RPMI

RAPID PROTOTYPING
AND MANUFACTURING
INSTITUTE

PUSHING THE ENVELOPE OF RP&M

A Report on the Fifth Year of the RPMI

Georgia Institute of Technology

December 2000

MANUFACTURING
RESEARCH
CENTER

Rapid Prototyping and Manufacturing Institute

Pushing the Envelope of RP&M

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Pushing the Envelope of RP&M

A Report on the Fifth Year of the RPMI

A Year of Progress and Change

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 dollar and time 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 Rapid Prototyping & Manufacturing's (RP&M) 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 in light of these changes.

What We Do

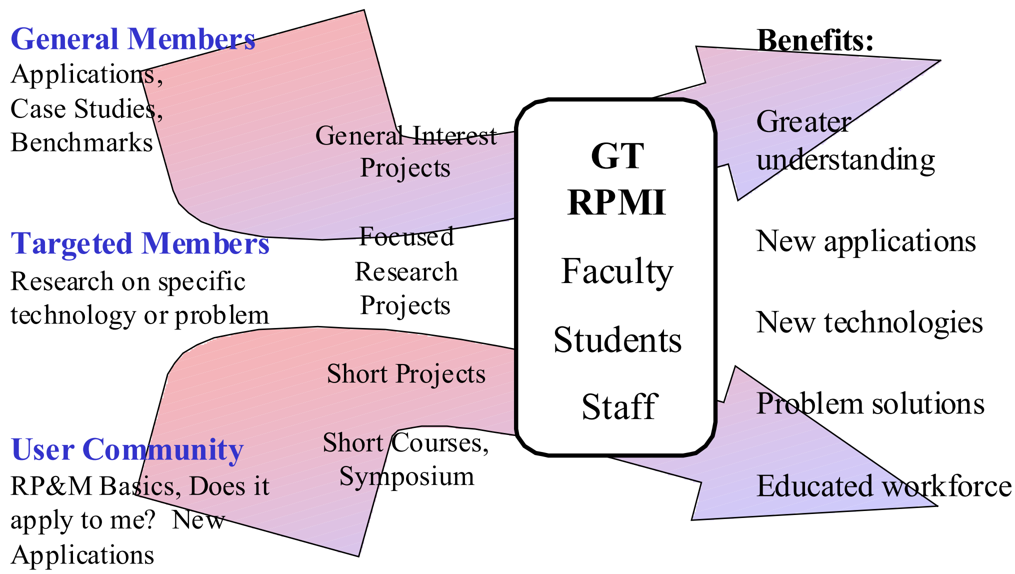
Our ***vision*** of RP&M's future includes a world where layer-based, additive fabrication technologies (e.g., rapid prototyping) are recognized as production manufacturing technologies. We want to leverage the unique capabilities of these additive fabrication technologies to produce unique geometries 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:

- Rapid Tooling
- Rapid Inspection and Computer-Aided Verification
- RP&M within Product Realization
- Design for Additive Fabrication
- Other Projects (like Machining of Non-Traditional Materials for Rapid Tooling)
- Other RPMI-Related Activities (like Rapid Manufacture of Composite Structures)

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 quite 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

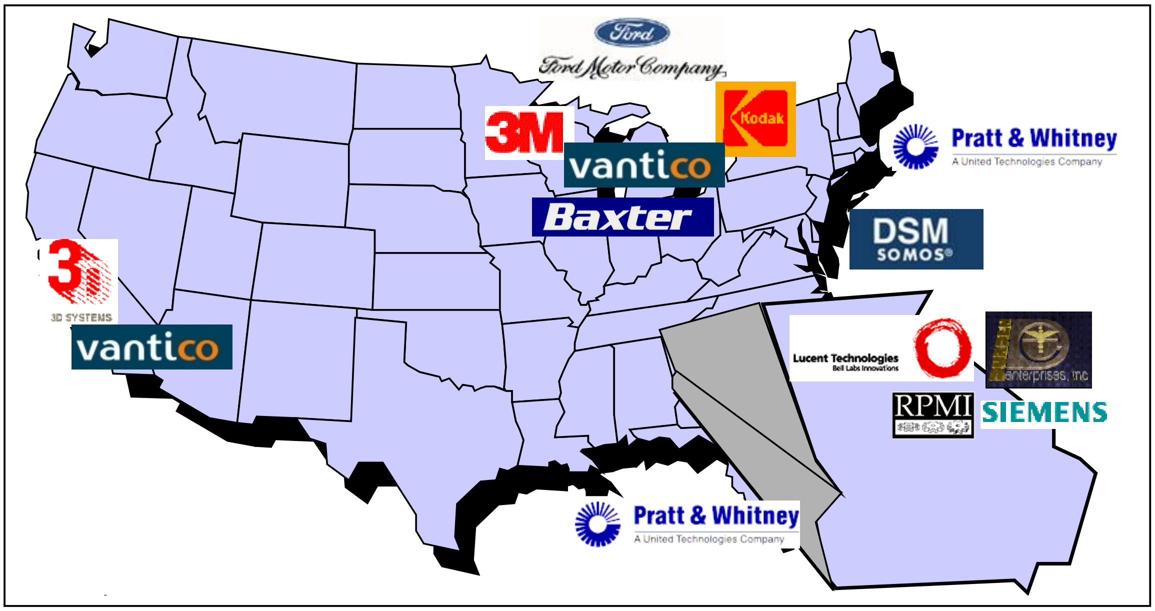
Our faculty provides the bulk of the technical know-how needed to carry out the projects. They recruit and advise the students in their individual activities. Faculty collaborate with industry representatives for a better understanding of the important issues facing the use and improvement of RP&M technologies. 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. Forty-two RPMI alumni are now working in industry.

Our twelve 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 continues today through the Rapid Tooling Testbed initiative, a $1.35M, three-year project funded from the NSF Distributed Design and Fabrication Initiative, 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. The RPMI is the focal point for this work, which is drawing together faculty from three disciplines.

In a third big win for Georgia Tech, NSF is funding a project to support important work in Laser Chemical Vapor Deposition – an additive fabrication process for building small metal and ceramic devices. Although this work was underway at Georgia Tech for several years, this NSF funding provides longer-term stability to the RPMI to better leverage our efforts. Industry interest in this technology is strong and growing.

(More information on both of these projects is included in a later section of this report.)

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.

How We are Changing

Important changes are occurring in the RPMI and in the RP&M industry. This year, change began in the summer when Reggie Ponder and Giorgos Hatzilias announced that they were leaving Georgia Tech to pursue other career interests. Additionally, Jo Funk retired, who was our Administrative Assistant from day 1. Change happens, and for Reggie, Giorgos and Jo, their changes were very positive for their careers (or retirement!). Reggie was our Director of Operations; he left for a managerial position in the State of Georgia government. Giorgos was our Laboratory Manager and left for an Applications Engineer position at Paraform (which you will read about several more times in this report!).

Personnel changes are a fact of life. Industry has learned to readily adapt to these changes – and so will we. We are actively recruiting a replacement for Reggie's position and should have someone in this position soon. However, their leaving prompted us to rethink the RPMI strategy: what should we be doing and how should we be doing it?

In the broader RP&M industry, many more changes are occurring. Most of the major service bureaus in the world went out of business in the past four years. Some RP vendors have gone out of business or are close to doing so. Industry wants better, more production-representative prototypes… No, they REALLY want production parts off of RP machines. The pressure is on to adapt and improve in "internet time."

And so, the RPMI is working on a new strategic plan to better position us for the future. You will get some hints into this plan throughout this report. But turn to the Outlook for 2001 section for the complete story.

Accomplishing Specific Goals

The RPMI has continued to make rapid progress in many areas since our last report in January 2000. In that report, we listed 26 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 2000 goals are in italics and denoted by a "☐" (or "☑" for goals met); results are denoted by an arrow, "⇨.")

Education

- ☐ *Develop and initiate distance learning course featuring RP.*
- ☑ *Involve Aerospace Engineering and Industrial Design schools in the RP & M mainstream through collaborative industry research in their respective colleges.*
- ☐ *Pursue outreach initiatives that tighten RPMI relationships with the Advanced Technology Development Center's education and economic development planning.*
- ☐ *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.*
- ☐ *Achieve project links with Environmentally Conscience Design for Manufacture focused on achieving the manufacturing goals of the Georgia Research Alliance Infrastructure.*

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. Test it internally.*
- ☑ *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.*
- ☑ *Identify promising applications that leverage the unique capability of RP technologies, including the RPMI's approach to building around inserts. Identify design principles and primitives for devices to be built on emerging RP machines.*
- ☑ *Demonstrate a working Generalized ("5-axis") SLA prototype machine that is capable of building around inserts.*
- ☑ *Publish five papers in refereed academic journals.*

Infrastructure

- ☑ *Maximize Enterprise value to all members by ensuring projects are structured with business affects in mind.*
- ☐ *Acquire resources to construct a Generalized ("5-axis") SLA experimental testbed.*
- ☑ *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.*
- ☐ *Structure our current "body of knowledge" in an easy to distribute "how to" format for dissemination to industry.*
- ☐ *Fill RPMI membership to 15 companies and retain twelve current member companies.*
- ☐ *Simplify our web site's project status by making information more readily available.*

Outreach

- ☑ *Gain international publicity through participation at major European and Asian conferences for leading edge work.*
- ☐ *Pursue and win 3DSNASUG Excellence award.*
- ☑ *Broaden faculty involvement in metallurgical and heat transfer research.*
- ☑ *Introduce 20 Georgia-based industries to the RPMI through site visits and meeting interaction.*
- ☐ *Sell every seat in the newly established Advanced RP & M 2000: Symposium & Expo.*
- ☐ *Teach three RP & M seminars and short courses for industry.*
- ☑ *Deliver eight RP presentations at five conferences.*

Education

❐ *Develop and initiate distance learning course featuring RP.*
⇨ The foundation for a RP&M short course was developed over the past two years. However, the course has yet to be delivered to its intended audience. This year we will attempt to tailor our course to meet the needs of the MEP program.

☑ *Involve Aerospace Engineering and Industrial Design schools in the RP & M mainstream through collaborative industry research in their respective colleges.*
⇨ Joint projects with Aerospace Engineering and Industrial Design have been very successful. With AE, we worked with them on a Mars Rotorcraft project, designing helicopters for use on Mars.
⇨ We continued our interactions and assisted on a design project for a premium kitchen appliance manufacturer. We look forward to exciting new developments with all of our on-campus partner organizations.

❐ *Pursue outreach initiatives that tighten RPMI relationships with the Advanced Technology Development Center's education and economic development planning.*
⇨ We had big plans for interacting with ATDC. Unfortunately, with the changes in RPMI staff, we could not build our relationships with them. In the coming year, we will re-double our efforts to collaborate with ATDC.

❐ *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 was another victim of the RPMI staffing changes. Again, we have most of the ingredients for an outstanding course, but have not had the opportunity to pull together all of the elements.

❐ *Achieve project links with the Environmentally Conscience Design and Manufacturing center focused on achieving the manufacturing goals of the Georgia Research Alliance Infrastructure.*
⇨ Working with the ECDM group has several intriguing possibilities, which we will continue to pursue. Until now, we have just not found the right opportunity.

Research

☑ *Develop injection molding process design guidelines that maximize SLA rapid-tool life.*
⇨ We have been very busy investigating AIM tools – and have the results to show for it. 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. See our RPMI Projects section for more information!

☑ *Demonstrate a working Rapid Tooling TestBed with which designers can submit part designs and get them fabricated by RP or through rapid tooling. Test it internally.*
⇨ In April, we demonstrated version 2 of the RTTB distributed computing environment. We demonstrated gear transmission and light switch components being designed, process planned, and fabricated using SLA. In August, we extended the gear transmission demonstration to include rapid tooling and injection molding. Work continues on an improved RTTB environment with additional capabilities. We hope to

demonstrate the RTTB to RPMI members and let them have an opportunity to see what we can deliver later in 2001.

- ☑ *Disseminate widely the results of an industry survey on RP, RT, and RM usage.*
  - ⇨ At present, the finishing touches are being completed on the industry survey. At the an invited audience. Additional presentations have been made, including at RPMI meetings.

- ☑ *Benchmark three-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! Tom Kurfess' start-up company, Applied Metrology, Inc., sold its inspection software and technology to Paraform, where Tommy Tucker, one of Tom's Ph.D. students now works. Two RPMI member companies are beta-testers for this software. A current RPMI project benchmarking metrology software for RP and RT applications has demonstrated the advantages of this Georgia Tech technology. We look for more great things from this successful research group.

- ☑ *Identify promising applications that leverage the unique capability of RP technologies, including the RPMI's approach to building around inserts. Identify design principles and primitives for devices to be built on emerging RP machines.*
  - ⇨ This is cool stuff! We have demonstrated far-reaching application areas in building around inserts. Our work culminated in the fabrication of a working SLA-250 model that was built in our SLA-250. It has 11 embedded components and 4 kinematic joints. Our work in Design for Additive Fabrication has also yielded tremendous results, with optimized robot arms, large light-weight automotive and aerospace models, and shape-memory-alloy-wire driven robots and hands!

- ☑ *Demonstrate a working Generalized ("5-axis") SLA prototype machine that is capable of building around inserts.*
  - ⇨ Hand-in-hand with our building around inserts work is the Generalized SLA research that we have pursued over the past two years. We demonstrated a prototype generalized SLA machine at the Gwaltney Symposium in February 2000, then improved it for subsequent demonstrations at RPMI meetings and other activities. As a result, we showed that it is possible to add additional capabilities and freedoms to SLA, and other RP, machines. On to Rapid Manufacturing!
- ☑ *Publish five papers in refereed academic journals.*
  - ⇨ As an academic activity, scholarly publications in leading journals are critically important. In 2000, we blew away our goal by authoring 12 journal papers, of which 5 have been published, with the remainder submitted, pending acceptance.

