Rapid Prototyping and Manufacturing Institute

Orchestrating the Path to RP&M's Future

A Report on the Fourth Year of the RPMI

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A Report on the Fourth Year of the RPMI

"Everyone is interested in doing more, faster, better. The RPMI is an organization that is actually making this happen - and we can show you how. We have a tremendous research program built around the idea of better utilizing technology to revolutionize engineered product realization. The best part of being RPMI Director is the opportunity to work with creative, world-class people on important, fun problems."

Dr. David Rosen
Director, RPMI

A Year of Growth and Enhancement

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 well poised to lead the way into RPM's future. In this report, we describe our accomplishments over the past year, and report on our plans for the future.

What We Do

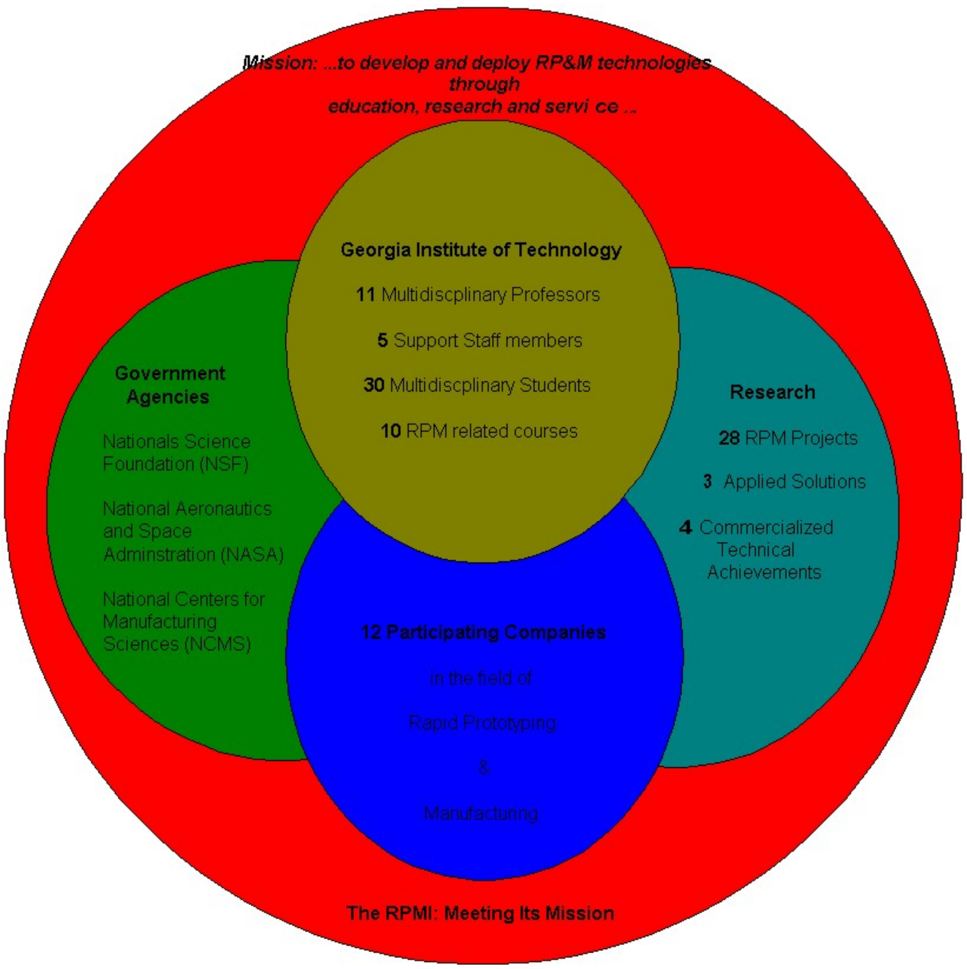
Our ***vision*** of RP&M's future includes a world where layer-based, additive fabrication technologies (e.g., rapid prototyping) are recognized as production manufacturing technologies. Our ***mission*** is to develop and deploy rapid prototyping and manufacturing technologies and applications through 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
- Alternative Applications of Stereolithography
- Other Projects (like Machining of Non-Traditional Materials for Rapid Tooling)
- Other RPMI-Related Activities (like Rapid Manufacture of Composite Structures)

