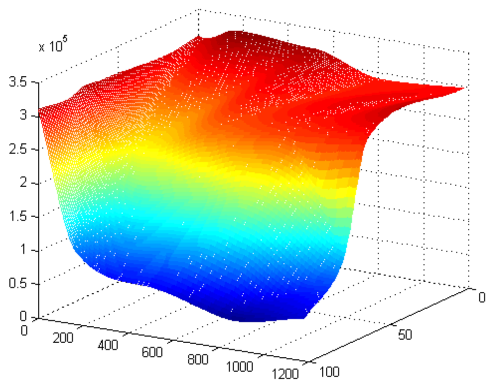
With the support of our NSF grant in the LCVD area, we have begun a project to develop process planning methods for LCVD, by extending our SL process planning methods from the RTTB project. Jae-Hyoung Park is a new graduate student who will be working in this area, supervised by David Rosen. There are several new challenges for LCVD, compared to SL. First, LCVD can be performed on a substrate of any shape, so "layers" are not necessarily planar, they can be whatever shape the substrate is. Second, no one has developed scan patterns for LCVD that seem to be generally useful, particularly given the sensitivity of the process to processing conditions. Third, we want to fabricate devices with composite materials and graded interfaces between materials. There are no available methods for controlling process conditions that enable the formation of such materials and interfaces. But, all of these challenges need to be overcome in order to ensure that our LCVD process lives up to its promise!

Aging, Fatigue, and Environmental Characteristics of Rapid Tooling Materials

Materials and material development continues to be an important area of research. One of the goals of the RPMI is to discover new ways and methods of using the existing generation of materials for more varied purposes.

Xavier Ottemer, under the guidance of Dr. Jon Colton, has completed his thesis entitled "The Effects of Processing and Environmental Conditions on the properties of Epoxy Materials." His work studied the effects of aging on rapid tooling materials. The main goal was to determine how temperature and humidity affect the mechanical and dimensional properties of rapid tooling materials. A secondary goal was to determine the diffusion coefficient of water in these materials. Test parts were fabricated from the two SL resins in the RPMI, SOMOS 7110 and SL-7510 from Vantico, as well as tooling board materials Renboard and Renshape, also from Vantico.

The figure below is a mesh-plot of the preliminary results of experiments completed on the time-temperature-humidity characteristics of SL-7510. A preliminary empirical model has been developed to better explain the aging phenomena associated with exposure to humidity over time. The sample Storage Modulus is plotted vs. humidity (0 – 100%) and time (0 – 1200 hours). Using these results, combined with the results of similar experiments with SOMOS 7110, Xavier developed an empirical model of resin aging, with an emphasis on the underlying phenomena, such as moisture absorption, random chain scission, oxidation, and side-group elimination.



One of the consistent problems that is encountered when using epoxy-based SL rapid tooling materials is a lower humidity tolerance as compared to end-use plastics. The network topology of SLA-built parts, in particular the presence of voids, allows moisture to diffuse into the part and be absorbed. The moisture bonds to the polar groups and weakens the hydrogen bonds in the polymer network. The result is increased material plasticity, decreased glass transition temperature, and a degradation of the materials tensile and flexural strength.

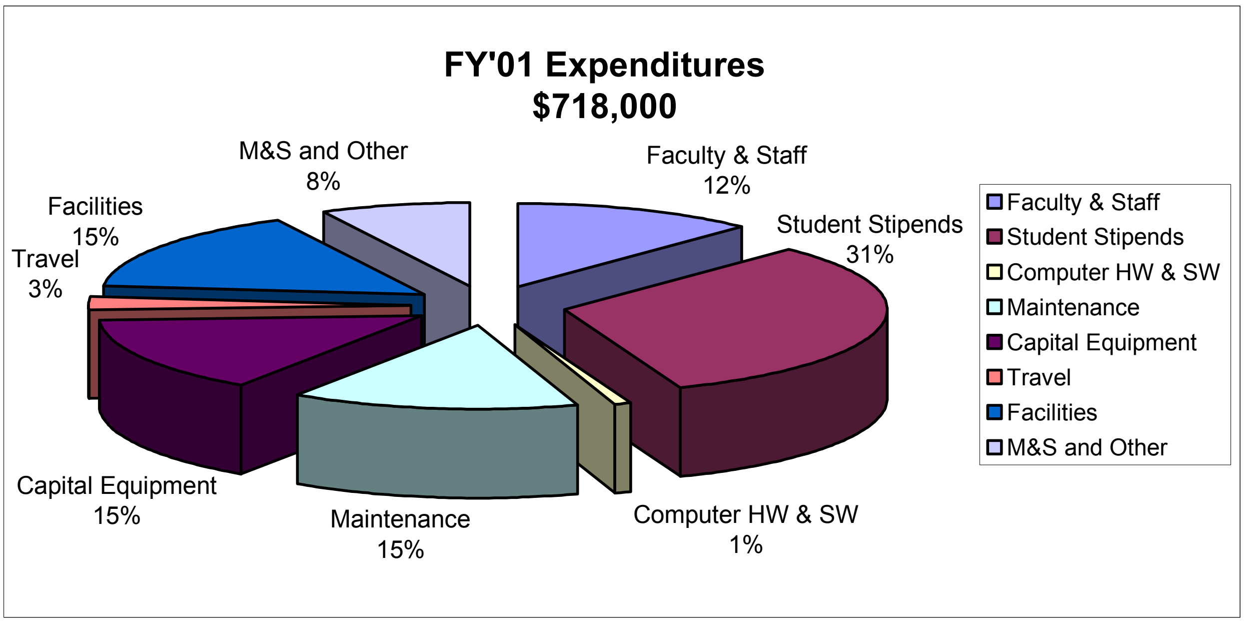
A new research topic, building on the base Xavier developed, has been initiated. Andrew Layton, under the guidance of Dr. David Rosen, will be examining ways to interrupt the moisture absorption process. Initially, he will concentrate on developing a method and processing plan that will attenuate the effects of hydrolytic aging on the material properties of the current epoxy-based stereolithography materials. The ability to maintain material properties under conditions of moisture exposure would open new areas of use for these materials.

FY '01 Financial Report and FY '02 Budget

Our finances in the RPMI are managed conservatively. In the university structure, we have no provision for deficit spending, and we are not normally able to borrow funds. The RPMI continued to operate on solid financial ground in fiscal year 2001 (ending June 30, 2001). However, we need to grow our membership base in order to ensure a healthy future.

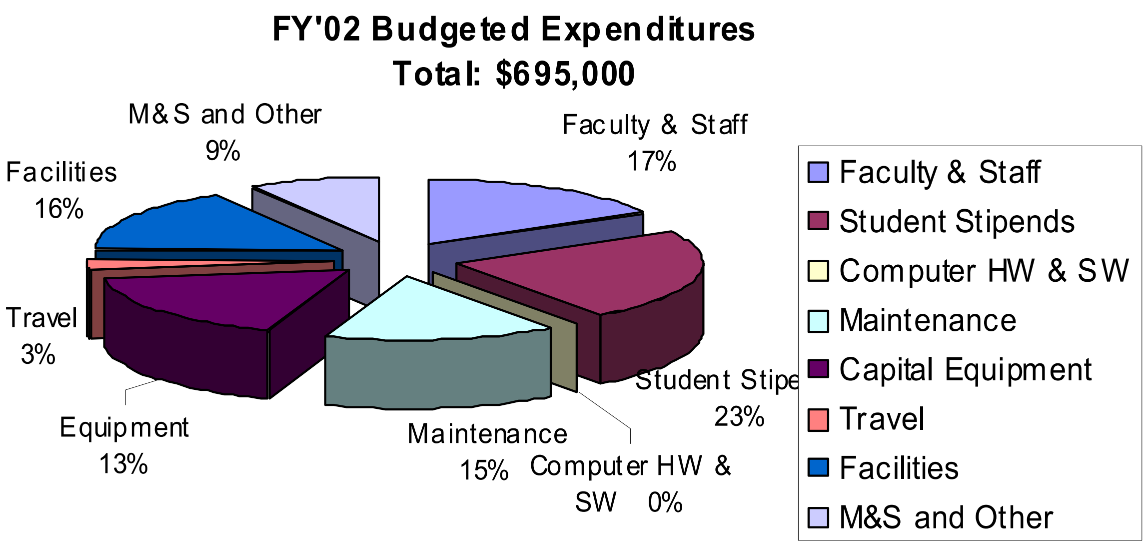
Expenditures

The largest single area of expenditure was for student stipends, which decreased to $231,000 compared to $344,000 in FY '00. This decrease reflected the declining membership levels and our reluctance to risk deficit spending. As the research results attest, we did an excellent job of delivering value, even though funding levels declined. Faculty and staff salaries also declined as a result of unfilled permanent staff positions for much of the fiscal year.



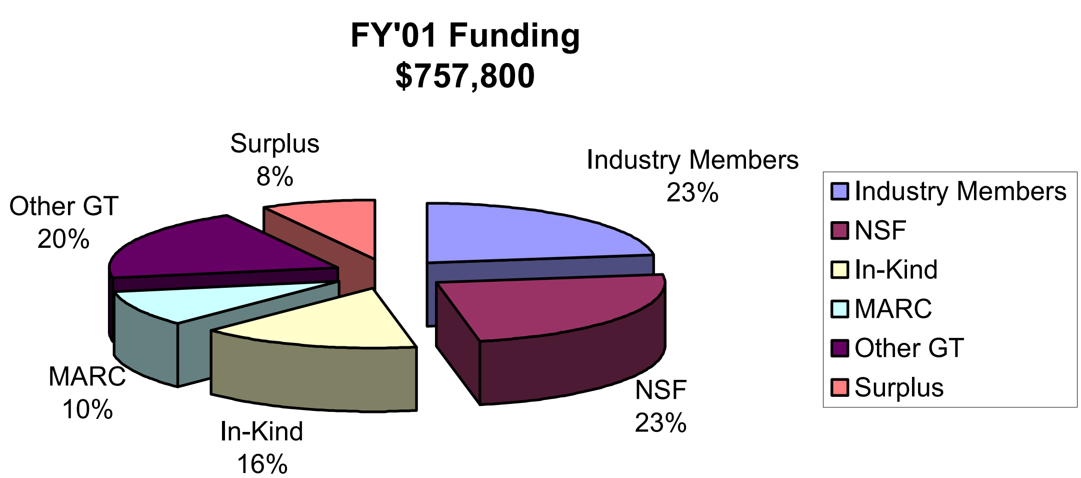
Capital equipment spending decreased slightly to $105,000 compared to $139,000 in FY '00. We made the second payment on our SLA-3500. Jon Colton purchased a differential photo calorimeter (DPC), with non-RPMI funds, in order to support polymer research. Other significant expenses included $105,000 in machine and software maintenance, about the same as in FY'00 to reflect our capital equipment inventory. Note that we are including $110,000 in Facilities expenses, which reflects the value of Georgia Tech and MARC contributions for lab space, utilities, etc. "Other" RPM-related expenses include expenses for project material and supplies, as well as overhead paid on the RTTB project. These expenses stayed about the same at $55,000.