Infrastructure

- ☑ *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.

RPMI Members Deliberating on New Projects

❒ *Acquire resources to construct a Generalized ("5-axis") SLA experimental testbed.*
- ⇨ Despite repeated attempts, we have not yet acquired resources to construct a SLA testbed, although we made important progress. 3D Systems aided our quest by donating a SLA machine frame and laser. However, our proposals to government agencies have as yet not yielded a big win. We will keep trying!

☑ *Evaluate the RPMI's directions in light of the changing nature of the RP industry. Fine-tune our strategic plan.*
- ⇨ Given the changes occurring in the RPM industry and within the RPMI, it was critically important for us to evaluate our directions and role! We have done much more than just fine-tune our strategic plan. As you will see in the Outlook for 2001 section, we have a new plan and have begun to implement it.

☑ *Begin a formal collaboration with at least one other university.*
- ⇨ We have begun collaborations with both the University of Louisville and DeMontfort University in the UK. Both of these collaborations have so far been limited to exchanging parts or tools, but we will pursue increased levels of activity in order to leverage our efforts and resources.

❒ *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.

❒ *Fill membership to 15 companies and retain twelve current member companies.*
- ⇨ We did not meet our ambitious goal of filling our membership to the 15-company limit. We began the year with a strong base of 12 active companies. Despite strong recruiting efforts, we were not successful in adding any new members. Additionally, we lost 3 member companies due to several reasons. Some of our best prospects, along with one member company, expressed tremendous interest in joining (or continuing), but were prohibited due to management cost cutting and restructuring initiatives.
- ⇨ We plan to hold an Open House in February 2001 to improve our recruiting results, along with other initiatives.

Outreach

☑ *Gain international publicity through participation at major European and Asian conferences for leading edge work.*
- ⇨ We have had a presence at three international conferences this year. One student presented a paper at a European conference and Shreyes Melkote presented at two Asian conferences, one in Singapore and one in India.

❒ *Pursue and win 3DSNASUG Excellence award.*
- ⇨ We had a sure-fire entry this year: our SLA model of the SLA-250. Unfortunately, the NASUG judges were not receptive enough to appreciate the superiority of our entry. We will pursue the Excellence award with even better entries in the future!

- ☑ *Broaden faculty involvement in metallurgical and heat transfer research*
  - ⇨ In the metals and ceramics area, Jack Lackey has increased his participation in the RPMI. See the write-up on LCVD research in the RPMI Projects section. In the fluids and heat transfer area, John Muzzy (Chemical Engineering) has helped, and Ari Glezer and Minami Yoda have run projects in the RPMI.

- ☑ *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 ViaSat, C.R. Bard, Yamaha, Motorola, Viking, Ciba Vision, Applied Parametrics, Synaps, Paraform, and Brown & Sharpe.

- ❒ *Sell every seat in the newly established Advanced RP & M 2000: Symposium & Expo.*
  - ⇨ Although we did not reach this ambitious goal, the Symposium was an outstanding success! About 75 paid attendees, dozens of GT faculty and students, and about 2 dozen exhibitors participated in the Symposium. Reviews from attendees were outstanding. Kudos for all who helped deliver this event!

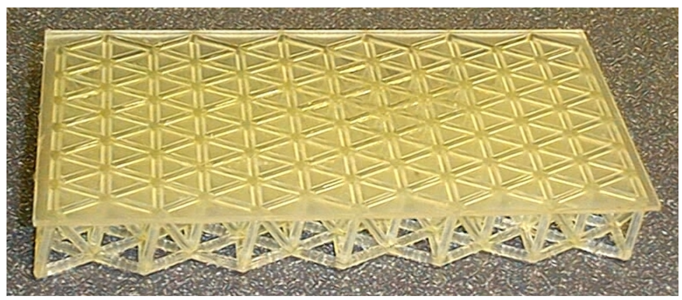
- ❒ *Teach three RP & M seminars and short courses for industry.*
  - ⇨ With the changes in RPMI staffing, no short courses were held. This is an area that will receive much more attention in the coming year!

- ☑ *Deliver eight presentations at five RP conferences.*
  - ⇨ This has been another banner year for presentations at conferences, universities, and industry. Fourteen conference papers were presented at eight different conferences, including the Japan-US Flexible Automation Symposium, ASME Design Technical Conferences, Die & Mold Technology Conference (Singapore), the European Conference on Rapid Prototyping and Manufacturing, the All-India Manufacturing Technology, Design and Research Conference, the NSF Design and Manufacturing Grantees Conference, and Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises at NIST. All of these conferences have significant RP&M content and we are making an impact!

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 fifth 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



As we face more and more industry challenges, the RPMI is no longer just solving problems, we are now well poised as **drivers**, helping to shape the entire industry's future! The RPMI helps support many diverse industry projects and uses advanced manufacturing and prototyping techniques to maintain a grip on cutting edge technology. As we increase awareness and promote the RP&M technologies, we find that it is becoming so well accepted that new applications are often designed based on the new capabilities. Following are some examples of RPMI supported projects that have been making significant achievements.

During our RPMI meeting at Ford in June, we saw a new type of RP application: the craftsmanship model. Ford builds sections of automobiles using several pieces built in a SLA machine; the pieces are assembled by hand over an "egg-crate" structure that was machined to shape. The critical aspect of a craftsmanship model is to faithfully reflect the mathematical surface models that the designers are developing in CAD. Typically, these pieces are built in a SLA-7000 using 0.001" layers to be as accurate as possible.

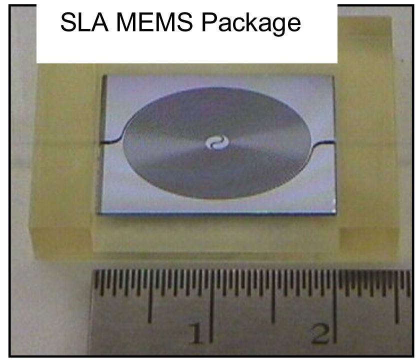
One issue with these craftsmanship models is that they age: the thin skins sag over time, generally within a month or two. But, the models are needed for up to six months. Hence, Ford is very interested in finding methods to improve dimensional stability over time. As part of the Design for Additive Fabrication project, RPMI researchers have been exploring the applications of truss structures that are built in SLA. Why not try to stiffen these craftsmanship models with a backing of truss structure? During the summer, RPMI researchers and Ford personnel teamed up to compare the conventional egg-crate stiffeners with truss structures. Results demonstrated the superiority of the truss structures. As a result, the RPMI is exploring methods for making the truss structure capability easily available for a wider variety of applications.

In late 1999 and early 2000, a very exciting development was taking place: Tom Kurfess' company Applied Metrology sold its metrology software technology to a small company called Paraform. Tom's student Tommy Tucker left Georgia Tech to lead the development of Paraform's new metrology product, transferring key RPMI and Georgia Tech technology to industry. Compounding the leverage, two of the RPMI's industry members, Baxter and Kodak, became beta-testers of Paraform's metrology product. Research on improved metrology methods continues in the RPMI, aided by the tremendous amount of activity generated by these developments. Furthermore, an important metrology benchmarking activity is underway within the RPMI. Advantages and disadvantages of metrology software on a variety of problems and geometries are being understood and documented. 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. One of the new MEMS faculty in Mechanical Engineering is Peter Hesketh. He approached David Rosen earlier in the year to explore applications of RP to MEMS. As a result, we have identified several applications that enable new capabilities and research directions. Also, we have teamed up with Dr. James Gole in the School of Physics. One of the applications that we are pursuing is MEMS packages for chemical sensors. That is, a MEMS chip senses the presence of a certain chemical in a gas or fluid. The package around this chip must provide suitable interfaces to the chip, as well as the machine into which the chip is to be inserted. By using SLA, we have as much flexibility in these interfaces as needed. In fact, the interfaces to the machine could be standardized, while customizing the interfaces to suit the particular chip design.



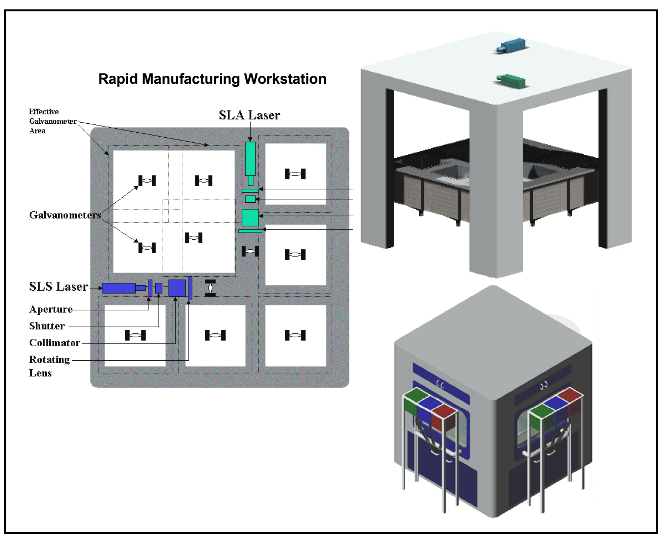
This research into MEMS packages has raised the need for improved small features in SLA. Features sizes on the order of 10-20 microns is needed, but no commercial SLA machines are available in this size range. This feeds one of the RPMI's new research directions very well: that of micro-SLA. Read more about this in the Outlook for 2001 section.

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. In December, we built several models of teeth and jaws on our RP equipment to aid visualization and to evaluate model suitability as patterns.

Our collaboration with the Industrial Design group at Georgia Tech continued with several activities. We worked with Jim Budd in ID on a design project on an improved kitchen appliance for a manufacturer of premium appliances. We helped evaluate geometries and production manufacturing methods, as well as the potential for RP to address product development questions. In an exciting development, our collaboration in a senior studio course in Fall 1999 and Spring 2000 was written up in the College of Architecture newsletter, a prestigious publication. Results from this course are also posted on our web site.

Deploying Solutions into Education

In Fall semester, David Rosen taught a new graduate-level course, ME 7227 – Rapid Prototyping in Engineering, to a class of 15 students. Key content for the course came from the many successful research and development projects within the RPMI over the years. One of the month-long modules in the course is on Rapid Manufacturing. Students worked in five groups, each of which is pursuing a different aspect of RM. For example, one group is focusing on the development of a home RP system, while another is developing concepts for a reconfigurable RM workstation that has SLA, SLS, and FDM capabilities. The final month-



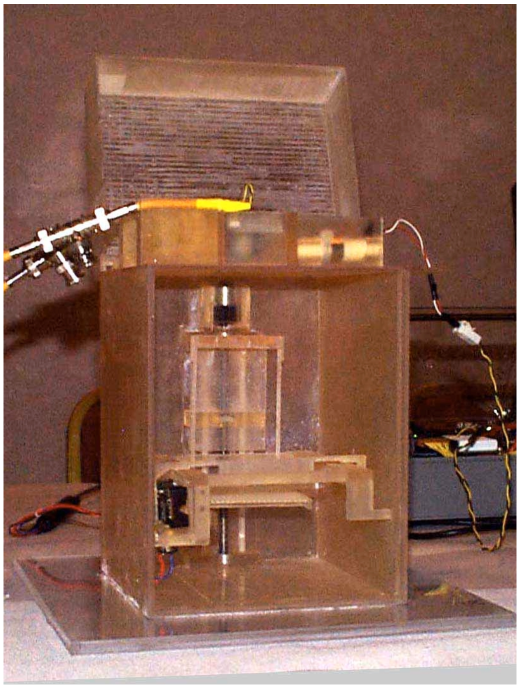
long course module covers the research frontier and enables each student to focus on a key aspect of their own research. This enables us to leverage past research achievements across the entire class and into each student's thesis research.

Another notable achievement is our Advanced RP&M 2000: Symposium and Expo that was held in February. Over 100 company and academic participants attended, along with 22 exhibitors. Speakers and attendees came from all over the country with a wide variety of interests. Sessions were held on "Realizing Rapid Manufacturing," "Unique Applications Using Layered Manufacturing Technologies," and "Visualization: Physical and Virtual." Two Georgia Tech speakers contributed to the Symposium, Jim Budd and Dave Rosen. This is a very important technology transfer vehicle for the RPMI, and we received rave reviews! Attendees really appreciated the quality of program and our CD ROM proceedings.