Maintaining our focus has been key 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

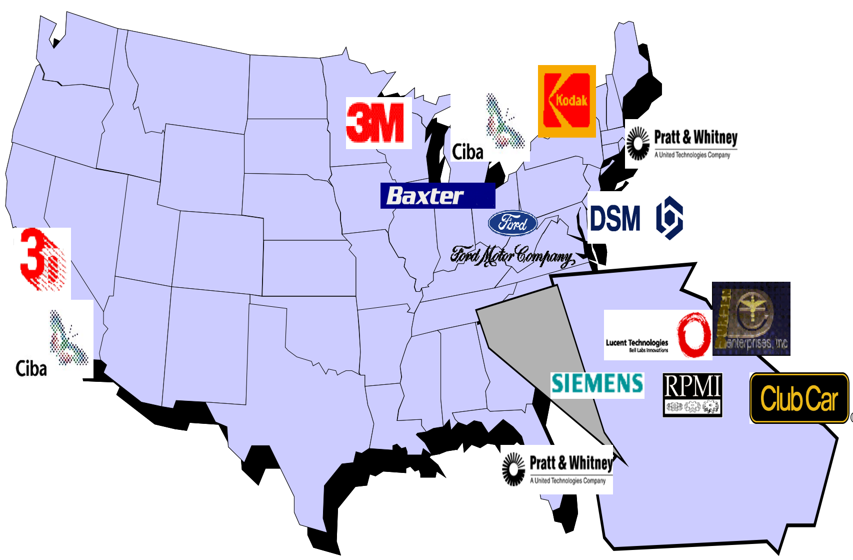
Our faculty provides the bulk of the technical know-how needed to carry out the projects. They recruit and advise the students in their individual activities. Faculty collaborates with industry representatives for a better understanding of the important issues facing the use and improvement of RP&M technologies. 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. Thirty-four 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 keep 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 and NASA Sponsors

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.

Long-standing research areas are gaining leverage from the RPMI's reputation. One example is a sponsored project involving the rapid creation of composite structures, launched in part because NASA officials heard that we were doing impressive work in RP&M. That led to their visit to the Georgia Tech's Manufacturing Research Center, which, in turn, gave us the opportunity to demonstrate how mechanical engineering faculty associated with the RPMI had the specific expertise and tools needed to attack the project.

(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.

Accomplishing Specific Goals

The RPMI has continued to make rapid progress in many areas since our last report in January 1999. In that report, we documented 25 goals for the year, and we've already met or exceeded most of them. The list of goals is repeated here along with comments regarding our performance relative to each: (January 1999 goals are in italics and denoted by a "☐" (or "☑" for goals met); results are denoted by an arrow, "⇨.")

Education

☑ *Develop RP&M short course to increase on-campus interest in RPMI.*
☐ *Publish a semi-annual newsletter based on RPMI laboratory research.*
☑ *Engage 120 students in substantive interactions in the RPMI (i.e., courses and projects.)*
☑ *Increase by 200 the number of collegiate and secondary students exposed to RP&M through lectures, lab activities, short courses and instructional site visits.*
☑ *Double the number of thesis graduates from 1998.*

Research

☑ *Identify and quantify failure mechanisms of AIM tools. Use this understanding to design better AIM tools.*
☑ *Publish four papers in refereed academic journals.*
☑ *Demonstrate new selection tools that identify RP and RT processes and materials that match desired production properties.*
☑ *Develop and demonstrate a distributed computing environment to support the Rapid Tooling TestBed. Test it internally at Georgia Tech.*
☑ *Demonstrate a model of value for RP and RT processes (Value = Benefit /Cost) and verify it using industry case studies.*
☑ *Develop and deploy three-dimensional metrology methods for RP- and RT-produced parts that gain acceptance as de facto standards.*
☑ *Demonstrate SLA process planning capabilities that combine adaptive slicing and orientation concerns with trade-offs among build time, surface finish, and accuracy.*
☑ *Identify feasible concepts for 5-axis SLA machines and evaluate these concepts for their capabilities in building smooth surfaces and building around inserts.*