For fiscal 2002, expect decreases in most categories to reflect the termination of the NSF-funded Rapid Tooling TestBed project and our falling industry membership. Staff salary will increase, reflecting our now full-time Program Manager. Capital equipment will be about the same, if we can make another payment on the SLA-3500, in addition to a payment on the Viper machine. Otherwise, that category will decrease. Total budgeted expenditures for FY '02 are $695,000. Maintenance and facilities levels will remain about the same. We will aggressively pursue additional industry members as well as government funding to boost funding levels during 2002.



Funding

For fiscal 2001, our cumulative surplus decreased to $40,000. This amount will be carried forward into FY '02. Membership dues, paid in cash, in FY '01 decreased to $187, 000 from $200,000 the prior year. However, we received $128,000 in in-kind contributions from member companies as part of their dues. Georgia Tech's direct and "Other" support focuses primarily on infrastructure (i.e., the staff salaries and lab and office space and utilities) needed to operate the RPMI. "Other GT" includes proceeds from an endowed fellowship fund used to fund RPMI students and the value of the physical lab and office space and utilities the university provides.

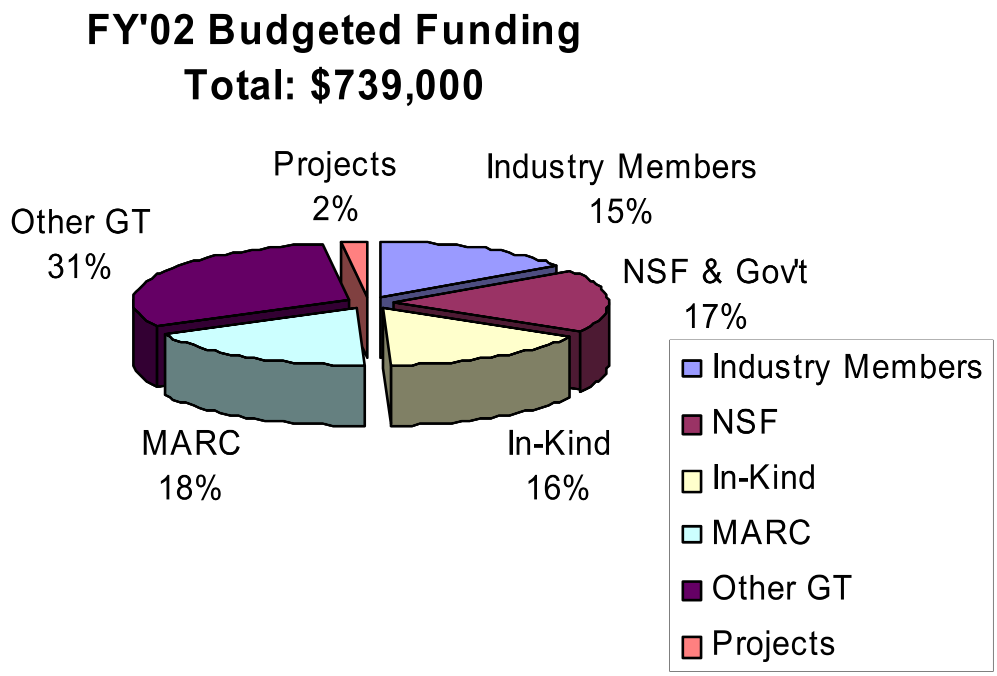


In FY '01, research sponsored by NSF is helping to support about 23 percent of the total RPMI activity, helping us fund students, buy equipment, and cover many materials and supplies expenses. Sponsored programs help us cover a portion of the fixed costs of operating the lab, e.g., staff and maintenance.

Leveraging funds from several sources helps us to do more with a single set of lab resources, reducing the costs seen by any single activity.

Membership dues are budgeted at the traditional rate of $25,000 for member companies. Two members provide substantial in-kind contributions as part, or all, of their membership dues. An increase in the number of members could increase the "Industry Members" amount by a maximum of $175,000. (As of December 2001, we have 8 active members, 15 is our limit.)

In 2002 and beyond we will be aggressive and creative in securing the funds needed to keep the RPMI on track. In future years, with a full complement of industry members, more successful federal proposals, and more broad participation by the colleges at Georgia Tech, the RPMI will remain fiscally healthy.



Outlook for 2002

The most important factor for our continued success is keeping all our constituents actively engaged in the RPMI. This means that each individual must have an important RPMI-related job to do - and that job must be well defined. During 2001, our committees composed of faculty and staff under the direction of elected company members continued to actively assist in the operation of the RPMI.

Committees

The three-committee structure (Operations, Technology and Membership) has continued to serve us well. Because they're small and focused on specific issues, the committees assure that the decisions affecting the future of the RPMI are well informed and are true to our charter.

Each committee is currently comprised of both industry and faculty members. Their function is to advise the RPMI directors on the most important decisions regarding the operation, direction and make-up of the RPMI. Along with directors the committee chairs make a fourth committee: the Executive committee. The Executive committee is primarily concerned with policy and longer-term strategy issues. These committees were very challenged in 2001.

2001 Committee Members List

Operations

Chair:	**Marc Bellotti**
Members:	**Diana Kalisz, Dave Rosen**

Technology

Chair:	**Neal Enke**
Members:	**Gary Beldue, John Malluck, Rick Pressley, Dave Rosen**

Membership

Chair:	**John Malluck**
Members:	**Doug VanPutte, Andrew Layton**

Executive

Chair:	**Doug VanPutte**
Members:	**Marc Bellotti, Neal Enke, John Malluck, Andrew Layton, Dave Rosen**

Operations Committee Year-End Report

Marc Bellotti from Baxter Healthcare served as Chairman of the Operations Committee until he left Baxter in July for a small health care company in California. During his Chairmanship, Marc continued with the screening and portfolio-planning foundation established over the past few years. The result is a balanced portfolio of research projects, which meet the needs of industry members as well as the academic community.

We continued to pursue a major initiative from last year. We need to ensure that members receive value from their participation on projects. As such, we instituted a requirement for specific technology transfer plans in opportunity statements and in final project proposals. These technology transfer plans should help ensure that means for handing off RPMI research results is in place. It should also make it easier to incorporate industry-relevant case studies into our projects. Continued member involvement in projects greatly facilitates technology transfer and ensures relevance.

As usual, opportunity statements for new projects were solicited in Spring. We received 5. Although the number was disappointing, it reflected the difficulty that members faced in being actively involved throughout the year, with corporate restructuring and travel restrictions due to the economic slowdown. All opportunity statements were reviewed and presented to the membership. The new proposals were screened for technical merit, academic fit and enterprise value. After a good discussion about projects at the June members meeting at Pratt & Whitney, we came to the conclusion that projects in two areas should be emphasized: truss structures and materials. As a result, we are looking to expand the truss structure efforts and have started a new materials related project.

Due to Marc's departure from Baxter and the RPMI, new blood was needed for the Operations Chair. Diana Kalisz from 3D Systems will be accepting this role for the coming year.

Technology Committee Year End Report

Neal Enke from Ford served as Technology Committee Chairman. Efforts in the Technology Committee over the past year focused on the equipment in the lab, more than on potential new acquisitions. With declining membership and budgets, the issue of the SLA-3500 was addressed. Since we finance the SLA-3500, making yearly payments consumes our technology budget. Could those funds be better spent? During the summer, we decided to sell the SLA-3500. However, no buyers surfaced. Fortuitously, we received the Digital Clay grant and had a good equipment acquisition budget to support the project. We refinanced the SLA-3500 and made this year's payment.

Consistent with our research interests in MEMS and Digital Clay, the capability of building small features and parts became critical. As a result, we arranged to pool funds from other folks at Georgia Tech (in the MEMS area) and utilized some Digital Clay equipment funds to purchase a new SLA machine, the Viper Si2, the new model intended to replace the SLA-250 model. With the dual spot-size feature, the laser beam spot can be as small as 75 microns. This will have a tremendous impact on our research capability and our ability to serve our members!

In the coming year, we will conduct another "Technology Survey" to better assess what technologies would be needed in the coming year. Discussions on new technologies must mesh with Operations and Membership activities. Rick Pressley from Pratt & Whitney was elected as the incoming Chairman of the Technology Committee and has this as his main mission.

Membership Committee Year End Report

The Membership Committee began the year with the goal of adding six new members and retaining the current members to reach the full compliment of fifteen members by the end of 2001. Unfortunately, no new members were added during the year even though there was an aggressive attempt to add new members beginning with the RPMI sponsored Open House on February 8, 2001. The Open House was scheduled in place of the cancelled RPMI Symposium 2001. Invitations were mailed directly to 124 RP&M related individuals in companies in aerospace, hardware, home appliances, auto parts, furniture, electronics, sporting goods, and many to previous guests at RPMI meetings and indirectly to over 1200 individuals on the Rapid Prototyping email list (rp-ml). As a result, about 30 individuals indicated that they were interested in attending. Eventually thirteen of these individuals attended the dinner reception on February 7th and the subsequent Open House on February 8th. Two additional guests that could not attend the Open House attended the RPMI members meeting on February 9, 2001 and another individual visited the RPMI separately following the 3DNASUG meeting in March 2001. With such a promising recruiting start at the Open House, the membership committee continued to stay in contact throughout the year with all of the individuals who expressed an interest in RPMI membership, including issuing invitations to the April and October RPMI meetings. Unfortunately, none of these individuals were able to successfully champion membership during the year. A common theme was present in all their situations: Poor business conditions and travel restrictions, and in some cases, layoffs and enhanced retirements. Invitations to the meetings were also sent to many of the previous guests and previously interested individuals. Only a few of the individuals accepted the open invitation.

Other recruitment efforts of new members were done by identifying companies and making contact with them through a variety of efforts. These efforts included contact through attendance at RP&M conferences, company visits to the RPMI lab, and the contact made through attendance at the Advanced RP&M Symposium 2001. The main effort to retain the existing members was to determine if their RPM needs were being served by their participation in the RPMI by conducting a membership survey.

The RPMI membership was surveyed in 2001 at mid-year for the third consecutive year. The purpose was to learn what benefits motivated each company to continue to participate in the institute, and to understand how their experience with the RPMI met their expectations. The RPMI takes this survey very seriously, with the intent to improve the value of the institute for its members each year. The survey covers the following benefits:

1. Stay current in rapid prototyping and manufacturing

2. Augment the members own R&D in rapid prototyping and manufacturing applications

3. Evaluate students as prospective employees

4. Identify customer contacts and business development opportunities

5. Help sponsor R&D in advanced rapid prototyping and manufacturing applications

6. Network with other companies involved in rapid prototyping and manufacturing

7. To consult with the RPMI staff in the field of rapid prototyping and manufacturing

The results of the 2001 survey are as follows:

Items of High Satisfaction:

- Investment of time and funds

- Openness and no nondisclosure agreement

- Well advised relative to maintaining RPMI membership

Opportunities to Improve:

- Evaluation of students for employment

- Successful completion of projects

- Development of customer contacts & opportunities through the RPMI

RPMI Events

There are a number of formal RPMI events each year. A majority of these are member meetings. The term "member" includes the representatives from our member companies, the Georgia Tech faculty, and the RPMI students.

In addition to the meetings, many of the members meet informally at several annual RPM industry events. These events include the 3D Systems National Stereolithography Users Group, the Solid Freeform Fabrication Conference at the University of Texas Austin, and the SME Rapid Prototyping and Manufacturing Conference in Cincinnati, Ohio. These activities keep the communication and sharing continuing throughout the entire year among the members.