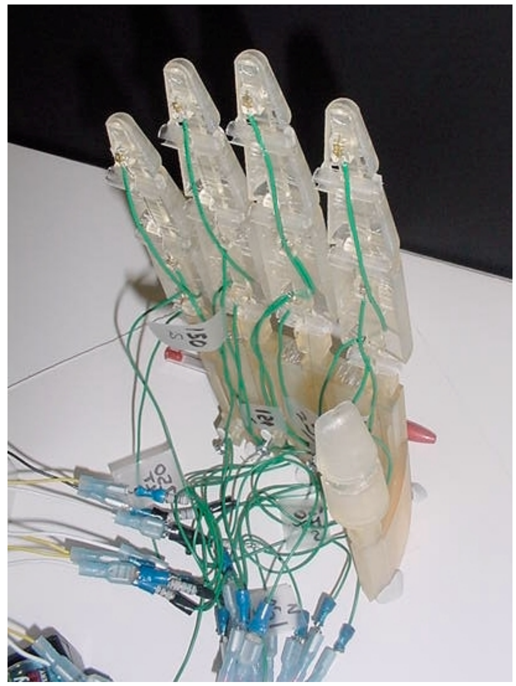
Advanced RP&M 2000 Attendees Enjoy an Intermission with an Exhibitor

RPMI Projects

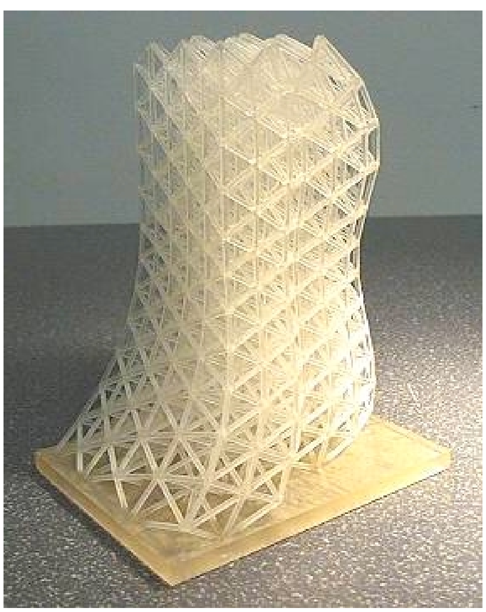
Rapid prototyping and manufacturing is an incredibly varied and exciting area. Opportunities abound. During the past year, we have continued our focus on four main areas: Rapid Tooling, Rapid Inspection and Computer-Aided Verification (CAV), RP&M within Product Realization, and Alternative Applications of SLA. Additionally, new projects in MEMS applications and machining have begun.



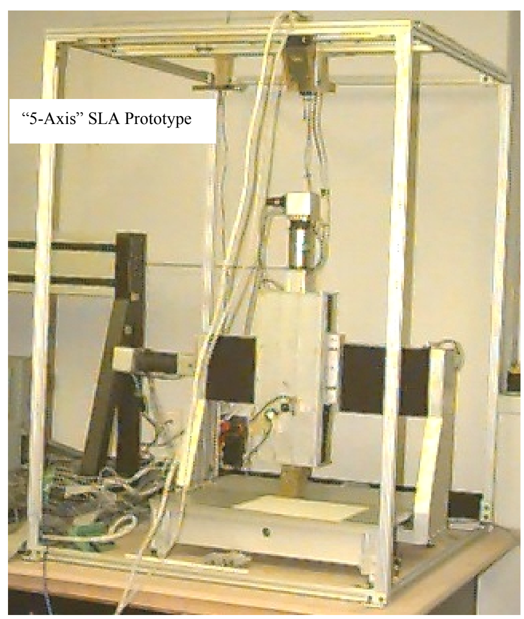
Working Model of an SLA



Hand Model with 13 Compliant Joints



Free Form Truss Structure



5-Axis SLA Prototype

Project Overview Table

Current RPMI & Proposed Projects	Students	Faculty	Industry/Govt
Tooling Life			
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, D. Feindel, L. Whitaker, G. Beldue, J. Malluck, C. Hull
Molding in Machined Tooling Board	Efe Arkayin	Steven Liang	M. Kotnis, Club-Car
Alternative Applications			
Building Around Inserts	Alok Kataria	David Rosen	C. Hull, M. Bellotti, L. Whitacker
5-Axis SLA	Chad Moore, Brad Geving	Tom Kurfess, Imme Ebert-Uphoff	
Design for Additive Fabrication	Jacob Diez, Vincent Wang	David Rosen, I. Ebert-Uphoff	L. Whitaker, M. Bellotti
Micro-SLA	Benay Sager	David Rosen	J Malluck, D Kalisz
SL Cure Modeling	Yanyan Tang	John Muzzy	D Kalisz
Aging, Fatigue, and Env Characteristics	Xavier Ottemer	Jon Colton	S Jayanthi
Heat Transfer Engineering	Alan P. Martin	J Muzzy, D Rosen	Pratt & Whitney
Rapid Inspection and CAV			
Point-To-Surface Assignment During Registration	Andre Claudet	Tom Kurfess	G. Beldue, C. Hull, B. Delisle
Metrology and Reverse Engineering Capabilities	James Nichols	Tom Kurfess	G. Beldue
Characterization & Calibration of SLA Products and Processes	Brian Davis	Janet Allen	C. Hull, S. Jayanthi
RPM Within Product Realization			Open
Best Practices Survey	Atul Mandal	Nagesh Murthy	D. Daruwala, 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 Metal Powder Injection Molding Distributed Computing Environment	 Marco Fernandez Yong Chen, Shiva Prasad Sunji Jangha Joe Crawford Andre Claudet UofL student J. Gerhard, A. Xiao, A. Gavrilovska, Yuan Chen	 Janet Allen David Rosen David Rosen Jon Colton Tom Kurfess Tom Starr Farrokh Mistree, Karsten Schwan	NSF
Other RPMI-Related Activities:			
Machining of Tooling Boards	Ruben Lanz, Tosin Tomori	Shreyes Melkote	M. Kotnis
Laser Chemical Vapor Deposition	C. Duty, D. Jean, B. Fuhrman, S Bondi, T. Elkhatib	Jack Lackey, David Rosen	GT & NSF
MEMS Applications of SLA	Laam Angela Tse	Peter Hesketh	GT

Rapid Tooling

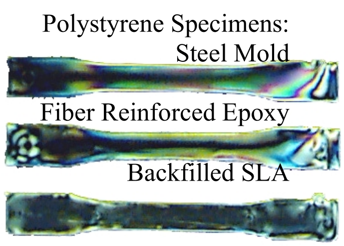
Rapid prototyping technologies are increasingly being used to fabricate patterns and tools for making parts in end-use materials. Rapid tooling was the first focus area for the RPMI and continues to generate the most interest in industry. By utilizing both high-pressure/high-temperature polymer injection molding and low-pressure/low-temp powder injection molding, we can fabricate parts in a variety of polymers, metals, and ceramics! Our projects this year span fundamental studies of molding and material behavior to ejection mechanism design for rapid tools.

Effect of RP Tooling on Final Part Properties

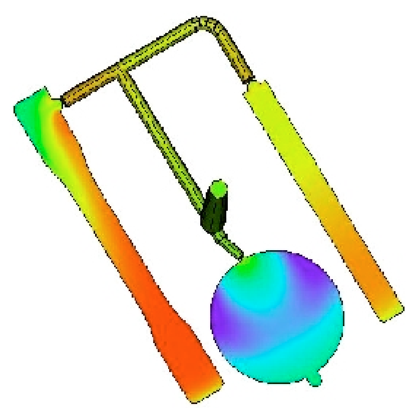
The development of a plastic part frequently involves several prototype iterations. Production of these prototypes with conventional metal tooling often results in high costs and long lead-times. A group of materials and processes known as rapid tooling can produce a limited number of prototypes faster 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 back-filled 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, is leading this investigation and is 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.



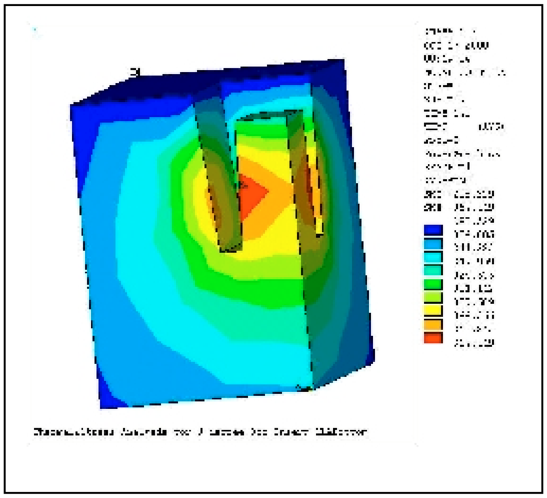
In order to understand how different mold materials and construction techniques affected the heat transfer characteristics of the part and mold, a one-dimensional heat transfer model for composite injection molds was developed to predict the heating and cooling rates of the injected polymer and mold 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.



Final work will attempt to predict the mechanical properties of certain injection-molded materials as a function of the mold material and molding conditions. The thermal properties of the part and mold during the filling and cooling stages of injection molding will be quantified with a C-Mold simulation of the test specimen mold. Thermo-mechanical stresses also will be predicted and related to the final part properties.

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 3 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, and pull-out failures due to part ejection.



Jon Colton is leading this project. Three Masters students are currently working on various aspects of the project. Joe Crawford is focusing on flow failures and quantifying their causes. Giang Pham and Vincent Rodet are concentrating on different aspects of fatigue failures. Giang is modeling ejection forces and relating them to tool failures, while Vincent is focusing on understanding the actual fatigue mechanisms within SLA resin. In particular, Giang is getting good correlation among analytical, numerical, and experimental results in quantifying ejection forces. Vincent is working on a visco-elastic model of material behavior and applying aging phenomena to these models to be able to predict mold life – results look very good. This work is critically important since, taken together, it explains what others have been experimentally observing, and brings much needed rigor to an area that is typically experience based. Furthermore, their work served as an important basis for other rapid tooling related work that is reported later in this Report.

Continued research will result in better predictive models for SLA tooling and good validation of these models. As part of their work, they are developing a standard test procedure that can be applied to new mold materials, tool designs, and part materials. All three students should graduate in Spring 2001.

Rapid Inspection and Computer Aided Verification

Many have made claims about the merits of new RP and RT related developments, but few can back up those claims with comprehensive dimensional data. 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.

Analysis of Three Dimensional Measurement Data and Multi-Surface CAD Models

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 is the graduate student working on this project, being 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.

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 is a second-year graduate student, supervised by Janet Allen. This project continues the research of Charity Lynn-Charney and Joel McClurkin, who conducted extensive accuracy studies of our SLA-250. Brian has the task of verifying past work and, more importantly, of developing a general experimental methodology for SLA accuracy assessment. Research results will provide input to many different projects, including our rapid tooling work, our other metrology work, and the Rapid Tooling Testbed project.

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.

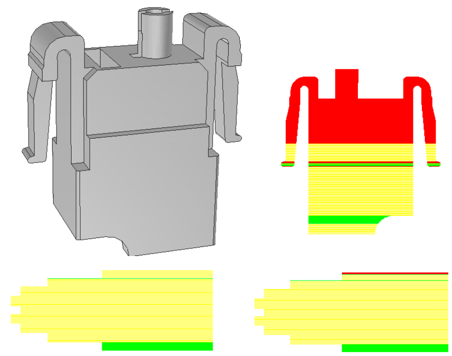
Under the guidance of Nagesh Murthy, we are identifying best practices in the development and implementation of RP technology. Bill Griffin and Atul Mandal were the graduate students researching different RP and RT methods through a literature search and site visits to RPMI member companies. But the 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. Currently, Nagesh is preparing a final report on RP/RT technology usage, highlighted with case studies and backed up with extensive data. We hope that with SME's cooperation, this report will be widely disseminated.

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 three-year NSF Distributed Design and Fabrication Initiative grant to develop the RTTB. We have completed our three years of funded work, and are continuing development to complete the work.

Product and Mold Design Methods

Janet Allen, Farrokh Mistree, and David Rosen are leading 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.



Different SLA process plans for a Lucent fiber-optic housing

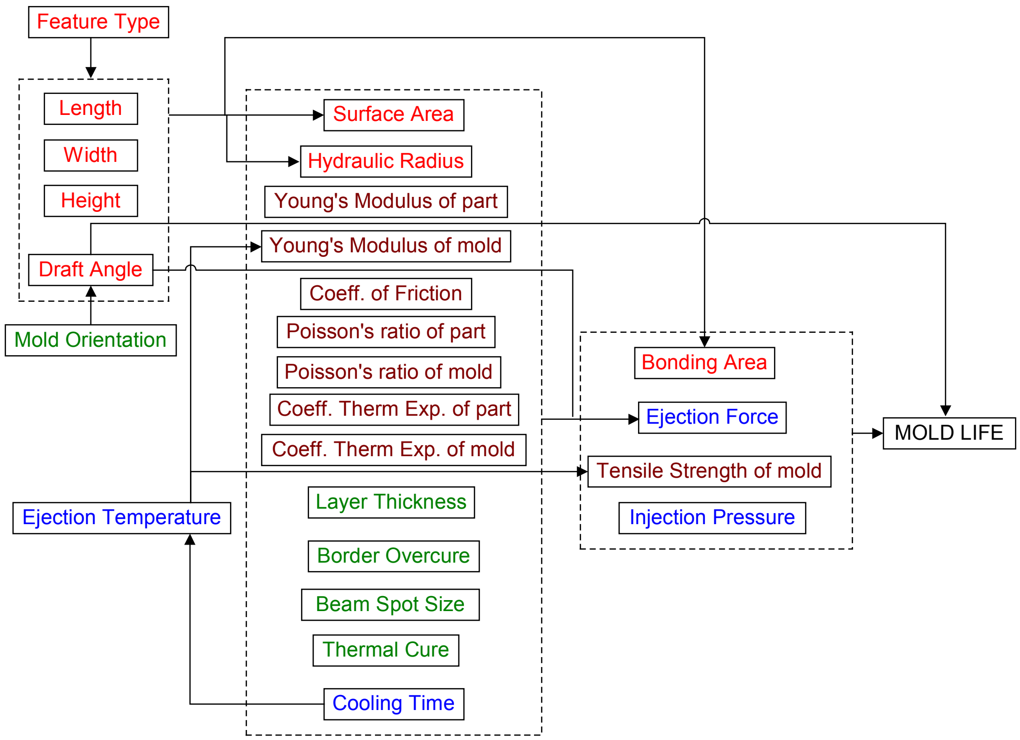
A tremendous amount has been accomplished thus far. Present work is focused on three primary decisions, resource selection, mold design, and fabrication process design, and on information modeling to support those decisions. Our new selection decision formulation has been implemented in a Visual Basic tool, integrated with a database of rapid prototyping and tooling processes and material information. A new model of designer preferences is being developed based in utility and decision theory. Marco Fernandez, a second year graduate student, is continuing to improve this tool, under the supervision of Janet Allen.