Infrastructure

☑ *Begin implementation of five-year strategic plan.*
☑ *Gain international publicity for leading edge work using current lab resources.*
☐ *Fill membership to 15 companies and retain ten current member companies.*
☑ *Increase existing RP&M capabilities to state-of-the-art RP&M technologies.*
☑ *Implement and enforce a formal procedure for keeping RPMI project status, library resources and general information up to date on web site.*

Outreach

☐ *Pursue and win 3DSNASUG Excellence award.*
☑ *Create, develop, maintain and present comprehensive outreach RP&M course for technical, industrial, medical and business audiences.*
☑ *Introduce 20 Georgia-based industries to RPMI through site visits and meeting interaction.*
☐ *Teach four short courses for industry.*
☑ *Deliver six presentations at five RP conferences.*
☑ *Gain publicity for our work in six national RP, manufacturing or business publications.*
☐ *Establish a new continuing education program based on RP&M.*

Education

☑ *Develop RP&M short course to increase on-campus interest in RPMI.*

The RP&M short course was developed. However, the course has yet to be delivered to its intended audience. The Computer Integrated Manufacturing Systems (CIMS) I and II programs terminated after Fall Quarter 1998. The Manufacturing Education Program (MEP) is the successor to the CIMS program. This year we will attempt to tailor our course to meet the needs of the MEP program.

"RPMI is in a unique position to help shape the future of one of the most exciting advanced technological fields. The distinct structure here opens a gateway for exceptional students and faculty to access cutting edge technology and work on challenging real world problems. What I like best about my role here is being able to inspire and motivate people through tours, training, and other events."

Giorgos Hatzilias
Laboratory Manager, RPMI

☐ *Publish a semi-annual newsletter based on RPMI laboratory research.*

We came very close to accomplishing this goal. Our first issue of RPMI's semi-annual newsletter slated to be released in January.

The email based newsletter will help keep everyone up to date with the latest in research developments, events, and other related news.

The electronic format allows for great flexibility in content, easily shares information to a wide audience, and provides documentation through the online archives

☑ *Engage 120 students in substantive interactions in the RPMI (i.e., courses and projects.)*

We've had 45 students working in association with RPMI; 40 of these are graduate students, and 5 are undergraduate students. Graduate students have responsibility for particular projects that will be the basis for their Masters or Ph.D. thesis. Undergraduate students work in the lab on developmental activities such as tutorials and web-based information resources.

At least eight courses have had some level of RP content. We estimate that 165 students have been involved in courses this year. Courses include graduate and undergraduate ME design courses, the ME Computer-Aided Design graduate course, the CIMS graduate courses, the undergraduate ME manufacturing laboratory course, and several Industrial Design studio courses.

☑ *Increase by 200 the number of collegiate and secondary students exposed to RP&M through lectures, lab activities, short courses and instructional site visits.*

Although these are difficult to track:

We estimate that a staggering 1,980 students were exposed to RP this past year

Student experiences range from focused individual or group projects (about 542 students), to campus lectures and lab tours associated with their required or elective courses.

Students come from many disciplines, including aerospace engineering, chemical engineering, materials science and engineering, industrial design, mechanical engineering, electrical engineering, and industrial and systems engineering.

Visiting students come from many schools and academic levels throughout the Metro-Atlanta area as well as from a variety of foreign countries. An estimated 443 students visited the lab.