RPMI Member Meetings

RPMI Members Meeting, February 9, 2001

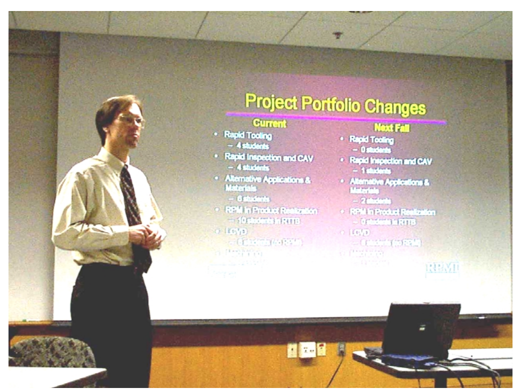
The first meeting at Georgia Tech of 2001 followed the successful RPMI sponsored Open House on February 8, 2001. The members hosted the following guests at the Open House: Gary Fudge and Andrew Shu from Arrk, Rob Connelly from BD, Andy Scott from Lockheed Martin, Charles Blair and Chris Koehly from MicroCoating Technologies, Michael Hirschmann from Morris Technologies, Eric Wolkoff from RPC, Rick Branham and Greg Floyd from Rubbermaid, and Tim Bianchi and Bobby Baker from Schlumberger. The Open House guests and RPMI members were exposed to RPMI member tutorials, project updates, lab tours, and participated in a discussion on how the guests might benefit from involvement in the RPMI. A number of the guests also attended the business meeting on February 9th.

The main purpose of the meeting on February 9th was to conduct the business of the RPMI, discuss current activities, upcoming conferences, new NSF proposals and various announcements affecting the RPMI. The current activities presentation by Dave Rosen included a MEMS packaging project, a soft tissue medical models project, a scanning and reverse engineering project, and a truss structures project. Dave indicated that members of the RPMI staff would be attending and participating in the 3D Systems NASUG meeting in March and the SME RPA RP&M 2001 conference in May. Dave also gave a report of the present NSF proposals (4) submitted by the staff and those proposals planned in the near future (2). These grants, if successful, will augment the research sponsored by the RPMI member fees. The meeting was adjourned following the introduction of Andrew Layton, the 'soon-to-be' RPMI Program Manager, and announcements concerning several current NSF project timelines.

RPMI Members Meeting, April 26-27, 2001

The second RPMI meeting of the year was a two-day format. The business meeting was held on the second day, following the first day that was devoted to student project presentations. The members welcomed the following guest: Chris Francino from NavAir-Pax River and Bill Durden from Durden Enterprises (former Founding Member).

Following a brief overview by Dave Rosen of the selected projects to be presented, the meeting on the first day began with an update of Rapid Tooling projects (Tooling Life and Molded Part Properties) by the responsible students. This was followed by student presentations on the following projects:



Rapid Tooling Test Bed: Mold Design, Process Planning, and Distributed Computing

Metrology and CAV: Metrology Research and SLA Accuracy Issues

SLA and Materials: SLA Material Aging, Micro-SLA, and SLA Cure Model Environment

Design for Additive Fabrication, Rapitronics, and Truss Structures, Laser CVD, and Machinability of Materials

Following the meeting, the members, staff, and students traveled to Bill Durden's Berry Patch Farm for an evening of barbeque, volleyball, and fellowship.

The second day began with a general overview by Dave Rosen of the RPMI project portfolio and the status of the student investigators. With many of the students graduating in the near future, the opportunity exists to continue the current research or change the focus of the portfolio with a new series of projects.   While some current NSF funded projects were being concluded by mid-year, the staff is aggressively working to replace that funding by submitting several new project proposals to NSF and NASA.

NSF Proposals: "Digital Clay" and "Distributed Computing Environment for Build-to-Order Systems"

NASA Proposal: "Human Exploration and Development of Space"

Andrew Layton began his duties as the new RPMI Program Manager by reviewing his vision for the RPMI members and guests. He announced that he would be developing an agenda and coordinating the activities required for the RPMI to host a symposium in 2002.

Doug VanPutte reported on his visit to the Milwaukee School of Engineering to deliver a talk on Space Puzzle Molding and to evaluate the success of their industrial consortium. Besides Doug's presentation, Robert Kilbert, representing Thixomat, gave a presentation on "Thixotropic Injection Molding of Magnesium." Doug reported the highlights of that presentation to the meeting attendees.

Guest presenter, Shayne Kondor, Georgia Tech Research Institute, gave a very interesting presentation on the use of RP technologies in dental restoration.

The meeting 'Show & tell' presentations were made by Diana Kalisz , 3D Systems, and students from the graduate level CAD course that used the RPMI lab SLA to build an operational differential gear designed in class.

The 'show & tell' was followed by discussions about recruiting new members, alternate RPMI structures, and possible new research initiatives.

The meeting was adjourned after the opportunity statements concerning new projects were collected from the members present.

RPMI Members Meeting June 14-15, 2001

Rick Pressley of Pratt & Whitney welcomed the RPMI members and staff to the Pratt & Whitney Facility at West Palm Beach, Florida for the third meeting of the year, a two-day format. The meeting combined a set of well-orchestrated tours and introductions to the Pratt & Whitney facility with the conduct of relevant RPMI business.

IR Building at Pratt & Whitney

Following a brief overview of the RPMI project portfolio for the Pratt attendees, Ken Head gave the first presentation. Ken described how RP was used in rocket engine manufacture at Pratt. The group then toured the jet engine test areas.

In the afternoon, the group toured the rocket engine test area and the ADL test lab, followed by a tour of the rocket engine assembly area.

The second day began with a hosted breakfast. The group was joined by Thomas Auxier, Vice President of Advanced Technology & Preliminary Design at Pratt. After reconvening at Pratt facility, Tom spoke on "Pratt & Whitney's Strategic Vision of Air Transportation by 2050." Tom's talk was followed by a brief overview of the continuing RPMI projects and their student investigators by Dave Rosen. Dave stressed the point that the graduation of many of the students within the next few terms opens the opportunity to redefine the RPMI portfolio.

During the business portion of the meeting, Andrew Layton introduced a series of new initiatives to attract new members. They include a new ''Affiliate Membership' program and the intent to deliver increased value to the RPMI current members. Following a presentation of the annual RPMI member survey results, the group discussed the new opportunity statements and potential new research directions. Material development and SLA surface coatings surfaced as important facets of any new research program.

RPMI Members Meeting, October 19, 2001

The last meeting of the year, presented on a one-day format, began with a welcome to all, including guest Michael Hirschmann from Morris Technologies and Paul Lewis and Charles France from the Georgia Tech Economic Development Institute. The welcomes were followed by project presentations by both the RPMI faculty and students as follows:

"Characterization and Calibration of SLA Products and Processes" by Dr. Janet Allen on behalf of Brian Davis.

"Rapid Prototyping Benchmark Study" by Dr. Nagesh Murthy

"Micro-SLA" by Benay Sager

"SL Cure Model" by Yan-Yan Tang

"Advances and Directions in Metrology" by Dr. Tom Kurfess

"Truss Structures Project" by Vincent Wang

"Digital Clay" by Austina Nguyen

"Laser Chemical Vapor Deposition" by Jae-Hyoung Park

"MEMS Applications" by Angela Tse

"Machinability of Ceramic Filled Epoxy Tooling Board" by Tosin Tomori

Following the lunch break, Andrew Layton gave the Program Manager's Report. Andrew reported several changes to the RPMI laboratory. In addition to refurbishing the Stratasys FDM 1650, Andrew announced the purchase of a new 3D Systems Viper to support the MEMS and Micro-SLA projects and the surplus of other equipment that is no longer required. Andrew also reported new efforts to support businesses outside of the RPMI membership through an Affiliate Membership. He completed his report by announcing that the RPMI symposium, originally scheduled for February 2002, has been rescheduled for October 2002. Andrew's report was followed by reports by Dave Rosen, Diana Kalisz, and Doug VanPutte

Dave Rosen took the opportunity to review the status of the Digital Clay project and the RPMI projected budget for 2002. Dave also charged the membership to identify and consider what new directions or "Grand Challenge" the RPMI should undertake in the future.

Diana Kalisz gave a presentation on the recent acquisitions by 3D Systems and some technology-related activities

Doug VanPutte announced the results of the search by the election committee for new RPMI Committee Chairs and asked for any additional nominations from the floor. With no additional nominations, Doug presented the slate as follows:

Diana Kalisz, 3D Systems, for Operations Committee Chair

Mahesh Kotnis, Vantico, for Membership Committee Chair

Rick Pressley, Pratt & Whitney, for Technology Committee Chair

The candidates were elected by a vote of acclamation.

Before the meeting was adjourned, the members indicated that they were satisfied with the current research portfolio of the RPMI.

2002 Meeting Dates, Locations & Agenda

Member Meeting, February 15, 2002	Georgia Tech, Atlanta Business Meeting, Project Reviews, Committee Agenda
Member Meeting, April 22, 2002	Georgia Tech, Atlanta Business Meeting New Proposal Generation, Year-End Project Completions
Member Meeting, June 13-14, 2002	Member Site, New Project Development, Technology Transfer
Member Meeting, October 16-18, 2002	Georgia Tech, Atlanta RP&M Symposium New Project Launch Business Meeting Year End Committee Reports Chair Elections

Focus on RP&M's Future

Increasingly, people are recognizing that the future of RP&M is on those applications that take advantage of the unique capabilities of these technologies. The RP&M industry is maturing and entering mainstream roles within product realization. As a result, the RPMI must find new challenges that are industry relevant and have potential long-term impact. At the same time, we must be structured in a manner that enables us to be responsive and to deliver value to our sponsors and customers.

Research Directions

To position us to attract steady, significant government and industry funding, we have formulated a research agenda that leverages our strengths and accomplishments. We have tremendous expertise in RP, rapid tooling, metrology, polymers, metal and ceramic materials, and design. Additionally, there is a major effort underway at Georgia Tech to explore micro- and nano-scales.

We believe that the new project portfolio positions us appropriately in this changing industry. There is a need for neutral technology evaluation sites, demonstrations of new applications, benchmark studies – we can do that in our Applications thrust. Market forces are driving products to be smaller, lighter, and more integrated – we are well positioned with LCVD and micro-SLA technology efforts to respond. The need for increasingly high performing designs that maximize material usage can be addressed – with our truss structure technology. Industry will benefit in the long-term as we develop a better understanding of materials and material processing fundamentals that underlie additive fabrication technologies – and we are doing that as part of our project portfolio. Additionally, industry needs greater productivity in product development – we are addressing that need with efforts in design and CAD methods that incorporate knowledge of RP&M technologies. Also, our digital clay initiative focuses on vastly improved human-computer interfaces that will greatly impact designer productivity.