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 is being developed to enable tailoring SLA mold designs. Yong Chen and Shiva Sambu are the graduate students investigating mold design. Additionally, Sunji Jangha is developing 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 is completing his mold design research. Shiva has finished geometric tailoring decision templates and is implementing them in software. These templates 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. The templates will be integrated with Yong's mold design software for geometric tailoring of parts and molds, simultaneously.

Tool Design Rules

Jon Colton and David Rosen are leading this research thrust. The goal is 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. This work, of course, builds on the injection molding research that we have performed over the past five years. As mentioned above, the ability to do "geometric tailoring" requires good knowledge of all aspects of molding. The design rules that we are developing enable geometric tailoring and provide feedback to designers about the moldability of their designs.

As mentioned above, Shiva Sambu is synthesizing the research work of the rapid tooling students. He has identified and classified the factors that affect mold life. Furthermore, he has developed quantitative models for many of these factors and integrated these together, enabling the quantitative prediction of mold life. Models and results are limited to the experimentation that we have performed, but it represents a very good step toward facilitating rapid tooling. Shown below is our "map" of rapid tooling factors and their relationships to tooling life. We now have these models and design rules implemented in prototype software.

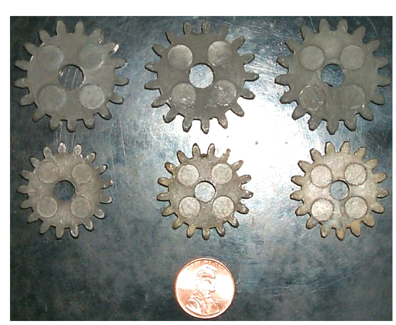


RP Error Characterization

Tom Kurfess is leading 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. However, typically tens of thousands or even thousands of points are sufficient to characterize a part's geometry. We have investigated methods of data point reduction, that is, how to take a point set of one million points and reduce it to ten thousand points. Currently, the research emphasizes point-to-surface assignment methods that drastically reduce the complexity of the least-squares best-fit registration methods.

Determining whether an SLA machine can meet a set of tolerances on a part is often difficult. To achieve a set of tolerances as closely as possible, relationships between part geometry, tolerances, and process variables must be understood quantitatively. We have developed an empirical model for SLA accuracy, as specified by geometric tolerances. A set of experiments was performed to identify the SLA process variables that most influence part accuracy, then to fit quantitative models to data measured from parts. This experimental process continues, with repeatability the focus of our efforts.

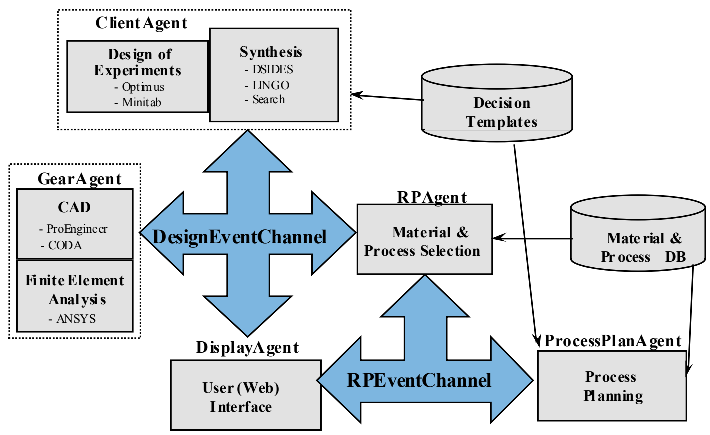
Metal Powder Injection Molding



Tom Starr leads 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. Preliminary 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 recently finished his Masters degree at the University of Louisville comparing the molding and removal of stainless steel parts in metal and SLA molds.

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 have developed a new distributed computing framework, called PRE-RMI, that provides a platform and operating system independent communications framework for enterprise integration and product realization. PRE-RMI was coded in Java and made use of the JAVA-RMI messaging system. We demonstrate that PRE-RMI is adaptable to different design processes, is modular and extensible, and is robust to network and computing failures. Our examples for testing PRE-RMI include gear trains and light-switch components. Using these examples, we demonstrated the successful integration of CAD, CAE, design, and manufacturing software tools and resources in a flexible distributed computing environment. Ongoing work focuses on the integration of additional software tools into the environment, and improving the interoperability of the tools using XML to transfer information around the system.

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. Angran is a senior Ph.D. student leading the development of an engineering design environment on top of PRE-RMI. Angran is supervised by Farrokh Mistree, and coordinates the work of Hae-Jin Choi and Rahul Kulkarni, two Masters students.

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 MOSS, the Mirror Object Steering System. More recently, they have demonstrated JMOSS, a Java implementation of MOSS. We have implemented the 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. Yuan Chen is the Ph.D. student developing JMOSS.

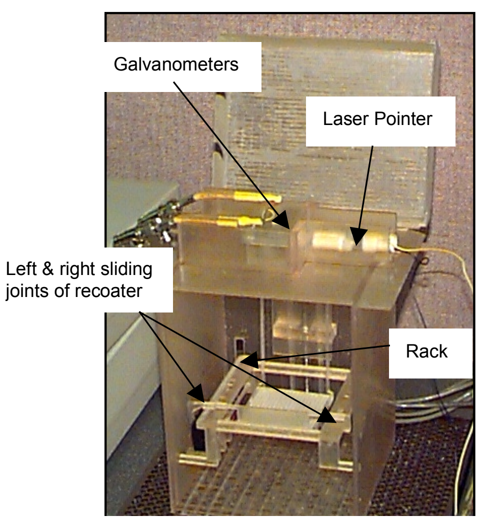
Additive Fabrication – "Rapid Manufacturing"

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.

Building Around Inserts

In order to achieve functional assembly fabrication and smooth surfaces, the SLA machines themselves will require additional functionality. It is sometimes necessary to build prototype assemblies that operate as mechanisms or that have multiple materials in them. In the context of SLA, one solution is to incorporate inserts into SLA parts or assemblies that are placed into the build vat during or prior to the start of a build. Imagine fabricating a working mechanism with metal shafts and bearings directly in an SLA machine. This vision requires both small and large changes in the operation of an SLA machine, and may require hardware changes as well.

Alok Kataria and advisor David Rosen investigated these issues. Many difficult issues arose in this project, including: addressing the laser beam shadowing problem when an insert is in the build vat, how to position and fixture inserts during builds, and methods to recoat the SLA vat with inserts sticking above the resin surface. Alok developed guidelines for designing devices with embedded inserts, including clearances and tolerances for inserts and kinematic joints, methods for handling motors, wires, and various shaped horizontal and vertical components, and redesign guidelines for the devices themselves to facilitate in-situ assembly and post-processing. Alok also developed process planning capabilities for the 5-Axis SLA machine described below.



Functional prototype of SLA-250 built in a SLA-250 with 11 inserts.

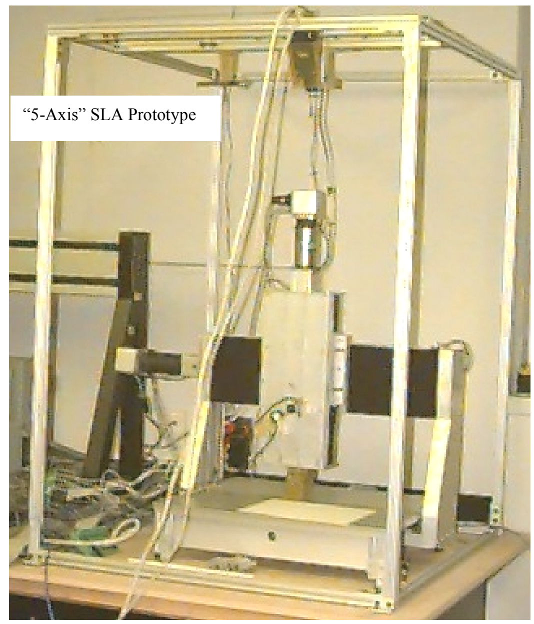
The culmination of Alok's work is a working scale model of an SLA-250, built with 11 inserts in one build in our SLA-250. It actually works! We inserted a laser pointer, two galvanometers with mirrors, two electric motors, a lead-screw, a rack gear, and other small hardware into the SLA-250 vat, then built the housing, elevator, and recoating mechanisms around them. It took about 78 hours in the -250, but it was worth it. By hooking the model to signal generators (drive the galvos), power supplies (for the motors), and a timing circuit, the model operates with the laser tracing part cross-sections on the build platform, platform lowers, then the recoating blade sweeps across the platform, then the cycle repeats.

Alok has graduated, but we are looking for new opportunities to extend this work.

5-Axis SLA

In order to achieve functional assembly fabrication and smooth surfaces, SLA machines will require additional functionality. We investigated the use of additional degrees of freedom in the operation of SLA machines, investigating 5-axes of motion or more. Conventional RP machines have three degrees of freedom (DOF); for example, the SLA has two DOF in the laser beam (scans XY), plus a third DOF with the elevator translating in Z. Additional DOF's could include platform swivel and tilt. Two broad approaches were taken to provide additional DOF's. The first involved modifying the mechanical subsystem to provide platform motions beyond simple elevation. The second involved adding additional capabilities to the optics system.

Tom Kurfess, Imme Ebert-Uphoff, and David Rosen supervised this project. Imme and her student, Brad Geving, investigated alternative mechanical and optical subsystem configurations. Tom Kurfess and Chad Moore focused on the development of a suitable machine controller. Alok Kataria was also involved in this project, contributing process-planning methods for our machine designs.


"5-Axis" SLA Prototype

The group developed an SLA machine design with seven DOF's, having added two galvanometers for additional capability in the optics subsystem, with these galvanometers mounted on a XYZ gantry robot. Shown at right is the working prototype machine – it is capable of drawing laser strokes on the gantry robot's metal base. We tested its accuracy, controllability, and ability to draw around inserts. Success! Furthermore, Brad developed the forward and inverse kinematics of the SLA machine, enabling us to actually generate scan patterns from part cross sections, then program the machine to draw them – with or without inserts.

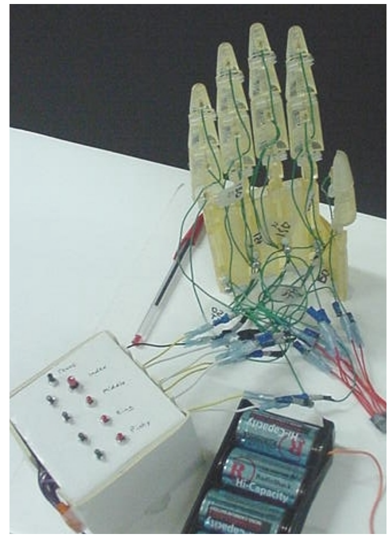
All these students have graduated. We are planning to incorporate some of these capabilities in our micro-SLA project.

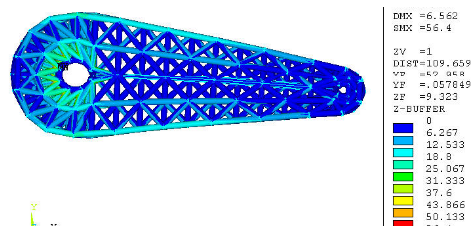
Design for Additive Fabrication

As mentioned, an interesting future of RP technologies is in applications for which conventional manufacturing processes are too costly, difficult, or impossible. But what types of applications are these? 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."

The research team working on this project consists of Imme Ebert-Uphoff, David Rosen, Jacob Diez, and Hongqing (Vincent) Wang. Jacob has nearly 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). The goal of this research is to show the feasibility of manufacturing functional robotic systems using Additive Fabrication techniques.

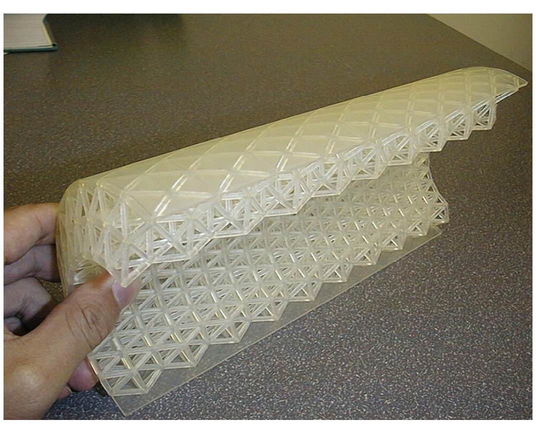
There have been substantial successes in this project to date. Compliant joints have been developed that function very well. These joints demonstrate compliance only along the intended axis of rotation, and have achieved rotations up to +/- 200°. Shape Memory Alloy (SMA) actuators have been utilized to successfully create motion in the robotic systems as well. These achievements have lead to the creation of a miniature robotic device as well as a model of the human hand (see hand image on right). 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. The remaining work involves utilizing sensors to develop a passive robotic system that will be capable of tracking the inputs of physical shape changes. Once completed, a clear potential to build non-assembly robotic systems will be demonstrated. This will open up new windows of opportunity for the manufacturing systems utilizing Additive Fabrication.





This is an exciting area! In addition to all of the good progress described above, we have been equally prolific in the development of truss structure geometries. Research is proceeding in two directions: light-weight robot arms and large, light-weight structures. We can take advantage of the shape complexity capabilities of SLA and other RP technologies to put material where it can best be utilized for robot arms. This means making robot arms as stiff, strong, and light as possible. The images in this section are of one arm design for a 7-link parallel manipulator. The truss structure is fine-tuned to provide the best stiffness-to-weight ratio possible. Markus Wahlberg, a visiting student from Sweden, helped Vincent with this work.

The other direction is in designing and fabricating large light-weight structures. These have applications in the aerospace and automotive industries, as well as others. Basically, we want to replace thick sections or thick skins of parts with a thinner skin that is backed-up with truss structure. This is the same principle demonstrated by honeycomb-like structures. Again, we take advantage of the capabilities of RP technologies to build virtually any shapes we want. As mentioned, we are working with Ford on an aging study of thin-skinned truss structures. Additionally, we are also working with Pratt & Whitney on demonstrating weight and cost savings of truss structure designs for large aerospace models. If successful, we will have a technology with widespread application for saving time and cost, plus eliminating many model construction difficulties. An invention disclosure was submitted on the truss structure results and a provisional patent application will follow soon.



Micro-SLA and SLA Process Modeling

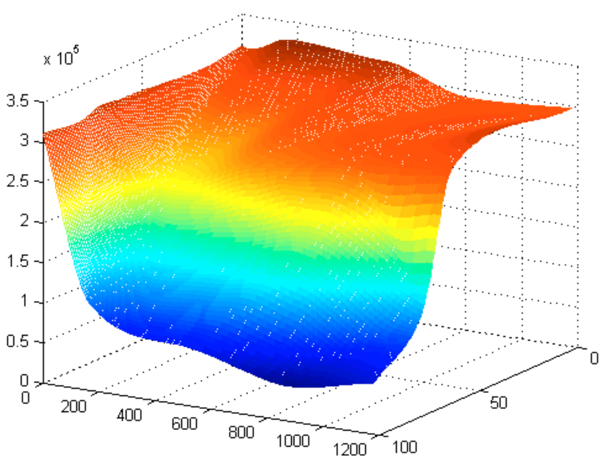
These combined projects address issues of understanding the laser-resin interactions in the stereolithography process. A related objective is to understand how small the SLA process can go – how small is small?

In order to address this issue a quantitative SLA cure model will be developed. John Muzzy, in Chemical Engineering, has begun working on this project and has identified a new student, Yanyan Tang who will start in 2001. This model will include a kinetic model for the polymerization process and a finite element heat transfer model for operation of a SLA. The reaction kinetics will be studied by differential scanning calorimetry (DSC) and, ideally, by photo-DSC. The SL cure model will be verified by comparing SLA simulations of temperature and degree of cure (DOC) profiles with SLA trials. The validated models will be used to simulate materials and process modifications. Some material modifications include altering the heat of reaction, the photopolymerization kinetics, the thermal polymerization kinetics and the thermal conductivity. Some process modifications include altering beam size, beam intensity, beam speed, beam pattern, bath temperature and convective cooling conditions.

Given that we better understand the SLA process, we can then investigate miniaturizing the process. Dave Rosen is working with a new student, Benay Sager, on exploring the developing of a micro-SLA machine. Currently, we are redesigning the optics system on the SLA-250 in order to gain an understanding of how to achieve small spot sizes. Our goal is a 10 micron spot. The longer term objective is to assess the feasibility of producing SLA technology that can fabricate parts and devices with 20 micron feature sizes. We need to understand the relationships among optics, resins, resin viscosity for recoating, and alternative methods of recoating. Accomplishments should enable entire new fields of applications in MEMS, electronic packaging, opto-electronics packaging, among others.

Aging, Fatigue, and Environmental Characteristics of Rapid Tooling Materials

This project will study the effects of aging on rapid tooling materials. The goal is to see how temperature and humidity affect the mechanical and dimensional properties of these materials. A further goal is to determine the diffusion coefficient of water in these materials. Parts will be 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.



Jon Colton is supervising Xavier Ottemer, a second-year graduate student, on this project. Currently, experiments have been completed on the time-temperature-humidity characteristics of SL-7510. A preliminary empirical model been developed to better explain the aging phenomena associated with exposure to humidity over time. The figure to the left is a mesh-plot of some results. The sample Storage Modulus is plotted vs. humidity(0 – 100%) and time (0 – 1200 hours). Work next semester will focus on developing an analytical model of resin aging, with an emphasis on the underlying phenomena, such as moisture absorption, random chain scission, oxidation, side-group elimination, etc. By the end of Spring semester, 2001, a prototype tool for predicting aging effects will be developed.

Heat Transfer Engineering and Evaluation

This project will compare heat transfer data from Stereolithography models to actual engine hardware. A study will be conducted utilizing available SL materials and SL build styles to determine and develop the best process to collect heat transfer data early in the design process. Furthermore, we will be able to correlate SL models and actual metallic engine hardware. A tool will be developed to accurately analyze the data acquired during test. A method for suspending and curing liquid crystals underneath the surface of the SL parts during the build process will be determined. Future sprayed solid SL pieces will be analyzed to determine whether data are affected by: build orientation, SL resin type, and part thickness. Joint co-op students Alan Martin and Steven Hoffman are co-supervised by John Muzzy and David Rosen.

Other RPMI Related Activities

Machining of Tooling Boards

In contrast to SLA based rapid tooling approaches, high speed machining is an alternative to SLA based rapid tooling methods when it comes to 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 epoxy tooling board materials. Both aluminum and ceramic filling materials are used in different formulations of these tooling boards. Since these materials can machine faster than aluminum, they hold tremendous promise for rapid tooling applications where speed is critical.

Profs Shreyes Melkote and Steven Liang are leading this project. Ruben Lanz worked with Shreyes on the initial machinability study of aluminum-filled tooling board materials. Ruben graduated in Summer 2000. He made tremendous progress and demonstrated conditions under which tooling board can be machined several times faster than aluminum – with better surface finish and accuracy. Furthermore, they demonstrated that partially cured tooling board materials can also be machined successfully, then fully cured. The advantage of this process is that it eliminates the large amount of dust that is generated when machining fully-cured materials. Shreyes has recently begun work with Tosin Tomori, a new graduate student, applying similar issues for ceramic-filled tooling board materials.

Steven Liang is supervising the work of Efe Arkayin, now in his second year at Georgia Tech. Efe's research takes Ruben's a step further. With the models that Ruben developed, Efe is developing an improved analytical process model that will underlie a process optimization method. The optimization will minimize surface roughness, form error and production time, while maximizing tool life. Variables include cutting speed, feed, and depth of cut, while considering constraints on machine tool power.

As a result, we will have the most complete machinability studies and models of tooling board materials. Also, we will have the ability to optimize machining parameters to obtain the best results.

Laser Chemical Vapor Deposition

A laser CVD rapid prototyping system (LCVD-RP) is 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 proposed 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.

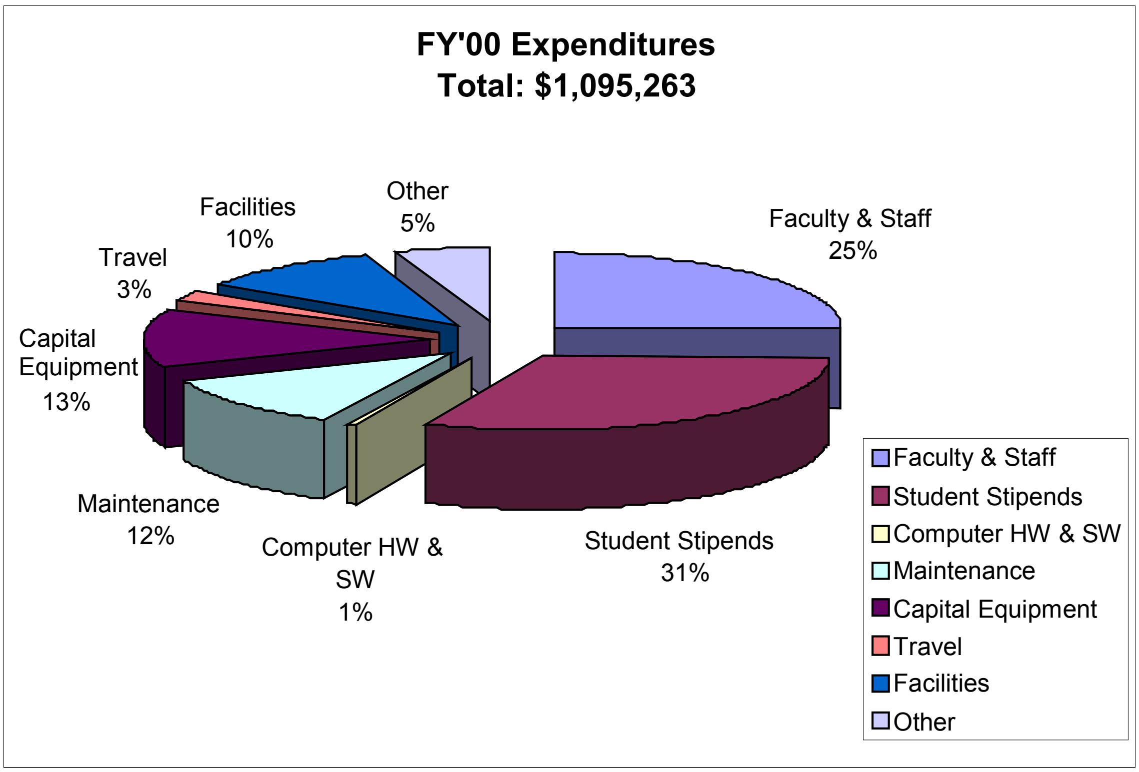
The team of Dr. Jack Lackey and students Chad Duty, Dan Jean, and Brian Fuhrman have successfully designed and constructed the LCVD-RP machine. As of September 1999, it is operational! Several deposits of carbon were produced. Now, the real research begins. Extensive material-process studies are necessary to understand the influence of process variables on the synthesis of LCVD structures for various applications. Additionally, new process planning methods will be needed due to the unique geometry of the LCVD-RP machine. Jack, David Rosen, and other faculty are submitting proposals to government agencies for further funding. The opportunities for such a technology are enormous!

FY ’00 Financial Report and FY ’01 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 2000 (ending June 30, 2000), and the outlook remains healthy.

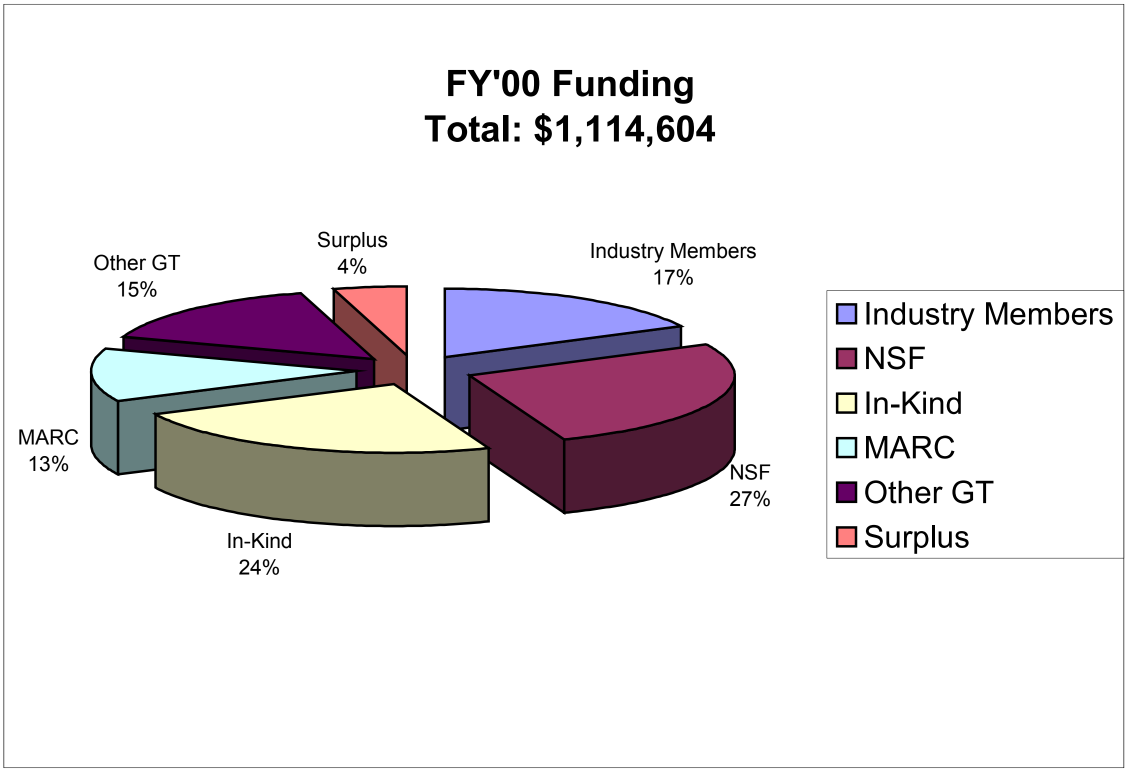
Expenditures

The largest single area of expenditure was for student stipends, which increased to $344,000 compared to $247,000 in FY ‘99. These expenditures were necessary to support the many projects launched in 1999. Faculty and staff salaries in remained about the same at $276,000. Expenses for RPMI faculty and staff salaries reflect the now full-time commitment of both the lab manager and the director of operations and an increased portion of our administrative assistant’s salary.



Capital equipment spending increased in FY '00 to $139,000, reflecting our purchase of the SLA-3500 and our acquisition of the Sanders ModelMaker. Other significant expenses included $127,000 in machine and software maintenance, which increased in FY’00 in proportion to our capital equipment acquisitions. 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. These expenses stayed about the same at $59,000.

For fiscal 2001, expect decreases in most categories to reflect the termination of the NSF-funded Rapid Tooling TestBed project, changes in RPMI staffing levels, and our falling industry membership. Total budgeted expenditures for FY ’01 are $786,000. 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 2001.