Ways to Get Involved

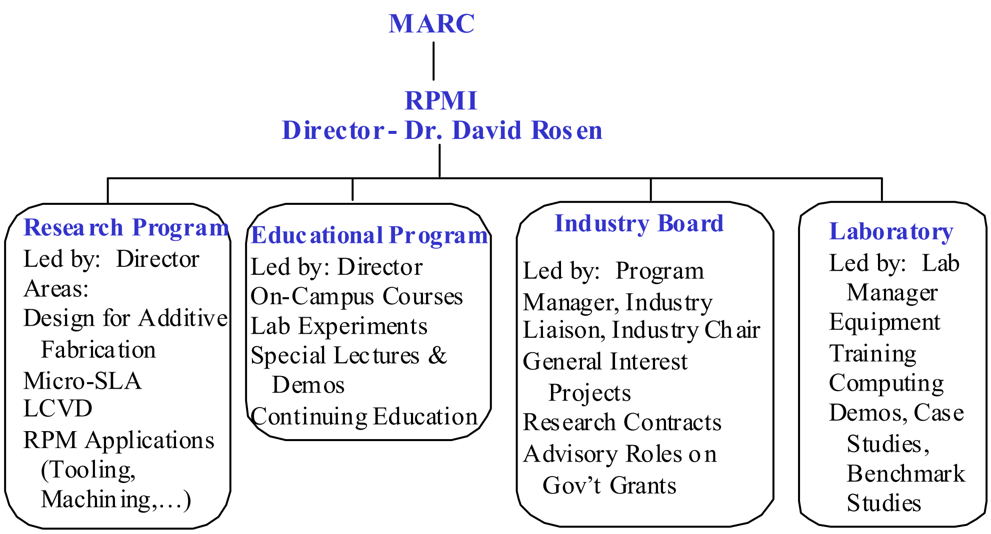
Rather than just relying on RPMI membership as the only means to participate in the RPMI, we have added several more. These changes fundamentally alter the funding mechanism of the RPMI and we are working with the Georgia Tech administration to put all necessary structures and procedures in place. These four ways to get involved enable the RPMI to be more responsive to the needs of industry and government agencies. We can fine-tune the level of involvement, the timing, and the content to suit our customer's needs. The four ways to get involved are:

- **Standard RPMI Membership**. Participate in group project selection and sponsorship, while networking with other RP&M experts, and keeping current in RP&M technologies on an annual basis.
- **Affiliate Membership**. An alternative to standard membership, we will provide access to our facilities and expertise with a focus on your issues. Two levels of membership enable you to get certain levels of parts made, perform a benchmarking study on your products, push the technology envelope in directions of your interest, etc. With an Affiliate membership, you may attend RPMI member meeting in a non-voting capacity.
- **Short Courses**. We offer several short courses, ranging from 1 to 4 days. We will provide a standard course, or customize it for your needs, including prototyping some of your designs. Our facilities or yours. Additionally, our biennial Gwaltney Symposium on Digital Fabrication and Manufacture attracts many practitioners and researchers with its state-of-the-art technologies, applications, and demonstrations.
- **Research Contract**. Let us solve your more challenging problems. We will develop technologies to license to you, your suppliers, or your customers, or explore other means of technology transfer.

Structure of the RPMI

Organizationally, the RPMI is within the Manufacturing Research Center (MARC) at Georgia Tech, with MARC operating under the Office of Interdisciplinary Programs. MARC Director Steven Danyluk has been tremendously supportive, providing additional space, managing personnel transfers, additions, and promotions, and generally being a strong advocate for the RPMI within the Georgia Tech administration. The current RPMI structure is shown in the org. chart below.

Having the right people is the key to success. The addition of Andrew Layton as Program Manager in April 2001 was a critical hire. Andrew is responsible for growing the industry membership, as well as assisting with the acquisition of government funding. Our Lab Manager, Steven Sheffield, has responsibilities for running projects and assisting with applications, in addition to the equipment and computing responsibilities necessary to run the laboratory. The Industry Liaison, Doug VanPutte, uses his experience, contacts, and networking skills to keep current members satisfied and help recruit new members. Lisa Teasley, our Administrative Assistant, is tremendously helpful and responsive to our needs. This staff integrates with the larger MARC and GT organization to make good things happen.



Long and Short Term Strategic Plan

Our founding charter (see Appendix B) served as our first strategic plan, guiding us to build the sort of organization that we have today. In 2002, we enter the RPMI's eighth year in existence, and the fourth year of the five-year strategic plan developed in 1998. Our strategic plan emphasizes both long- and short-term goals consistent with our mission and vision. The up-and-down realities of the RP&M industry compel us to continually evaluate the relevance of our programs and activities, but we remain true to our central mission of delivering valuable RP&M education.

We have made good progress on our five-year strategic plan, which can be seen in Appendix C. The reality of the RP&M industry is that a focus on expensive prototype technologies will not succeed in the long-term – low-cost "concept" prototyping technologies are becoming available. As highlighted in the NCMS Road-Map, the future of RP&M technologies rests in their successful application to design/manufacture problems that are impossible or too expensive for traditional manufacturing technologies. The longer-term elements of our research program are driven by this recognition. Specifically, we are pushing the size envelope in both directions: focusing on large parts through our truss structure work, and small part in our Micro-SLA and LCVD research. We will have the knowledge and know-how to design, process plan, and manufacture products to take advantage of the unique capabilities of these technologies.

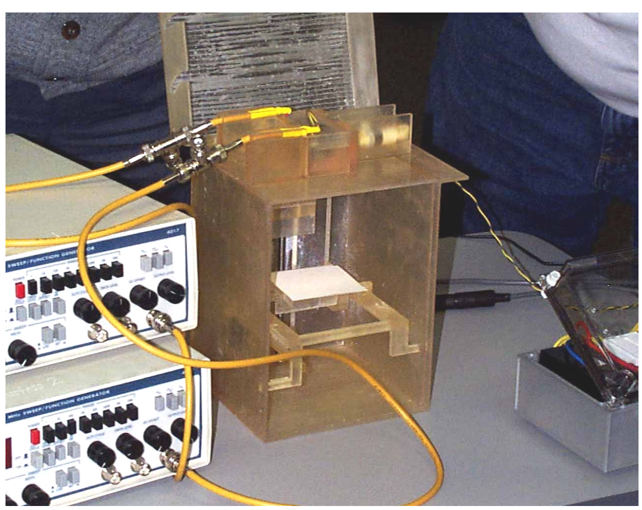
There is a need to balance short-term and long-term activities. We need to deliver value to our industry members – and all of our stakeholders – on a periodic basis. However, we cannot get trapped into obsolete technologies, nor be driven by irrelevant issues. Our strategic plan seeks to guide us in achieving this short- and long-term balance. Each of our activities has a short-term objective, but fits into the long-term plan. In the Year 3 plan, our strategic plan called for us to deliver significant metrology results, commercialize truss structure technology, refocus the rapid tooling effort, and pursue a rapid manufacturing program. We had significant efforts in each of those areas. Additionally, we began a new strategic planning initiative. As stated in the Accomplishing Specific Goals section, we did not pursue short courses to the extent that we hoped.

In Year 4, our strategic plan calls for us to continue identifying new directions. As time progresses, strategic plans must be modified to reflect new realities. Instead of studying 3D home printers, we will focus more on rapid manufacturing technologies for fabricating unique devices. This fits much better with our MEMS efforts, the Digital Clay project, our new Viper SL machine, and the progress in LCVD. Our modified Year 4 plan is below. We have a good start on each element of this plan and look forward to achieving our objectives. In doing so, we believe we are true to the title of this Annual Report: ***Focusing toward RP&M's Future***.

As always, we invite your comments, concerns, and questions on our strategic plan.

Year 4 - 2002

Research	Reassess the generalized SLA technology project. Refocus the rapid manufacturing effort consistent with our MEMS and Digital Clay initiative and our Viper SL machine. (De-emphasize) Start an effort to study <$10,000 3D home printers. May involve working with a commercial developer. Demonstrate feasible GT solid freeform fabrication technology (begun in 1999). This is the LCVD technology. Develop and pursue a rapid manufacturing program.
Strategy	Fine-tune our strategic plan to reflect changes in the RPMI and industry.
Infrastructure	Acquire new RP technology to support research activities for the next three years.
Education	Develop short courses and investigate novel methods of delivery, e.g., web-based. Plan for a major Symposium in 2002. Host a major continuing education event.



Goals for 2002

Education

- *Continue our involvement with the Aerospace Engineering and Industrial Design schools with the aim of introducing RP&M techniques to mainstream / traditional design practices.*
- *Design, produce and make available an updateable web-based RP&M course for industry outreach in conjunction with College of Engineering's continuing education program.*
- *Pursue collaborations with Electrical and Computer Engineering School in MEMS research and education.*
- *Graduate one Ph.D. candidate and five Master's candidates.*

Research

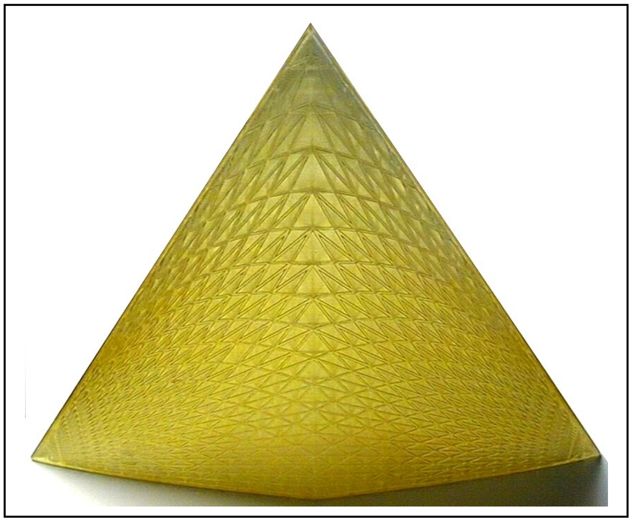
- *Develop and demonstrate internal structure shape concepts for the Digital Clay project.*
- *Work with the DuPree School of Management to disseminate the results of an industry survey on RP, RT, and RM usage.*
- *Develop software for truss structures that can be disseminated to members and other users.*
- *Develop and demonstrate micro-SLA applications and the ability to form very small features with repeatability.*
- *Continue to develop methods used to create complex working devices, which may utilize embedded actuators and / or sensors, directly from the vat*
- *Publish five papers in refereed academic journals.*
- *Receive patent approval.*

Infrastructure

- *Enact our new strategic plan while continuing to monitor the RPMI's direction in a changing industry. Fine-tune our strategic plan to emphasize the value proposition.*
- *Formalize a collaboration agreement with at least one other university.*
- *Enact the new marketing plan based on current member referrals. Recruit three new members.*
- *Begin work with the Office of Foundation Relations to locate new grant sources.*
- *Begin project-based interactions with companies through the Affiliate member offering.*
- *Increase the value of our web site by making information ever more readily available to members.*

Outreach

- *Continue initiatives that enhance RPMI relationships with the Georgia Tech Economic Development Institute, the Georgia Tech Research Institute, and the Georgia Tech Office of Technology Licensing.*
- *Broaden faculty involvement in materials research.*
- *Introduce 20 Southeastern industries to the RPMI through site visits and meeting interaction.*
- *Sell every seat and vendor booth at the 2002 Symposium & Expo.*
- *Teach one RP&M seminar or short course for industry.*
- *Deliver six RP presentations at three conferences.*



Appendices

A. Contact Directory

Name and Address	Phone	Fax	Email
Baxter International, Inc.			
Mr. Don Smith Baxter International, Inc. Advanced Engineering/Design Center Route 120 & Wilson Road RLP – 30 Round Lake, IL 60073-0490	847-270-4950	847-270-4077	don_smith@baxter.com
Mr. Terry Kreplin Baxter International, Inc. Advanced Engineering/Design Center Route 120 and Wilson Road RLP – 30 Round Lake, IL 60073-0490	847-270-4067	847-270-4008	Terry_kreplin@baxter.com
Vantico (formerly Ciba Specialty Chemicals)			
Dr. Mahesh Kotnis Ciba Specialty Chemicals Technical Manager, Tooling Group 4917 Dawn Avenue East Lansing, MI 48823	517-324-1317	517-324-1383	mahesh.kotnis@vantico.com
Dr. Rich Leyden Director of Product Creation Adhesives and Tooling 5121 San Fernando Road West Los Angeles, CA 90039	818-265-7231	818-247-6616	rich.leyden@vantico.com
DSM Somos			
Mr. Jim Reitz DSM Somos Two Penns Way, Suite 401 New Castle, DE 19720	302-328-8189	302-328-5693	jreitz@dsmdesotech.com
Ms. Michelle Wyatt DSM Somos Two Penns Way, Suite 401 New Castle, DE 19720	302-328-5472	302-328-5693	gthommes@dsmdesotech.com
Durden Enterprises, Inc.			
Mr. Bill Durden Vice-President & General Manager Durden Enterprises, Inc. P.O. Box 909 1317 Fourth Avenue Auburn, GA 30203	770-963-0637 Ext. 102	770-995-7067	bdurden@durdene.com
Eastman Kodak Company			
Mr. Gary Beldue Development Technician Eastman Kodak Company 2400 Mt Read Blvd Rochester NY 14650-3013	716-726-4569	716-726-0398	Gary.beldue@Kodak.com

Name and Address	Phone	Fax	Email
Ford Motor Company			
Mr. Neal Enke Rapid Prototyping and Tooling Ford Motor Company 20901 Oakwood Boulevard P.O. Box 2053 Cube 1A-C07 Mail Drop 106, PDC Dearborn, MI 48121-2053	313-390-1641	313-322-1426	nenke@ford.com
Lucent Technologies			
Dr. John J. Malluck Technical Staff, Bell Laboratories Lucent Technologies 2000 Northeast Expressway Room 2D-12 Norcross, GA 30071	770-798-2680	770-798-2690	jmalluck@lucent.com
Mr. Marc Jones Technical Staff, Bell Laboratories Lucent Technologies 2000 Northeast Expressway Room 2D-12 Norcross, GA 30071	770-798-3977	770-798-3218	
Pratt & Whitney			
Mr. Robert Delisle Manufacturing Technology Pratt & Whitney 400 Main Street MS 118-40 East Hartford, CT 06408	860-565-0631	860-565-5611	delislrp@pweh.com
Mr. Chris O'Neill Manufacturing Technology Pratt & Whitney 400 Main Street MS 118-40 East Hartford, CT 06408			oneillcf@pweh.com
Mr. Rick Pressley Senior Engineering Associate Technical Pratt & Whitney Aircraft P.O. Box 109600 MS 729-04 West Palm Beach, FL 33410-9600	561-796-5571	561-796-5666	pressley@pwfl.com
Siemens Energy and Automation			
Mr. Bud Bollinger Circuit Protection & Controls Div. Siemens Energy and Automation 5400 Triangle Parkway Norcross, GA 30092	770-326-2240	770-326-2322	bud.bollinger@sea.siemens.com
Mr. Greg Cornish Circuit Protection & Controls Div. Siemens Energy and Automation 5400 Triangle Parkway Norcross, GA 30092	770-326-2110	770-326-2322	greg.cornish@sea.siemens.com

Name and Address	Phone	Fax	Email
3D Systems, Inc.			
Dr. Chuck Hull 3D Systems, Inc. 26081 Avenue Hall Valencia, CA 91355	661-295-5600 Ex 2584 (Sandra)	661-295-8367	hullc@3dsystems.com
Ms. Diana Kalisz 3D Systems, Inc. 26081 Avenue Hall Valencia, CA 91355	661-295-5600	661-295-8367	kaliszd@3dsystems.com
Dr. Yong Chen 3D Systems, Inc. 26081 Avenue Hall Valencia, CA 91355	661-295-5600 Ext 2194	661-295-8367	cheny@3dsystems.com
Mr. Rusty McDonald Senior Applications Engineer 3D Systems, Inc. 1082 Stoval Ridge Court Lawrenceville, GA 30043	770-277-0723	770-277-3616	mcdonaldr@3dsystems.com

Georgia Tech Participants			
Name and Address	**Phone**	**Fax**	**Email**
Mr. Andrew Layton Program Manager, RPMI Manufacturing Research Center Georgia Institute of Technology Atlanta, GA 30332-0406	404-385-1053	404-894-0957	andrew.layton@marc.gatech.edu
Dr. David Rosen Director, RPMI School of Mechanical Engineering Georgia Institute of Technology Atlanta, GA 30332-0405	404-894-9668	404-894-9342	david.rosen@me.gatech.edu
Mr. Douglas VanPutte RPMI Industry Liaison Cross-Bow Rapid Tool Associates 18 Cross Bow Drive Rochester, NY 14624	716-889-3601	716-889-7335	dvanputt@rochester.rr.com
Mr. Steven Sheffield RPMI Laboratory Manager Manufacturing Research Center Georgia Institute of Technology Atlanta, GA 30332-0406	404-894-9639	404-894-4133	steven.sheffield@marc.gatech.edu
Ms. Lisa Teasley Administrative Assistant Suite 301 Manufacturing Research Center Georgia Institute of Technology Atlanta, GA 30332-0406	404-894-9100	404-894-4133	lisa.teasley@marc.gatech.edu
Dr. Janet Allen School of Mechanical Engineering Georgia Institute of Technology Atlanta, GA 30332-0405	404-894-8168	404-894-9342	Janet.allen@me.gatech.edu
Dr. Jon Colton School of Mechanical Engineering	404-894-7404	404-894-9342	jonathan.colton@me.gatech.edu
Dr. Imme Ebert-Uphoff School of Mechanical Engineering	404-385-0667	404-894-9342	imme.ebertuphoff@me.gatech.edu
Dr. Tom Kurfess School of Mechanical Engineering	404-894-0301	404-894-9342	tom.kurfess@me.gatech.edu
Dr. Peter Hesketh School of Mechanical Engineering	404-385-1358	404-894-8496	Peter.hesketh@me.gatech.edu
Dr. W. Jack Lackey School of Mechanical Engineering	404-894-0573	404-894-9342	Jack.lackey@me.gatech.edu
Dr. Shreyes Melkote School of Mechanical Engineering	404-8499	404-894-9342	shreyes.melkote@me.gatech.edu
Dr. Nagesh Murthy College of Management Georgia Institute of Technology Atlanta, GA 30332-0520	404-894-4197	404-894-6030	nagesh.murthy@mgt.gatech.edu
Dr. John Muzzy School of Chemical Engineering Georgia Institute of Technology Atlanta, GA 30332-0100	404-894-2882	404-894-2866	john.muzzy@che.gatech.edu

B. Founding Charter

September 1, 1995

The founding members of the Rapid Prototyping and Manufacturing Institute (RPMI) have come together with a common goal: to further the deployment of rapid prototyping and manufacturing through education. All activities of the RPMI will focus on education.

Rapid Prototyping and Manufacturing (RP&M) is an emerging collection of materials and process technologies, design and processing methodologies, and business practices and relationships, which together shorten product development cycles, improve product designs, and reduce product development costs. RP&M is often associated with additive fabrication processes, such as stereo lithography or selective laser sintering, and includes many other prototyping technologies, as well as such conventional processes as CNC machining, and a host pc computer-based design, engineering, and analysis tools.

The Need

Companies that are potential adopters of RP&M and students who may need to work with RP&M share a need for information and education that advances RP&M deployment. RP&M is one of the fastest growing areas of manufacturing technology today. RP&M holds the promise of saving both time and money in bringing new products to market. Other technologies, involving data handling, global networking, CAD, CAM, CAE, CNC machining, investment casting, RTV molding and virtual prototyping, all come together around RP&M. But, only a few companies are reaping the benefits of the RP&M and its associated technologies. Even companies already using RP&M are struggling to keep up with the rate of change, and few students are familiar with RP&M and its benefits.

The founding members of the RPMI share a need for an organization that serves as a clearing house for information, that can host case studies and research to address both specific and generic concerns, and that promotes education for both degree students and practicing professionals. The RPMI is intended to meet those needs.

The Impact

The RPMI will dramatically impact education in several ways:

Assembling an Information Resource: The RPMI will become an information clearing house for a community that includes manufacturers, professionals, students, and faculty. Information will flow freely among all members, students, and the broader community. Institute members are expected to help Georgia Tech to identify specific educational needs and to work with Georgia Tech to create appropriate educational opportunities (e.g., workshops, short courses and seminars). Members will share ideas with each other and will work together to solve common problems.

Increasing Knowledge of RP&M: Most RPMI activities will revolve around an RP&M laboratory at Georgia Tech. Institute members will play a key role in helping Georgia Tech to select the equipment for the lab that is most relevant for our educational objectives. This lab will be open to Institute members and to GT students pursuing educational opportunities in RP&M, and will be equipped with industrial grade equipment representing the current state-of-the-art. The lab will provide all participants with an opportunity to experiment and learn in a controlled setting.

Creating an Environment that Encourages Case Studies: The RPMI will focus on learning about existing and emerging technologies and how they can be used to meet specific current needs in industry. Institute members are expected to help Georgia Tech identify these specific needs, and to work with Georgia Tech students, RP&M lab staff, and Georgia Tech faculty to create educational experiences in which RP&M methods will be developed and refined.

Developing Highly Skilled People: The RP&M lab will be sustained by an identifiable nucleus of experts. The lab will be a source of well-trained and talented engineers, managers, and scientists. Students who use the lab will be uniquely prepared to enter industry through their experiences with RPMI members. Members, too, will learn and grow through their hands-on experiences.

Goals of the RPMI

The specific goals of the RPMI include:

- To engage industry in the education of their future engineers, designers, scientists, and managers
- To align our students' education more closely with the true needs of their future employers
- To enhance the educational experience of Georgia Tech's students by exposing them to state-of-the-art technologies in an interdisciplinary instructional laboratory
- To promote current rapid prototyping and manufacturing technologies by developing, refining, demonstrating, and communicating creative case studies of these technologies
- To develop new methods in areas related to RP&M, such as rapid tooling, rapid fixturing, rapid casting, and flexible tooling
- To develop necessary integration between RP&M technologies and design, manufacturing, and business functions
- To continually change and grow to meet the needs of industry as communicated through the members
- To increase the competitiveness of manufacturers in Georgia, and throughout the Southeast, by helping them to fully exploit RP&M technologies

Measuring Success

Measuring our progress will ensure that we will remain focused on our goals and that our industry partners, students, and faculty see the benefits that they expect. We will track our progress relative to those benefits.

1. Assembling an Information Resource: Count the number of and track attendance at seminars, workshops, short courses, and symposia sponsored and delivered by the RPMI. Track member participation specifically. Record specific interactions fostered by the RPMI within the broader community that create competitive advantages for members. Report on the growth and use of the RPMI's information resources (e.g., a library including current publications, electronic bulletin boards, vendor information, equipment benchmarks). Document publications and presentations that result from RPMI activities.