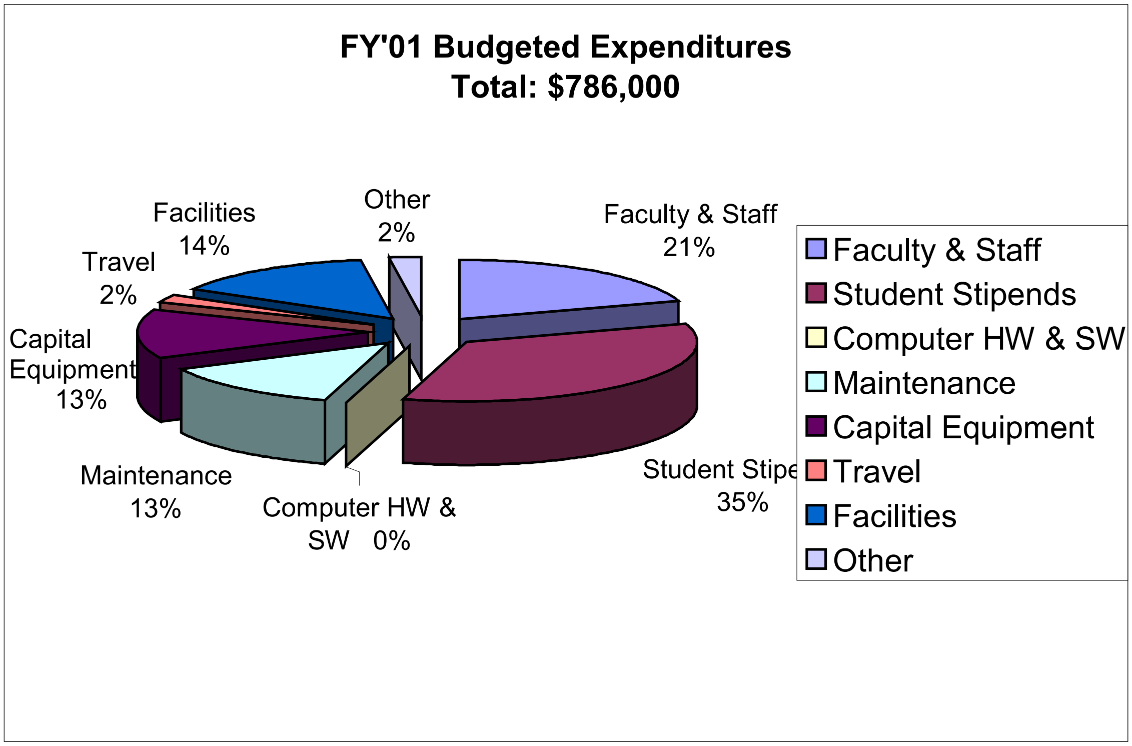


Funding

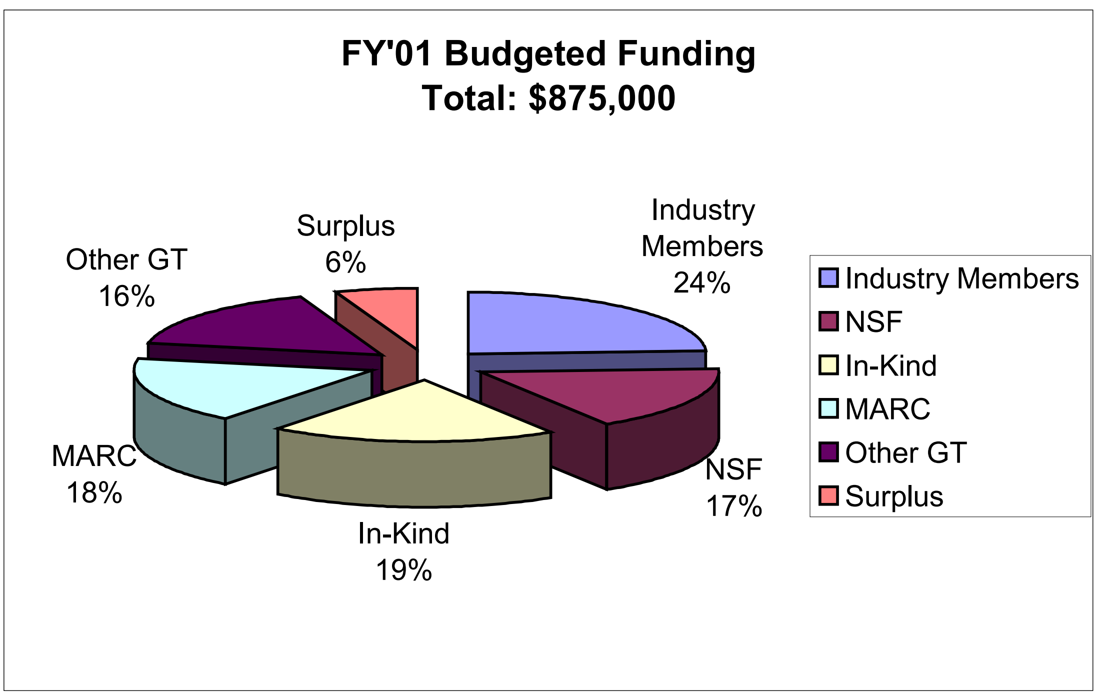
For fiscal 2000, our cumulative surplus decreased to $56,000. This amount will be carried forward into FY '01. Membership dues, paid in cash, in FY '00 decreased to $200, 000 from $220,000 the prior year. However, we received $270,000 in in-kind contributions, most of which was from member companies. 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-Kind" includes donated hardware, software, materials and supplies from non-RPMI members. In-kind (non-cash) contributions from members totaled $45,000 and are included as "Industry Member" contributions.

In FY '00, research sponsored by NSF is helping to support more than 25 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 eleven of twelve companies. One small company pays a special dues rate. An increase in the number of members could increase the "Industry Members" amount by a maximum of $125,000. (As of December 2000, we have 10 active members, 15 is our limit.)



In 2001 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 2001

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 2000, 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 active in 2000.

2000 Committee Members List

Operations

Chair:	**Bill Durden**
Members:	**Marc Bellotti, Darius Daruwala, Diana Kalisz, Dave Rosen**

Technology

Chair:	**Larry Whitaker**
Members:	**Gary Beldue, Suresh Jayanthi, John Malluck, Dave Rosen, Doug VanPutte**

Membership

Chair:	**Dwight Williams/Dave Feindel,**
Members:	**Doug VanPutte, Reggie Ponder**

Executive

Chair:	**Doug VanPutte**
Members:	**Bill Durden, Larry Whitaker, Dwight Williams, Reggie Ponder, Dave Rosen**

Operations Committee Year-End Report

Bill Durden from Durden Enterprises finished his first term as Chairman of the Operations Committee. Bill and his group 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.

In addition to fine-tuning our project proposal and selection process, we pursued one major initiative this past 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.

As usual, opportunity statements for new projects were solicited in Spring. We received a total of 15. All these were reviewed and presented to the membership. The new proposals were screened for technical merit, academic fit and enterprise value. Some consolidation of opportunity statements was accomplished due to overlapping coverage. Project proposals were then fit into one of the key "Thrust Areas" within the existing portfolio. The resulting portfolio is focused on short, medium, and long-term projects in the following areas:

- Tooling Life
- Additive Fabrication
- SLA Process and Materials

- Rapid Inspection and CAV
- Other RPMI Related Activity

Projects were rank-ordered, with the top 6 selected for funding, contingent upon funding. Four projects were launched in Fall and students were recruited for each of these.

Bill will be passing the baton to Marc Bellotti from Baxter Healthcare who was elected the new Chairman of Operations at the fall meeting.

Technology Committee Year End Report

During the year the Technology Committee lost the participation of Reggie Ponder and Giorgos Hatzillias due to employment changes and Larry Whitaker due to 3M's decision not to continue with RPMI.

The Technology committee completed a "Technology Survey" to determine what technologies would be needed in the year 2000, what technologies were in place, and what technologies or equipment would need to be purchased and at what cost. The results of the survey indicated that there was enough equipment and the technologies were in place to accomplish the proposed student projects for year 2000.

Giorgos Hatzilias and Suresh Jayanthi jointly proposed that a "Technical Body of Knowledge" be created to allow the accomplishments of the RPMI to be readily available to the members. Now that they have departed a new RPMI member is needed to champion the effort. The next steps for the "Technical Body of Knowledge" are as follows. Initially a web master needs to be appointed, and then an off-the-shelf database needs to be implemented. This should be followed by a survey of the accumulated data, the development of a research accounting system, the organization of the existing archives, and the establishment of a maintenance system. The new Technology Chairman for 2001, Neal Enke of Ford, will have this as one of his first projects.

My hope for the RPMI is that there is a strong focus on "Additive Fabrication" which emphasizes new design concepts, CAD issues, fabrication issues, and materials issues in future years. I would like to see a "road map" of how to transfer and execute additive fabrication into industry is one of the results of this study.

I am sorry that 3M must leave the RPMI. Our participation in the RPMI has expanded our awareness of RP applications, challenged our perceptions, and has provided valuable networking opportunities. The GT staff, students, and member companies have been excellent partners. Good Luck to you all!

Membership Committee Year End Report

The Membership Committee began the year with the goal of adding three new members and retaining the current members to reach the full compliment of fifteen members by year-end. Unfortunately, no new members were added and two of the existing members withdrew during the year leaving a total membership at nine members at the end of 2000. Although the Membership committee made numerous contacts throughout the year and hosted six representatives from interested companies at member meetings, none of them were able to make the membership commitment. The primary reason given for not joining the RPMI was the lack of funding available to join the institute. The recruitment of new members was done by identifying companies and making contact with them through a variety of efforts. These efforts included contact through attendance at R&PM conferences, company visits to the RPMI lab, and the contact made through attendance at the Advanced RP&M Symposium 2000. 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 2000 at mid-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 survey showed that the highest ranked benefits of the survey by the members are to augment their company's R&D effort in RP&M applications (2) and to network with other companies (6). The next highest ranked benefits were to keep their company current in RP&M (1) and the ability to sponsor advanced R&D in RP&M (5). Since not all companies ranked the same benefits equally, there is some work to do to understand the shortfall of the RPMI in some areas for specific companies.

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 Rosemont, Illinois. These activities keep the communication and sharing continuing through out the entire year among the members.

Advanced Symposium 2000

The RPMI presented a forward-looking two-day RPM symposium on February 7-8, 2000 at Georgia Tech. Over one hundred company and academic participants attended the symposium. In addition, fourteen exhibitors welcomed the symposium attendees at an evening reception.

The symposium program featured three sessions:

- *Realizing Rapid Manufacturing, Chair Mrs. Elaine Hunt, Clemson University*
- *Unique Applications Using Layered Manufacturing Technologies, Chair Mr. Ken Johnson, NCMS*
- *Visualization: Physical and Virtual, Chair Dr. Jim Budd, GA Tech*

The chair of each session was a person with excellent credentials to represent their individual sessions, and each led off their sessions with thought provoking remarks. Each session was geared to present a view of the RPM future and presented some of the challenges that must be met to move the industry forward into the new millennium. The session chairs in the image from left to right are Jim Budd, Georgia Institute of Technology, Elaine Hunt, Clemson University, and Ken Johnson, National Center for Manufacturing Sciences.

At the beginning of the first day, Mr. Dave Howard from Ford Motor

Company presented the symposium keynote address, *Journey to Rapid Manufacturing*. On the second day, after the third session, Mike McEvoy, Baxter Healthcare, spoke about *RPM 2000 and Beyond*. Dr. Phill Dickens, De Montfort University, UK, provided the session wrap-up presentation by discussing *Rapid Manufacturing-Near or Far*.

RPMI Members Meeting, February 9, 2000

The first meeting at Georgia Tech of 2000 followed the successful RPMI sponsored symposium on February 7-8, 2000. The members hosted the following guests: Larry Winnen and Erling Hansen from Tyco Electronics (Raychem), Tim Bianchi from Schlumberger, Merlin Warner from Baron Cast, Beth Israelnaim from BD, and Ward Jensen from Oreck. The main purpose of the meeting was to conduct the business of the RPMI, look ahead at the activities planned for the year, and host special presentations by RPMI members and guests. The first item on the agenda was a presentation by Bill Durden, Durden Enterprises. Bill presented the results from a benchmarking study he conducted on rapid tooling in conjunction with the RPMI, *How Do Rapid Tooling Approaches Stack Up?,* which was published in the December issue of Modern Mold & Tooling. This presentation was followed by presentations by Larry Whitaker, 3M, on Additive Fabrication, Tom Kurfess, GA Tech, on rapid inspection software, Larry Winnen, Tyco Electronics, on RP&M at his company, and Tim Bianchi, Schlumberger, on product development at his company.

These presentations were followed by the 2000 outlook by each of the committee chairs, Dave Feindel, Kodak, Membership Chair, Bill Durden, Durden Enterprises, Operations Committee Chair, and Larry Whitaker, 3M, Technology Committee Chair.

The meeting was adjourned following a period of show & tell by Gary Beldue, Kodak, and Ward Jensen, Oreck, several student updates, and the traditional "Around the Table" in which everyone participated.

RPMI Members Meeting, April 27-28, 2000

The second RPMI meeting of the year was a two-day format. The first day of student project presentations ended with the annual picnic at Bill Durden's "ranch" (image on right). At the business meeting on the second day, the members welcomed the following guests: Beth Israelnaim and Gene Fleischer from BD, Phillip Smith, Mark McDermott, Jim Griffen and Bud Hine from Bard Medical, J.P. Henderson from Paraform, Frank Middleton from ViaSat, and Ken Richardson from CAMmatic. The items featured in this meeting included a year-end project status report, an update on government proposal submissions, presentations by staff and guests, and a review of new project submissions to date. David Rosen began the year-end project status report by recapping the major accomplishments of the graduating students. This was followed by a student presentation on auto-generated truss structures by Vincent Wang. David Rosen then reviewed the three proposals that the RPMI staff is submitting to the NSF this year. Three presentations by guests then followed.