2. Increasing Knowledge of RP&M: Record both the breadth and depth of the technologies available in the RP&M lab. Report on specific successes in deploying RP&M technologies. Track the growth of the use of RP&M technologies among members and the broader community. Tally the number of hands-on hours members, students, and faculty spend learning and using each technology in the lab. Log visits by members of the broader community of manufacturers, and record the nature of their interactions.

3. Creating an Environment that Encourages Case Studies: Document each case study -- the processes, outcomes, and investment in time and dollars. Quantify the business results from each case study, i.e., what did members learn and how did each use the knowledge. Request from industry members,

GT faculty, and students, an annual review of the Institute's accomplishments and opportunities for improvement.

4. Developing Highly Skilled People: Track the nature of the interaction for each activity in the lab. Count the numbers of students and faculty using the lab. Ask the members to report on new professional relationships initiated and nurtured through RPMI participation. Track instances of members hiring students as co-ops, interns, or full-time employees.

The key to good measurements is in keeping good records. We will establish reliable procedures to collect, store and report on all measures listed above. Results will be reported in the RPMI annual report.

General Principles

Education is our mission. Education will be the primary focus of all activities at the RPMI.

- RPMI members will be active partners Each member is expected to be involved in identifying, supporting, and evaluating student projects in the lab. Each of these projects will involve GT students and/or faculty. Institute members will be encouraged to be directly involved in lab activities through appropriate staffing and operating hours.
- The RP&M lab will not operate as a service bureau. That is, the lab will avoid taking on projects if they can be executed by a commercial source. The RP&M lab will focus on projects that provide an educational experience for both members and students.
- Equipment content in the RPMI lab will be reviewed annually. Members will critically review each major piece of equipment to assess its use in the lab. Members may recommend to replace outdated equipment with more current or appropriate technologies.
- Institute members will act as an Industrial Advisory Board. The industry members of the institute will be expected to act as an industrial advisory board (IAB) to the RP&M lab. The IAB will routinely review the operations of the lab, and make recommendations for improvement in facilities, operations, or activities.

Membership Guidelines

The Rapid Prototyping and Manufacturing Institute is critical to the success of Georgia Tech's educational programs in rapid prototyping and manufacturing. The industrial members of the Institute, individually and collectively, are key partners with Georgia Tech in these educational activities.

RPMI member companies will be selected carefully. The first few founding members will be invited by GT alone. Then, founding members will work together with GT to identify and recruit additional members. This careful selection of members will help the RPMI focus its energy on issues of common interest.

Membership is limited. The regular, meaningful participation of each member is crucial. A limit will allow us to ensure that the quality of interactions between members and students remains high. The initial limit will be fifteen (15) industrial members, but the limit may be raised or lowered in the future if appropriate.

The RPMI will have a single rank of membership. Each member will have an equal voice, and each member will provide Georgia Tech with an annual gift of $25,000 earmarked for the RP&M lab. Companies may renew their membership each year on the anniversary of their original membership date. Each year, the amount of the request may be raised or lowered as the Institute's need for funds changes.

The RPMI may invite new members under special terms. The standard cash gift may not be appropriate for some members. The RPMI may elect to make a special invitation to certain members if extenuating circumstances exist. For example, a small company may have crucial interests and skills to bring to the institute, but $25,000 may be too much of a burden for the small firm. Similarly, a RP&M vendor may have unique expertise, equipment, material, or services to contribute as a member instead of a cash donation.

Members joining under special terms will have the same membership status as members contributing the standard cash amount.

Founding members will have unique opportunities. Founding members, i.e., members joining the Institute by October 23, 1995, will be recognized as founding members. Founders will be particularly well positioned to influence the initial development of the Institute, the RP&M lab, and the Institute's agenda.

Organization and Procedures

This charter will guide the activities of the RPMI. The purpose of the charter is to describe how Georgia Tech intends to conduct this educational activity. Georgia Tech may amend this charter at any time, to reflect the changing needs of industry or of the RPMI. The charter is not a contract.

Major decisions will be guided by a vote of the RPMI members Major decisions regarding the equipment or operations of the RP&M lab will be informed by a vote of the Institute members, but will remain the responsibility of Georgia Tech.

Members will influence the RP&M lab's activities. Members of the Institute will work with each other and with GT participants to define projects and to see them through to some meaningful conclusion. It is expected that at any time, the Institute would have a portfolio of potential projects, and that a project selection process would involve a vote among the Institute members. Choosing activities in this way will help us all ensure that the lab will host projects of specific importance to industry, and therefore of greatest value to GT students.

Members will meet quarterly. Frequent meetings between Georgia tech and the Institute members will ensure that the activities of the RPMI are achieving the educational goals set forth in this charter.

RPMI officers will be elected annually. It is expected that the IAB will organize itself in order to be effective and efficient in its interactions with Georgia Tech. Founding members will help structure the offices and duties of each office.

Summary

The Rapid Prototyping and Manufacturing Institute exists to meet the needs for education and demonstration of rapid prototyping and manufacturing. Its success is defined by the willingness of its private sector members to continue their participation, and the willingness of Georgia Tech faculty and students to continue their involvement. This charter expresses the intent of both Georgia Tech and the other Institute members with regard to participation, operation, and governance of the RPMI

C. Long and Short Term Strategic Plan

The RPMI Strategic Plan is intended to present the overall objectives and mission of the RPMI. Additionally, yearly objectives are presented for a five-year time frame, which become increasingly less specific. This plan is intended to be complementary to the RPMI Charter.

Mission:

To develop and deploy Rapid Prototyping and Manufacturing (RPM) technologies and applications through education, research, and service.

Objectives:

- To be an internationally recognized center for RPM education activities.
- To develop RPM technologies that enhance a company's capability to bring products to market much more quickly and at less cost.
- To foster the growth of intellectual capital among all RPMI stakeholders.
- To maintain an open facility for all RPMI partners equipped with technologies representing the current state-of-the-art in RP.

Focus Areas:

These focus areas are of current research interest in the RPMI and will be expected to evolve over time.

- Rapid Tooling
- Rapid Inspection
- Rapid Manufacturing (5-Axis SLA + Alternative Applications)
- RPM within Product Realization

Specific Areas of Contribution:

More comprehensive than the Focus Areas above, these areas of contribution establish the breadth of activities within the RPMI. Specific activities, goals, and tactics are described in the RPMI Annual Reports.

Research	Education	Service
Scholarship	Undergraduate Students 150/yr	**Georgia Tech**
Product Realization	Graduate Students 30/yr direct	Laboratories
Design	100/yr indirect	Projects in courses
Materials and Processing	Practicing Engineers & Others	Guest Lectures
	120+/yr	
CAD/CAM	Through academic courses and	**National Organizations**
	projects, and Industry Short	SME RPA
	Courses	
Metrology		3DNASUG
Practice		ASME
RT, RP Methods		**State**
RT, RP Processes and Standards		EDI
Rapid Inspection and Metrology		

Year 1 - 1999

Research	Implement research plan established in 1998. Deliver useful rapid tooling results and RP/RT selection tools. Demonstrate SLA process planning capabilities. Acquire funding to begin the development of the GT solid freeform fabrication technology, that is fundamentally different from commercial RP technologies. Probable direction is LCVD.
Infrastructure	Acquire new RP technology to support research activities for the next three years. Probable acquisition is a SLA-3500.
Education	Establish new continuing education plan. Lay foundation for relationships with US universities. Run projects with the University of Louisville. Lay foundation for relationships with international universities.

Year 2 - 2000

Research	Demonstrate feasibility of generalized SLA technology ("5-Axis SLA") to enable the fabrication of mechanisms, multiple material components, and smooth surfaces. Deliver best practices report. Establish the economics of rapid manufacturing using commercial RP technologies. Establish product realization process standardization needs. Deliver the Rapid Tooling TestBed. Demonstrate its use on education and industry projects. Acquire funding for a successor to the RTTB.
Education	Begin the continuing education plan from 1999. Host a major continuing education event. Conduct a student exchange with national or international university.
Strategy	Reassess the RPMI strategic and operational plans. The RPMI will have been in existence for five years. Do we need to refocus our efforts?

Year 3 - 2001

Research	Deliver significant metrology and rapid inspection results. Demonstrate true rapid CAV methods and tools. Contribute to metrology standards. Reassess and refocus the rapid inspection effort. Commercialize technology for large, light-weight models (truss structure). Refocus the rapid tooling effort. Is it still relevant? Develop and pursue a rapid manufacturing program.
Strategy	Begin implementation of new strategic plan presented in the Overview of Changes in the RPMI section.
Education	Develop short courses and investigate novel methods of delivery, e.g., web-based. Plan for a major Symposium in 2002.

Year 4 - 2002

Research	Reassess the generalized SLA technology project. Refocus the rapid manufacturing effort. Start an effort to study <$10,000 3D home printers. May involve working with a commercial developer. Demonstrate feasible GT solid freeform fabrication technology (begun in 1999).
Infrastructure	Acquire new RP technology to support research activities for the next three years.
Education	Host a major continuing education event.

Year 5 - 2003

Strategy	Reassess the RPMI. Is rapid prototyping still relevant? Should the RPMI continue as is, change its purpose and/or direction, or shut our doors?
Research	Deliver on rapid manufacturing efforts.
Education	Host a major continuing education event.

D. Publications

Ph.D. Dissertations

1999

Beth Judson, Dimensional Accuracy in Rapid Prototyping of Ceramics Formed by Injection Molding Using Rapid Tooling

2000

Tommy Tucker, A New Method for Parametric Surface Registration

2001

Andre Claudet, Analysis of Three Dimensional Measurement Data and Multi-Surface CAD Models
Yong Chen, Computer-Aided Design for Rapid Tooling: Method for Mold Design and Design For Manufacture
Kent Dawson, The Effects of Rapid Tooling on Final Product Properties
Chad Duty, Design, Operation, and Heat and Mass Transfer Analysis of a Gas-Jet Laser Chemical Vapor Deposition System
Dan Jean, Design and Operation of an Advanced Laser Chemical Vapor Deposition System with On-Line Control

Masters Theses

1997

Joel McClurkin, A Computer-Aided Build Style Decision Support Method for Stereolithography

1998

Bryan Blair, Post-Build Processing Of Stereolithography Molds
Andre Claudet, Data Reduction for High Speed Analysis of CMM Data
Kent Dawson, Effect of Rapid Prototype Tooling on Final Product Properties
Charity Lynn-Charney, Computer-Aided Build Style Decision Support For SLA Parts
Tommy Tucker, Measurement and Verification of Models to CAD data

1999

Jessica Brown, Rapid Production System for Composites
Thomas Cedorge, Surface Roughness and Draft Angle Effects on Stereolithography Molds
Chris Franck, Assessing the Value of Rapid Prototyping in Product Development
James Hemrick, Release Characteristics of Stainless Steel Metal Injection Molding in SLA Epoxy Molds
Amy Herrmann, Coupled Design Decisions in Distributed Design
Janet Kinard, Material Systems for Rapid Manufacture of Composite Parts
Yann Lebaut, Design of SLA Molds for Plastic Injection
Tim Lloyd, Pattern Recognition in Coordinate Measurement Data for Dimensional Analysis
Anne Palmer, The Effect of Feature Geometry on the Life of Stereolithography Molds
Aaron West, A Decision Support System for Fabrication Process Planning in Stereolithography