Beth Israelnaim, BD, gave a short presentation on the RP activities at BD and showed a variety of parts to illustrate the types of projects undertaken by her group. Ken Richardson of CAMmatics presented the rapid prototyping methodology developed by his company and proposed that the RPMI investigate the practicality of the technology. Doug VanPutte, acting as the senior sales representative of Protoform North America, gave a presentation on Space Puzzle Molding, a unique injection-molding concept for making complex prototypes marketed by the company. This was followed by parallel presentations by J.P Henderson on the metrology software marketed by Paraform and a Rapid Tooling TestBed demonstration conducted by the students.

Bill Durden ended the formal part of the business meeting by discussing the recently submitted opportunity statements and having each project sponsor briefly discuss the project and its relevancy to the RPMI. Following the traditional "Around the Table", the meeting was adjourned.

RPMI Members Meeting June 15-16, 2000

Ford Training and Development Center

Neal Enke of Ford Motor Company welcomed the RPMI members and staff to the Ford Training and Development Center in Dearborn, MI for the third meeting of the year, a two-day format. The main goal of the meeting, beside the introduction to RP&M at Ford, was to determine the research program of the RPMI for the next year. The first day included presentations by Ford, Ford vendors, and several members of the RPMI faculty.

Following an introduction by Neal Enke, Pete Sferro of Ford gave a talk on *The Need – More than Rapid Prototyping*. His talk made the case for changing the company product development process utilizing a Ford DOME Integrated MGS Process Modeler that integrated RP and other technologies into the product development cycle.

Three Ford vendors then gave presentations on rapid prototyping and tooling. They were Wesley Cox of Agile Manufacturing (rapid castings), Kevin Foley of Excel Engineering (prototype epoxy molds), and Dennis Reiland of General Pattern (large, interlocking SLA prototypes).

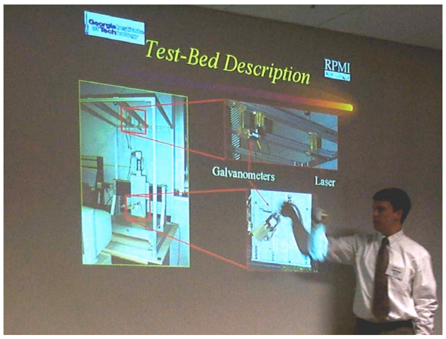
David Rosen, Director of the RPMI, initiated the last presentations of the day. Dave introduced the new project proposals and distributed handouts, which gave an understanding of how the new proposals fit within the current research portfolio. This was followed by presentations by Tom Kurfess on the RPMI metrology research program and Jon Colton on the RPMI rapid tooling research program. The first day was concluded with a tour of the Spirit of Ford building that featured NASCAR automobiles.

The second day began at the Ford FTDC with a talk by instructor Merlin Warner, Warner Technologies, on the Ford Rapid Prototyping and Rapid Tooling Training Course. The remainder of the morning was spent on discussing, organizing, and ranking the new project proposals followed by a presentation of the results of the membership survey, conducted by Dwight Williams, 3D Systems.

Following a lunch break, the group toured the Ford PDC Rapid Prototyping Lab and Model Shop, the Rapid Tooling Lab at the Ford Research Labs, and the Engine Rapid Prototyping Lab before the meeting was adjourned.

RPMI Members Meeting, October 19-20, 1999

The last meeting of the year was again presented on the two-day format. The project status presentations on the first day were well received by the members. The students reported good progress on the projects, including the projects recently launched in the project portfolio by the newly recruited students at the beginning of the fall quarter. David Rosen concluded the first day with a presentation on possible changes in the RPMI organizational structure and the research focus of the RPMI prepared by the RPMI faculty. He indicated that with the resignations of Reggie Ponder and Giorgos Hatzilias and the changing RP&M industry, there was an opportunity to modify the RPMI.



On the second day David Rosen began the last business meeting of the year by highlighting the feedback from the members resulting from the proposed changes in the RPMI on the previous day. Following the generation of additional ideas, Dave indicated that he would discuss the feedback with the RPMI staff and prepare more concrete plans for the future. Bill Durden of Durden Enterprises discussed his recommendations for the RPMI followed by a confirmation that his company would be leaving the RPMI at the end of the year.

John Malluck presented a short review of the RPMI budget. He indicated that a dollar invested in the RPMI by a member company has been matched by over 50 dollars by GA Tech in the past. The bad news is that since the membership has decreased from 12 to nine in 2000 and the existing NSF grant is ending this year, about half of the contingency budget had to be spent this year to fund the existing students. Therefore there may be a short fall in the funding for students next year. Dave Rosen indicated that there would be an increased effort to bring in both new RPMI members and new NSF grants to solve the funding problems.

The RPMI year-end committee reports were presented by Doug VanPutte (for Membership), Bill Durden (for Operations), and Dave Rosen (for Technology).

Nominations and voting for new 2001 committee chairs resulted in the election of John Malluck for Membership chair, Marc Bellotti for Operations chair, and Neal Enke as Technology chair. Following the traditional Around the Table with all participating, the meeting was adjourned.

2001 Meeting Dates, Locations & Agenda

Member Meeting, February 8-9, 2001	Georgia Tech, Atlanta Open House Business Meeting, Project Reviews, Committee Agenda
Member Meeting, April 26-27, 2001	Georgia Tech, Atlanta Business Meeting New Proposal Generation, Year-End Project Completions
Member Meeting, June 14-15, 2001	Pratt & Whitney, West Palm Beach, FL New Project Development, Technology Transfer
Member Meeting, October 18-19, 2001	Georgia Tech, Atlanta New Project Launch Business Meeting Year End Committee Reports Chair Elections

Overview of Changes in the RPMI

Fundamentally, the RPMI will retain its focus on RP&M, but with an emphasis on pursuing 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. Changes to the RPMI can be categorized as:

- Industry involvement and funding – we exploring several additional means for industry to get involved in the RPMI;
- Adopting a more aggressive research posture – consistent with our presence at a major research institution, Georgia Tech. This helps position us for making major impacts over the long-term.

Each of these areas of change is described below.

Ways to Get Involved

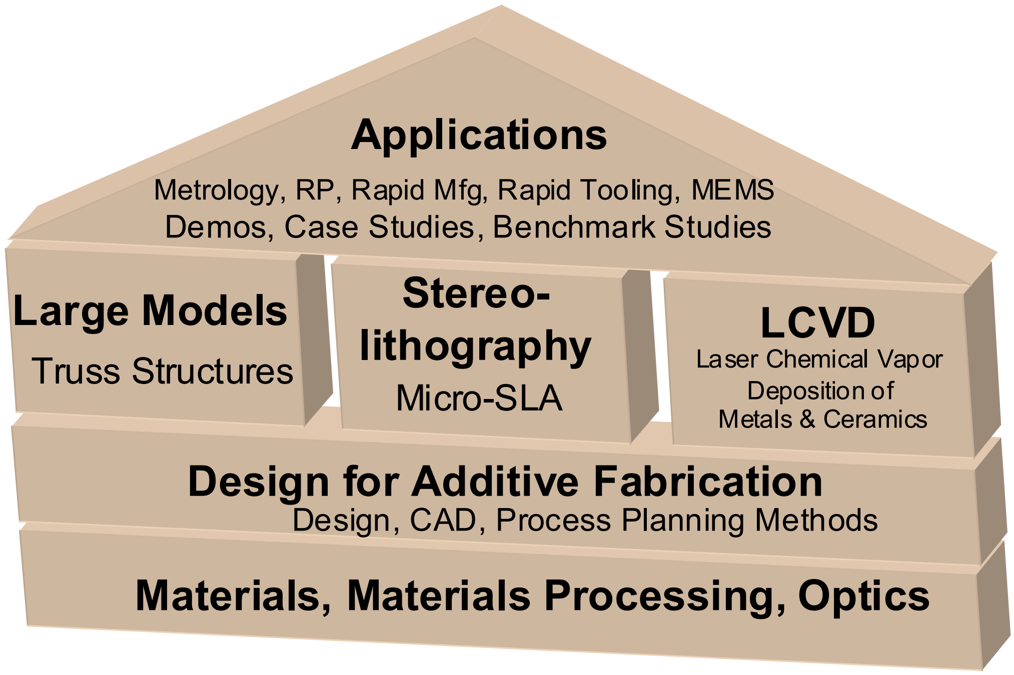
Rather than just relying on RPMI membership as the only means to participate in the RPMI, we have added several more. These changes fundamentally alter the funding mechanism of the RPMI and we are working with the Georgia Tech administration to put all necessary structures and procedures in place. These 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:

- **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.
- **Projects**. We will run projects for you, whether it is benchmarking a set of RP processes, building functional prototypes, constructing large light-weight prototypes, pushing the envelope, etc. Various durations to suit your needs: 1, 3, or 6 months.
- **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.
- **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.

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.

As a result, our research directions can be summarized as: pushing size limits in both large and small directions, pursuing more complex material compositions across polymers, metals, and ceramics, and developing design and CAD technologies that enable designers to take advantage of these capabilities. Schematically, the structure of our research and projects agenda is shown below.



Applications means the current type of RPMI project, with a focus on applications of RP&M technologies, rather than research on RP&M technologies. As a result, this is where we would conduct benchmark studies, work on case studies, demonstrate RP&M technologies on problems of industry interest, etc. Members propose, select, and direct projects of mutual interest.

In the *Stereolithography* area, we will focus on research aimed at developing a SLA machine for micro-size devices. Our promising collaboration with the MEMS researchers is driving much of our interests here. Ultimately, our objective is to enable rapid manufacturing for the micro-world. This work will leverage our past research in 5-axis SLA, building around inserts, and Design for Additive Fabrication, as well as tying in well with our new projects in SLA cure modeling and micro-SLA.

The *LCVD* area was established several years ago. With the new NSF grant funding some of our work, we already hit the ground running in this area. It is here where we can fabricate devices with complex material structures in metals and ceramics, providing us with tremendous coverage of industry needs.

The area of Large Models leverages our work in design for additive fabrication. By applying our truss structure work, we can fabricate large, light-weight structures that can be used for a wide range of applications. Significant research is needed to optimize these structures to best suit the needs of the application. For example, large automotive craftsmanship models must be very accurate and remain dimensionally stable for months on end. For large aerospace structures, weight, fabrication time, and cost must all be minimized while remaining strong enough to support the entire model.

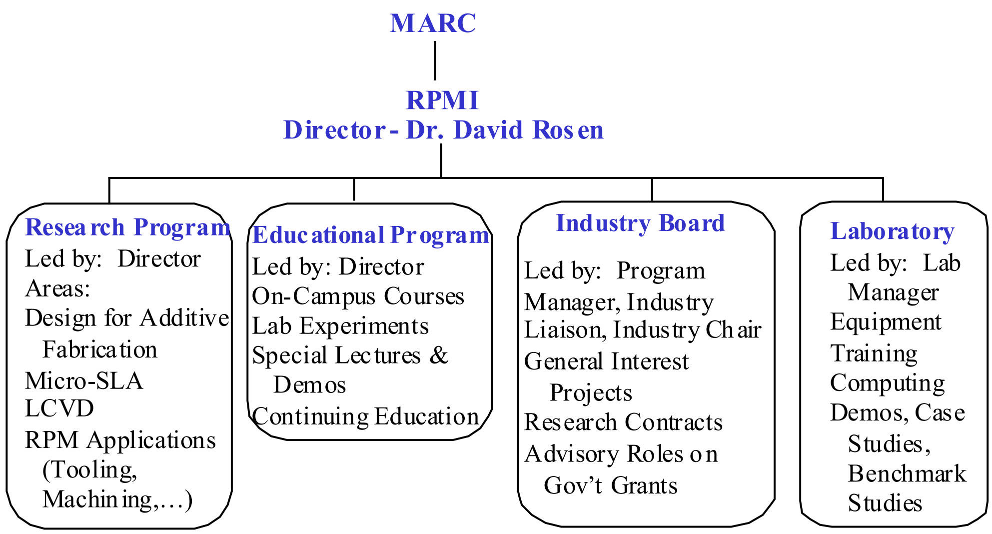
Underlying the technology areas are more fundamental research programs in Design and in Materials Processing.

Structure of the RPMI

To support these changes, some reallocation of responsibilities among the RPMI staff is required. The structure that we will transition to is shown below. As mentioned, we hope to have a Program Manager in place in early 2001. The person in that position will be responsible for growing the industry membership, as well as assisting with the acquisition of government funding. The Lab Manager gains responsibilities in running projects and assisting with applications, in addition to the equipment and computing responsibilities necessary to run the laboratory.

These positions fit into the larger RPMI organizational structure, which is shown in the figure below. Over the past 2.5 years or so, the RPMI has operated within the Manufacturing Research Center organization. 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. Thanks, Steve!

No organization becomes successful by just rearranging boxes in an organization chart. It takes people! The RPMI Committee Chairs have been terrific in building the organization. Faculty have developed a world-class research program and have been tremendously successful in attracting great students. We have a total of nine RPMI faculty supervising 28 graduate students.



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 2001, we enter the RPMI's seventh year in existence, and the third 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. Our research in rapid tooling is a good example. We are investigating tool life for SLA and epoxy injection molds. By its nature, this research must be performed using today's technologies and many specific results are applicable only to today's technologies. But to ensure long-term relevance, we are developing a standard experimental method that can be applied whenever new materials or RP processes become available. We believe that we have structured all of our activities so that we remain current with technology – and demonstrate the leadership necessary to prepare for the future.