2000

Jonathan Gerhard, Towards a Decision-Based Distributed Product Realization Environment for Engineering Systems
Brad Geving, Enhancement of Stereolithography Technology to Support Building Around Inserts
Alok Kataria, Standardization and Process Planning for Building Around Inserts in Stereolithography Apparatus
Ruben Lanz, Machinability of Polymer Composite Materials for Rapid Tooling
Chad Moore, A Multi-Axis Stereolithography Controller with a Graphical User Interface
Michael S. Pearson, Rapid Tooling for Powder Injection Molding, University of Louisville

2001

Joe Crawford, Injection Failure of Stereolithography Molds
Brian Davis, Characterization and Calibration of SLA Products and Processes
Jacob Diez, Design for Additive Fabrication: Building Miniature Robotic Mechanisms
Sundiata Jangha, An Ejection Mechanism Design Method for Rapid Injection Molding Tools
Rahul Kulkarni, Designing Open Engineering Systems in a Distributed Environment
James Nichols, Metrology Techniques for Turbine Airfoils
Xavier Ottemer, Effects of Processing and of Environmental Conditions on the Properties of Epoxy Materials
Giang Pham, Ejection Failure of Stereolithography Molds
Vincent Rodet**,** Tool Life and Failure Mechanisms of Stereolithography Molds
Shiva Prasad Sambu, A Design for Manufacturing Method for Rapid Prototyping and Rapid Tooling
Hongqing Vincent Wang, Computer-Aided Design Methods for the Additive Fabrication of Truss Structures

Journal Papers

Blair, B.M. and Colton, J.S., "Post-build Cure of Stereolithography Polymers for Injection Molding," *Rapid Prototyping Journal*, Vol. 5, No. 2, 72-81, 1999.
Blair, B.M., and Colton, J.S., "Polishing behavior of Stereolithography Polymer, " *Rapid Prototyping Journal*, submitted for publication (1998). Also, Proceedings of ANTEC '98, Society of Plastics Engineers, 884-887, Atlanta, April 26-May 1, 1998.
Cedorge, T., and Colton, J.S., "Draft Angle and Surface Roughness Effects on Stereolithography Molds," *Polymer Engineering and Science*, Vol. 40, No. 7, 1581-1588, 2000.
Cedorge, T., LeBaut, Y., Palmer, A., and Colton, J.S., "Design Rules for Stereolithography Injection Molding Inserts," *CIRP - Journal of Manufacturing Systems*, 30:2, 2000.
Chen, Y. and Rosen, D.W., "A Region Based Method to Automated Design of Multi-Piece Molds with Application to Rapid Tooling," submitted to *ASME Journal of Computing and Information Science in Engineering*, 11/01.
Chen, Y. and Rosen, D.W., "A Reverse Glue Approach to Automated Construction of Multi-Piece Molds With Application to Rapid Tooling," submitted to *ASME Journal of Computing and Information Science in Engineering*, 11/01.
Choi, W., Kurfess, T. R., Cagan, J., "Sampling Uncertainty in Coordinate Measurement Data Analysis," The Journal of the American Society for Precision Engineering, Vol. 22, No. 3, pp. 153-163, July 1998.
Choi, W., Kurfess, T. R., "Dimensional Measurement Data Analysis Part I, a Zone Fitting Algorithm," *ASME Journal of Manufacturing Science and Engineering*, Vol. 121, No. 2, pp. 238-245, May 1999.
Choi, W., Kurfess, T. R., "Dimensional Measurement Data Analysis Part II, Minimum Zone Evaluation Design," *ASME Journal of Manufacturing Science and Engineering*, Vol. 121, No. 2, pp. 246-250, May 1999.
Claudet, A. and Kurfess, T., "Data Reduction for Computational Analysis of 3D Coordinate Measurement Data," *Transactions of the North American Research Institute*, Vol. 27, pp. 287-292, May 1999.
Claudet, A. C., Kurfess, T. R., "Face Assignment for Three Dimensional Coordinate Measurement Data," *Transactions of the North American Research Institute*, Vol. 29, pp. 557-562, May 2001.
Colton, J.S. and Y. Lebaut, "Thermal Effects on Stereolithography Injection Mold Inserts," *Polymer Engineering and Science*, **40:6**, 1360-1368 (2000).
Colton, J.S. and X. Ottemer, "Effects of Aging on Epoxy-based Rapid Tooling Materials," *Rapid Prototyping Journal*, submitted for publication (2001).
Colton, J.S., J. Crawford, G. Pham, and V. Rodet "Failure of Rapid Prototype Molds during Injection Molding," *CIRP Annals*, **50:1**, 129-132 (2001).
Colton, J.S. and G. Pham, "Ejection Force Modeling for Stereolithography Injection Molding Tooling," *Polymer Engineering and Science*, accepted for publication (2001).
Colton, J.S., and LeBaut, Y., "Thermal Effects on Stereolithography Injection Mold Inserts," *Polymer Engineering and Science*, Vol. 40, No. 6, 1360-1368, 2000.
Dutta, D., Prinz, F.B., Rosen, D., and Weiss, L., "Layered Manufacturing: Current Status and Future Trends," *ASME Journal of Computing and Information Science in Engineering*, Vol. 1, No. 1, pp. 60-71, 2001.

Ebert-Uphoff, I., Gosselin, C.M., Rosen, D.W., and Laliberte, T., "Rapid Prototyping for Robotics and Automation." Book chapter in: *Prototyping for Robotics and Automation*, Ed. K.M. Lee and T. Sobh, IEEE Press, 2001.
Gerhard, J.F., Rosen, D., Allen, J.K., and Mistree, F., "A Distributed Product Realization Environment for Design and Manufacturing," accepted in *ASME Journal of Computing and Information Science in Engineering*, 10/00.
Hemrick, J., Starr, T., and Rosen, D., "Release Behavior for Powder Injection Molding in Stereolithography Molds," *Rapid Prototyping Journal*, Vol. 7, No. 2, pp. 115 - 121, 2001.
Kataria, A. and Rosen, D.W., "Building Around Inserts: Methods for Fabricating Complex Devices in Stereolithography," *Rapid Prototyping Journal*, Vol. 7, No. 5, pp. 253-261, 2001.
Kulkarni, R., Rosen, D.W., Allen, J.K., and Mistree, F., "An Information Model for Finding and Integrating Distributed Resources for Engineering Design-Manufacturing Processes," submitted to *ASME Journal of Computing and Information Science in Engineering*, 12/01.
Lanz, R., Melkote, S.N., and Kotnis, M., "Effect of Process Parameters and Tool Shape on the Machinability of a Particulate-Filled Polymer Composite Material for Rapid Tooling," *Int. J. of Machining Sci. & Tech.,* Vol. 5, No. 2, pp. 217-237, 2001.
Lynn-Charney, C.M. and Rosen, D.W., "Accuracy Models and Their Use in Stereolithography Process Planning," *Rapid Prototyping Journal*, Vol. 6, No. 2, pp. 77-86, 2000.
Palmer, A.E., and Colton, J.S., "The Effect of Feature Geometry on Stereolithography Tooling," *Polymer Engineering and Science*, Vol. 40, No. 6, 1395-1404, 2000.
Sambu, S. and Rosen, D.W., "Stereolithography Mold Life Prediction and Improvement," submitted to *Rapid Prototyping Journal*, 11/01.
Sambu, S., Chen, Y., and Rosen, D.W., "Geometric Tailoring: A Design For Manufacturing Method for Rapid Prototyping and Rapid Tooling," submitted to *ASME Journal of Mechanical Design*, 12/01.
Tucker, T., Kurfess, T., "Newton Methods For Parametric Surface Registration: Part I," *Computer-Aided Design*, submitted 2001.
Tucker, T., Kurfess, T., "Newton Methods For Parametric Surface Registration: Part II," *Computer-Aided Design*, submitted 2001.
West, A.P., Sambu, S., and Rosen, D.W., "A Process Planning Method for Improving Build Performance in Stereolithography," *Computer-Aided Design*, Vol. 33, No. 1, pp. 65-80, 2001.

Conference Presentations - 2001

Chen, Y. and Rosen, D.W., "Problem Formulation and Basic Elements for Automated Multi-Piece Mold Design," ASME Computers and Information in Engineering Conference, paper #DETC2001/CIE-21293, Pittsburgh, Sept. 9-12, 2001.
Chen, Y. and Rosen, D.W., "A Region Based Approach to Automated Design of Multi-Piece Molds with Application to Rapid Tooling," ASME Computers and Information in Engineering Conference, paper #DETC2001/CIE-21294, Pittsburgh, Sept. 9-12, 2001.
Colton, J.S. and X. Ottemer, "Effects of Aging on Epoxy-based Rapid Tooling Materials," Proceedings, Symposium on Solid Freeform Fabrication Austin, August 6-8, 2001.
Colton, J.S., J. Crawford, G. Pham, and V. Rodet, "Failure of Rapid Prototype Molds during Injection Molding," Proceedings, 51st CIRP General Assembly, Paper E/3, Nancy, August 18-25, 2001.
Fernández, M.G., Seepersad, C.C., Rosen, D.W., Allen, J.K., and Mistree, F., "Utility-Based Decision Support for Selection in Engineering Design," ASME Design Automation Conference, September 9-12, 2001, Pittsburgh, PA, DETC2001/DAC-21106.
Mistree, F., Optimization in Industry III, Barga, Tuscany, Italy, June 18, 2001: A Framework for Interactive Decision-Making in Collaborative, Distributed Engineering Design.
Mistree, F., Allen, J.K. and Rosen, D., GINTIC-GT Realizing the Vision Forum, Singapore, September 27, 2001: Towards system Realization in the Year 2020.
Rosen, D.W., "Utility Theory Based Methods for Rapid Prototyping Selection," Software Solutions for Rapid Prototyping Workshop, Hong Kong, July 5, 2001.
Rosen, D.W., "Achieving Distributed Design-Manufacturing Through Design Decision Interoperability," Korea/US Joint Workshop on Information Technology for Product Development, Kyungju, Korea, July 11-12, 2001.
Rosen, D.W. and Ebert-Uphoff, I., "Rapitronics – Combining RP with Mechatronic Systems to Fabricate Complex Functional Devices," 3D Systems North American Stereolithography Users Group Conference, Destin, FL, March 19-21, 2001.
Rosen, D.W., "Rapitronics - A New Application Area for RP and Mechatronics," SME Rapid Prototyping and Manufacturing Conference, May 14-17, 2001.
Tse, L.A., Noh, H-S., Seals, L, Gole, J., Rosen, D.W., and Hesketh, P.J., " Fabrication Of Chemical Sensor Packaging With Stereolithography," International Symposium on Olfaction and

the Electronic Nose - 8, Proceedings of the Electrochemical Society, 198th Meeting of the Electrochemical Society, Washington, DC, March 25-28, 2001.
Tse, L.A., Hesketh, P.J., and Rosen, D.W., "Stereolithography on Silicon for Microfluidics and Microsensor Packaging," Proceedings of 4th International Workshop on High Aspect Ratio Micro-Structure Technology, Baden-Baden, Germany, June 17-19, 2001.
Tse, A., Seals, L., Hesketh, P.J., Gole, J. and Rosen, D.W., "Rapid prototyping of gas chromatograph with stereolithography," Fall ECS Meeting, San Francisco CA, Sept. 2001.
Xiao, A., Choi, H-J, Kulkarni, R., Allen, J.K., Rosen, D., and Mistree, F., "A Web-Based Distributed Product Realization Environment" ASME Computers in Engineering Conference, September 9-12, 2001, Pittsburgh, PA, DETC2001/CIE-21766.

E. Students Graduated

1996	1997	1998
Ware Bedell Steve Carr Scott Casmer Kent Churchill Michael Harrington David Hartkopf Tom Kuhn Laura Morgan	Matt Damrau Kevin Kamphius Marcial Machado Joel McClurkin Brian Van Hiel Imran Yusuf	Bryan Blair Andre Claudet (MS) Kent Dawson (MS) Kenneth Escoe Paul Keegan Charity Lynn-Charney Melissa Sandlin Tommy Tucker (MS)
1999	**2000**	**2001**
Jessica Brown Thomas Cedorge Chris Franck Bill Griffin James Hemrick Amy Herrmann Beth Judson (PhD) Janet Kinard Yann Lebaut Tim Lloyd Anne Palmer Aaron West	Jonathan Gerhard Brad Geving Alok Kataria Ruben Lanz Atul Mandal Chad Moore Ricardo Niedermeyer Michael Pearson Tommy Tucker (PhD)	Efe Arkayin Yong Chen (PhD) Andre Claudet (PhD) Joe Crawford Brian Davis Kent Dawson (PhD) Jacob Diez Chad Duty (Ph.D.) Sunji Jangha Dan Jean (Ph.D.) Rahul Kulkarni James Nichols Giang Pham Vincent Rodet Shiva Sambu Hongqing Wang
2002 (Expected)		
Scott Bondi Marco Fernandez Benay Sager Yanyan Tang Tosin Tomori Angela Tse Angran Xiao (PhD)		

F. Laboratory Equipment

Major Equipment

SLA Viper Si2
Our latest addition to the lab, the Viper enables us to achieve small features with its dual laser spot capability: 0.003 inch and 0.01 inch laser spot sizes. The Viper also embodies 3D Systems latest machine design approaches to maximize productivity and usefulness.

SLA-3500
With its solid state laser, automatic resin dispensing system, Zephyr recoater, SmartSweep, large build envelope, and .002 - .006 layer resolution, the SLA 3500 lets us do more and do it better. We especially like its large build envelope of 14x14x16 inches for large parts.

Photo courtesy of 3D Systems, Inc.

SLA-250/50
The most productive member of the SLA-250 line is the Series 50. Our first equipment acquisition - from way back in 1995 - our SLA-250 still runs very well and remains a very productive part of our laboratory.

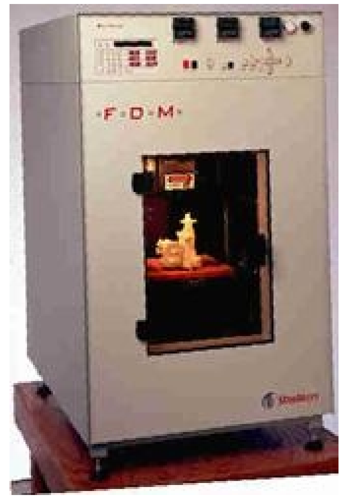
Photo courtesy of 3D Systems, Inc.

CMM PFx-5
MicroVal® PFx® The Personal Flexible Gage For Any Measurement Need. Its large measuring range of 457 mm X 508mm X 406 mm is 50% larger than other systems in its class. Advanced volumetric performance makes the MicroVal PFx one of the most accurate measuring machines in the world. Both manual operation and fully automatic modes are available, with the Direct Computer Control capability.

Photo courtesy of Brown & Sharpe

FDM 1650

This system was developed for the final design and prototyping phase of product development. Using the Fused Deposition Modeling technology, the FDM1650 lets us turn a design concept into a functional prototype. We utilize our FDM 1650 for many student projects in design and CAD courses.



?Photo courtesy of Stratasys

?Photo courtesy of 3D Systems, Inc.

ACTUA 2100

The Actua 2100: Rapid Concept Modeling. Now, with the Actua™ 2100 from 3D systems, a designer can produce a three-dimensional model as easily as a plot or print. Elegantly packaged to offer speed and simplicity, the Actua 2100 ushers in a new age of productivity, the age of rapid concept modeling in the design office.

Surveyor 1200

Laser Design Inc® makes the Surveyor 3D Laser Digitizing System for a wide range of digitizing needs. The Surveyor 1200® system consistently provides linear accuracy of .0005" (.0127mm). Although very compact, the Surveyor 1200® still boasts a full two cubic-foot work envelope along with three axes of computer-controlled automated or manual scanning. The system package includes new DataSculpt® software with scan control, RSP™ 150 or 450 Rapid Profile Sensor.

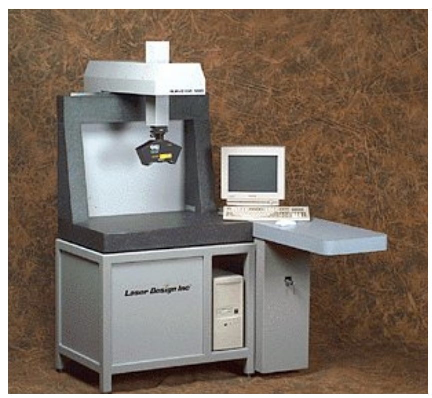


Photo courtesy of Laser Designs, Inc.

Morgan Press

The morgan press allows students easy access to small injection molding experiments and greatly facilitates our rapid tooling research. The simplicity of the machine makes it easy to learn and use. Some of the machine's features include: two-zone, temperature control system for accuracy and wide heat range (0-800 F), three-mode digital controllers for greater accuracy, material melting cylinder with hard chrome bore. We have added a modular mold base to accommodate a wide range of SLA or other rapid tooled inserts.

Benchman VMC 4000 CNC Milling Machine

Our Benchman benchtop CNC machine greatly facilitates a wide range of jobs, from rough cutting to finish machining mold inserts. The Windows-based software and automated tool changer makes learning and usage easy.

G. Membership Application

Through philanthropic support, the Georgia Institute of Technology has established the Rapid Prototyping and Manufacturing Institute (RPMI), with the mission of developing educational programs in the field of rapid product realization and related areas of interest to the member companies.

Contributions to the RPMI are accepted by the Georgia Tech Foundation, Inc., a Section 501(c)(3) charitable corporation which aids the Georgia Institute of Technology in its development as a leading educational institution under applicable provisions of the Internal Revenue Code. Charitable contributions to the Georgia Tech Foundation, Inc. do not entitle the donor to any tangible benefits and the Georgia Institute of Technology does not incur any contractual obligation by virtue of a donation made to Georgia Tech Foundation, Inc.

The undersigned Member has agreed to support the programs of the RPMI through a contribution of $25,000. Memberships may be renewed annually. Payment should be made to:

Georgia Tech Foundation, Inc.
177 North Avenue, N.W.
Atlanta, Georgia 30332-0182
Attention: Gift Receipts

The Member acknowledges and agrees that:

(a) The Member is making this contribution and participating in the RPMI for the purpose of advancing the cause of education at the Georgia Institute of Technology and does not expect to receive tangible benefits in return for its contribution;

(b) Acceptance of Member's contribution does not create any contractual relationship or obligation on the part of the Georgia Institute of Technology, the Georgia Tech Foundation, Inc., the Georgia Tech Research Corporation or, the Board of Regents of the University Systems of Georgia;

(c) Member shall not receive rights to any intellectual property developed by the RPMI as a benefit of Member's contribution, and all rights to intellectual property created by the RPMI will become the property of the Georgia Tech Research Corporation;

(d) While RPMI may, from time to time distribute brochures or other informational material to members and others, none of these materials are intended to and none of them will create binding obligations on the Georgia Institute of Technology, the Georgia Tech Foundation, Inc., the Georgia Tech Research Corporation, or the Board of Regents of the University System of Georgia.

This day of ________________ ____. 2001.

Member's Mailing Address: ____
(Name of Member Company)

______________________________ Signature: ______________________________

______________________________ Printed Name: ______________________________

Title:

Direct questions to: David Rosen, Director of the RPMI

H. RPMI Member Emeritus

Purpose
To keep the RPMI strong by having the option to include key non-member, individual contributors in our activities.

Definition
A member emeritus would be similar to an invited guest who would participate in the RPMI. Such members would pay no cash dues, but they would be expected to play an active role in the RPMI. Guests would enjoy a similar rank as any other industry (non-Georgia Tech) member. They would be encouraged to come to all meetings, propose and monitor projects and would be eligible to serve on a committee. However, they would not be eligible to serve as or vote for a committee chair.

Eligibility and Selection
Any member or Georgia Tech person could nominate someone for the honor. Members would help Georgia Tech make the selection in the same format as for committee chairs.

Term
An individual's member emeritus status would be reviewed annually and may or may not be renewed for another year. Assuming his/her status is renewed each year, there is no limit to the number of consecutive terms an individual can serve as Member Emeritus.

I. Affiliated Faculty Members from Outside of Georgia Tech

Purpose

Faculty from outside Georgia Tech may complement the research capabilities, facilities, and equipment of GT faculty in areas of significant interest to the RPMI. Also, methods of operating consortia and other operational experience may be of interest to the RPMI. As such, having affiliated faculty broadens the technological, operational, and experiential base of the RPMI. From another perspective, having affiliated faculty helps build a broader RP&M community and informs them of our accomplishments. The affiliated faculty can leverage the resources and experience of the RPMI to achieve their own objectives.

Two classes of affiliation are proposed: Observers and Participants.

Observers

Goals of Affiliation: Exchange of technical results and operational practices. Community building. Evaluation of the merits of results or practices.

Mechanisms of Affiliation: Arrangement is to observe the activities of the RPMI through exchange of project reports, meeting minutes, periodic on-site and reciprocal meetings, etc. Attendance at open RPMI meetings is encouraged. Attendance at closed RPMI meetings will not generally be allowed.

Participants

Goals of Affiliation: Investment in the RPMI, with significant, tangible benefits to be derived by all parties. To contribute directly to the technical aspects of the RPMI Mission. To leverage the expertise of the RPMI to achieve research or development objectives.

Mechanisms of Affiliation: Active involvement in the research activities of the RPMI through the supervision of RPMI funded projects, involvement in RPMI projects, regular attendance at open and/or closed RPMI meetings, etc.

Supervision of RPMI funded projects elevates a Participant to the same level of stature as a RPMI faculty member at GT. This is possible and desirable. The same expectations and opportunities apply.

Involvement in RPMI projects could take the form of part or tool fabrication, part or tool design, software development, or other experiments or activities.

Funding: For some projects, it will be necessary to transfer funds from GT to the affiliated faculty member's university, or vice versa. This will be arranged on an as-needed basis.

How to Get Involved:

Contact the Director of the RPMI to outline your objectives and discuss the possibilities. We will develop a proposed Affiliation Agreement that will identify your class of affiliation and outline the mechanisms of involvement between you and the RPMI.

Intellectual Property:

Unless other arrangements are made, no intellectual property agreements will be imposed, by either side. This requires a level of prudence and trust to exist between the parties.