The Year 3 plan is presented here. We have a good start on each element of this plan and look forward to achieving our objectives. In doing so, we believe we will be living up to the title of this Annual Report: ***Pushing the Envelope of RP&M***.

We invite your comments, concerns, and questions on our strategic plan.

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.

Goals for 2001

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 three-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.*
- *Begin project-based interactions with companies, in addition to standard membership.*
- *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.*

Appendices

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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.

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 120+/yr	Guest Lectures
CAD/CAM	Through academic courses and projects, and Industry Short Courses	**National Organizations** SME RPA
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.

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

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

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.
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.

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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.

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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 Marco Fernandez Giang Pham Vincent Rodet Shiva Sambu Tosin Tomori Angela Tse Hongqing Wang Angran Xiao (PhD)

Laboratory Equipment

Major Equipment

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 you spend less time on maintenance and more time working.

- up to 2.5 times faster than SLA-250
- improved resin characteristics
- automatic resin refill system
- modular design

Photo courtesy of 3D Systems, Inc.

SLA-250/50

The most productive member of the SLA-250 line is the Series 50. A potent combination of power and speed, this machine integrates productivity enhancing components to deliver a quantum leap in part building efficiency to meet even the most rigorous production schedules.

- Interchangeable vat for rapid and easy resin exchange
- Multiple polymers available
- Zephyr™ Recoating System
- Easily builds multiple identical or unique parts simultaneously
- Unattended build operation

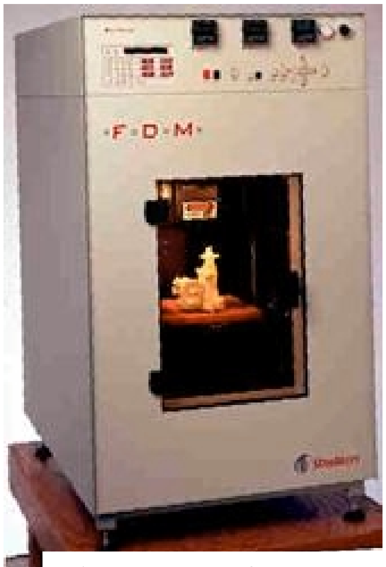
'Photo courtesy of 3D Systems, Inc.

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. The MicroVal® PFx® combines the award-winning MicroVal design with an advanced disengagable drive into one of the most versatile coordinate measuring machines available. At the flip of a switch, you can change it from manual operation to fully automatic, Direct Computer Control (DCC).

'Photo courtesy of Brown & Sharpe

FDM 1650



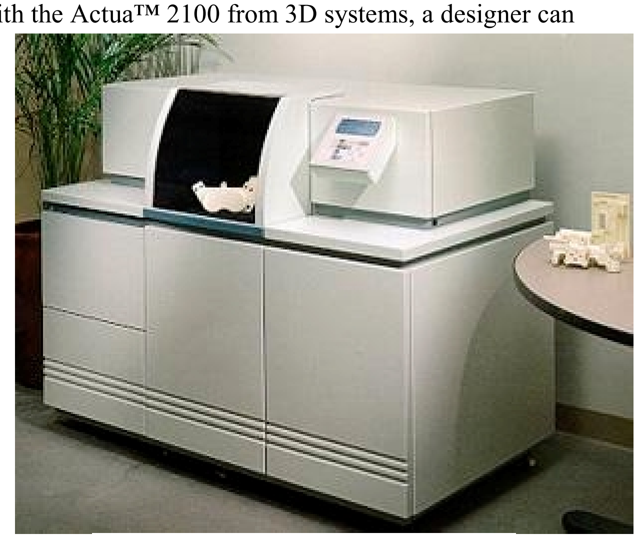
'Photo courtesy of Stratasys

This system was developed for the final design and prototyping phase of product development. Using our exclusive Fused Deposition Modeling technology, the FDM1650 lets you turn a design concept into a prototype. The fast, precise bench top system generates three-dimensional prototypes from 3D CAD software data. You can test the prototypes for fit and form--even simulate product performance without the excessive cost and time of traditional prototyping methods. Users typically report 85-90% savings in labor costs and time on medium- to high-complexity designs.

- Versatile system
- Three times the throughput of its predecessor (the FDM1600)
- Multiple modeling materials
- Easy to use

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.



'Photo courtesy of 3D Systems, Inc.

- Cut Design Time, Increase Design Quality
- Allegro Software Makes Model Building Simple
- Continuous Build, No Post-Processing
- Simple, Reliable Everyday Operation
- Efficiency and Economy, A Winning Combination
- Raster Action Speeds Complex Parts
- Office Environment-Friendly

Surveyor 1200

Laser Design Inc® makes the Surveyor 3D Laser Digitizing System for every application size, large and small. The economical Surveyor 1200® system fists conveniently in the same floor space as a coffee table and 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.

- Rapid Profile Sensor
- Optional Motion Control Pendant
- Ideal for measuring gaps, sectional profiles, and feature heights and locations
- Accelerates mold/tool/die production and CNC machining applications

Morgan Press

The morgan press allows students easy access to small injection molding experiments. The simplicity of the machine makes it easy to learn and use. The following are some of the major features of the machine:

- Two-zone, solid state electronic temperature control system for accuracy and wide heat range (0-800 F)
- Three-mode digital controllers for greater accuracy with temperature indication (optional)
- Eye-level pressure gauges for clamp and injection
- Material melting cylinder with hard chrome bore
- Hand-placed aluminum mold
- Temperature selection chart
- Operating controls grouped for convenience
- Heavy-duty cast base construction

Benchman VMC 4000 CNC Milling Machine

Today's manufacturers face a number of challenges, from custom manufacturing to mass production. To meet these challenges, manufacturers must adopt agile manufacturing techniques and use cost-effective equipment like benchtop CNC machines.

General Features:

- Vibration-dampening polymer composite machine base
- Full enclosure
- Coolant ready
- Built-in chip and coolant tray
- Coolant resistant Gortite® way covers
- Precision-ground cast iron cross slide
- Linear motion system

Standard Operating Procedures

Executive Committee Standard Operating Procedure

Responsibilities

The purpose of this committee is to address matters of RPMI policy and strategy.

Participants

This committee is composed of the Chairs of the Membership Committee, Technology Committee, Operations Committee and the RPMI Staff, including the Director, Director of Operations, and the Industrial Liaison.

Leader

The chair of this committee is the RPMI Industrial Liaison.

Activities

This committee will meet to discuss matters of policy and/or strategy as brought forth by a member of the Executive Committee or by an industrial member, faculty or student. The recommendations of this committee will be brought to the membership for discussion at the next regularly scheduled member meeting. The Georgia Tech staff has ultimate responsibility for making policy and strategy decisions taking into account the recommendations of the Executive Committee. This committee will also approve all invitations to attend member meetings.

Schedule

The committee will meet at least twice annually at scheduled times which coincide with the member meetings, with other meetings being called by the chair as they are required.

Membership Committee Standard Operating Procedure

Responsibilities

The purpose of this committee is to address current member satisfaction and new member recruiting.

Participants

This committee is composed of the industry members, the RPMI Director of Operations, and the RPMI Industrial Liaison.

Leader

The chair of this committee is elected from the industry membership. (See the Chairs Election Procedure)

Activities

Membership Satisfaction: Members of this committee maintain contact outside of the normal meetings with individual members to assess the level of satisfaction with the progress of RPMI research projects and the perceived return on investment with their RPMI membership. A survey may be circulated among the members to determine the level of member motivation and member satisfaction. The survey results are shared with the membership and remain a benchmark for future surveys. Outstanding issues are discussed and addressed by the membership committee.

New Member Recruiting: The committee maintains a list of prospective members. The committee prioritizes the list based on how well they think prospective member companies might fit into the current membership. Each committee member takes responsibility for a few companies on the list and manages the process of exploring their interests and educating them about the RPMI.

The courtship period might include sharing of literature, telephone conversations, informal meetings at industry events, visits to the company, company visits to GT, and (with Executive Committee approval) an invitation to attend one or more RPMI members meetings. Some companies make a membership decision in days or weeks. Others may take years. Each case is managed individually.

Schedule

The committee meets late in the calendar year to plan the activity for the following calendar year. Following an update to the prospective membership list, the list is divided among committee and new relationships are established and nurtured with candidate companies. At the appropriate time during the year a decision is made to issue a meeting invitation to the candidate company representative.

The committee maintains contact throughout the year with the individual members by personal conversations to address any concerns expressed. If appropriate, the committee develops and circulates a survey about mid-year to assess member satisfaction and motivation. The chairman makes a presentation at the last meeting of the calendar year that summarizes the committee activity during the year.

Operations Committee Standard Operating Procedure

Responsibilities

The purpose of this committee is to manage the RPMI project selection process.

Participants

This committee is composed of interested industry members and RPMI staff members, including the RPMI Director.

Leader

The chairman of this committee is elected from the industry membership. (See the Chairs Election Procedure)

Activities

This committee plans and executes a formal process each year to determine the projects to be undertaken by the RPMI students. (Available in RPMI#0001, Project Proposals and Selection Process)

Schedule

Prior to the second member meeting of each year (usually in May), the chairman calls for Project Opportunity Statements from the RPMI members and faculty. These statements contain the preliminary title, objectives, and resources required for a new project. At the second meeting, the committee has organized these submissions into categories and reviews the statements with the meeting attendees. The most appropriate projects opportunity statements are selected through extensive discussions by the members and RPMI staff.

Prior to the third meeting (usually in August) of the year, the RPMI staff has reviewed the selected statements and available resources, which includes faculty, students, and funding. A project proposal is generated for each project, which can be undertaken. At the third meeting, these proposals are reviewed by the members and formally prioritized by voting. The ballot contains voting criteria to establish the relative priority of the proposed projects: technical merit, compatibility, and enterprise value. The technical merit criterion is used to determine if the project technical content suitably challenges a student investigator for his degree program. The compatibility criterion is used to determine how well the project is perceived to fit into the RPMI program. The enterprise value criterion is used to gauge the perceived benefit to the member’s financial bottom line. These criteria are useful metrics for the generation of the initial project proposals. Following the meeting, the RPMI faculty identifies and makes offers to prospective graduate students to carry out the highest priority projects.

At the last meeting of the year (usually October-November), the RPMI Director gives an overview of the projects, which have been initiated. In addition, the chairman of the Operations Committee presents a summary of the committee activities for the year.

Although the above procedure establishes a formal project proposal process linked to the Georgia Tech calendar, project proposals may be submitted to the Operations Committee at any time during the year. The new proposals are judged on a case-by-case basis as they are presented to the membership at the next schedule meeting for discussion and potential adoption.

Technology Committee Standard Operating Procedure

Responsibilities:
The purpose of the Technology Committee is to keep the RP laboratory at the leading edge of RP technology development and plan for future RP technology needs.

Participants:
The committee is composed of a balance of RPMI industry members, Georgia Tech Academic Faculty, and Georgia Tech Research Staff.

Leader:
The Chair of the Technology Committee is an industrial member.

Activities:
The scope of the Technology Committee activities encompass:

- Determining current RP lab needs to support RP projects.
- Assessing emerging technology for future lab planning.
- Providing industry input for equipment purchases.
- Reporting equipment utilization levels.
- Maintaining a library of RP literature resources.
- Compiling and communicating RP seminar and conference information.

Schedule:
Committee meetings are held as needed throughout the year. Meetings are usually held through teleconference. Committee formation occurs with an open invitation for participation following the election of the chair at the last meeting of the year. Technology needs are addressed by mapping needs to planned RP projects following project selection in November.

RPMI Committee Chair Selection Policy

Chair Positions

A person holding the position of chair leads each of our three RPMI committees. In general, each chair's duty and responsibility is to assemble and lead his or her committee in setting annual goals, in performing the required tasks to reach those goals, and in communicating such plans and results to the RPMI members, students, and faculty.

Chair Eligibility

Any employee of any of the RPMI's current member companies is eligible to hold a chair. Georgia Tech faculty, staff and students are not eligible for chair positions, but may serve as members of a committee.

Terms of Service

The term for each chair is nominally one year, beginning on January 1 (or on the actual selection date, whichever is later) and ending on December 31 of the same year (or on the actual selection date, whichever is later).

Consecutive Terms

An individual may only hold the position of chair for two consecutive years. This applies even if that person served as chair of different committees in those years. After one year passes when an individual holds no chair, that individual's chair eligibility returns. (The purpose of this clause is to encourage broad participation among the member companies.)

Nominations

Early in the agenda of the last members' meeting of each year (usually October-November), the RPMI staff will circulate ballots for each of the three positions. The attending members will be asked to consider placing nominations for each position during the course of the meeting. The ballots may already contain nominations previously submitted.

Polling

Near the end of the last members meeting of the year, the attending members will be asked to tender all nominations. The ballots will be updated with the nominations. Following the nominations, each member company will be asked to mark a ballot indicating their preferred candidates. Results of the balloting will be shared with the voting members prior to the end of the meeting.

Change of Status

If, during a chair's term, his/her company leaves the RPMI as a member, or the chair leaves his/her company for any reason, he/she may or may not be asked to serve out his/her term as chair. The RPMI staff, with input from the committee members and general RPMI membership, will make the final determination. If the individual does not serve out his/her entire term, we will hold a special nomination and poll to select an interim chair. An interim position will not be counted in the "consecutive terms" tally.

Committee Members

Committee members are either volunteers or recruits. Any member, faculty or student may serve on a committee. The chair will help to divide duties among the committee members. Committee members have no limit to the number of consecutive terms they may serve. In fact, long-term, active participation is strongly encour

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

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.

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.