☑ *Double the number of thesis graduates from 1998.*

This was an ambitious goal and we achieved it! In 1998, we had five Masters students graduate. This year, we had 12-thesis students graduate, including our first Ph.D. graduate, Beth Judson. Congratulations to Beth and her advisor, Tom Starr. Other graduates included: Jessica Brown, Thomas Cedorge, Chris Franck, James Hemrick, Amy Herrmann, Sunji Jangha, Janet Kinard, Yann Lebaut, Tim Lloyd, Anne Palmer, and Aaron West.

Research

☑ *Identify and quantify failure mechanisms of AIM tools. Use this understanding to design better AIM tools.*

We have been very busy investigating AIM tools – and have the results to show for it. Rapid tooling remains our industry members' leading interest. We proposed four failure mechanisms of AIM tools: mechanical interlocking, heat effects, shrinkage stresses, and adhesion. Experiments in these areas have been performed and have yielded some definitive results. Failure has a significant fatigue component, where heat effects and shrinkage stresses cause fatigue. Mechanical interlocking due to stair steps does not appear to cause failure, while adhesion has been shown not to occur.

☑ *Publish four papers in refereed academic journals.*

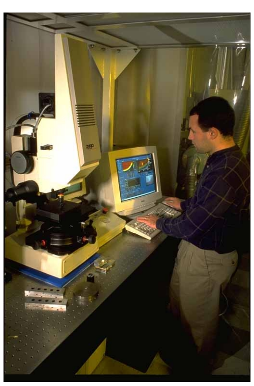
As an academic activity, scholarly publications in leading journals are critically important. In 1999, we blew away our goal by authoring nine journal papers, of which 3 have been accepted for publication, with the remainder submitted, pending acceptance.

☑ *Demonstrate new selection tools that identify RP and RT processes and materials that match desired production properties.*

A key element of the Rapid Tooling Testbed is the ability to identify promising RP and RT technologies, given a design problem. To date, we have experimented with two different selection methods: one based on typical decision-theoretic methods, and one that utilizes the model of value discussed below. In both cases, good results were obtained, leading us to believe that such decisions can be well supported by software tools.

☑ *Demonstrate a model of value for RP and RT processes (Value = Benefit /Cost) and verify it using industry case studies.*

Prototypes are not just constructed for the sake of building one; they must add value to a product development project. We have investigated several models of prototype value, based on measuring the knowledge gained by building and testing a prototype. Knowledge gained can be measured – we do this by assessing the confidence that the designer has in the design's characteristics. We have tested our models of value on 5 industrial design projects, and our results demonstrate that our models can successfully predict benefits of different prototyping technologies. Our value models have been incorporated into a web-based prototype selection decision tool.



☑ *Develop and demonstrate a distributed computing environment to support the Rapid Tooling TestBed. Test it internally at Georgia Tech.*

The Rapid Tooling Testbed has been the focus of a major research effort within the larger RPMI community. Through the first two years of a three-year National Science Foundation funded grant, several demonstrations of a distributed design and manufacturing environment have been performed. A planetary gear train was designed and prototyped using SLA, FDM, and Actua technologies. These demonstrations included internal Georgia Tech experiments as well as demos at an RPMI meeting and for NIST and other industry visitors. Progress has been achieved!

☑ *Develop and deploy three-dimensional metrology methods for RP- and RT-produced parts that gain acceptance as de facto standards.*

Our metrology work has proceeded at a rapid pace, with two Ph.D. students and one Masters student graduated. A particularly exciting development was Tom Kurfess starting a new company called Applied Metrology, Inc., which marketed inspection software. This software, including some Georgia Tech metrology technology, has been sold to a major software company and a new release of software is expected in

February 2000. Tommy Tucker has joined this major software company to aid in technology transfer. More specifics later, after all the legal proceedings are completed.

☑ *Demonstrate SLA process planning capabilities that combine adaptive slicing and orientation concerns with trade-offs among build time, surface finish, and accuracy.*
When building a part on SLA machine, sometimes a designer is interested in the best surface finish available, sometimes the most accurate part, and sometimes he just wants the part as soon as possible. Until now, it has not been possible to investigate trade-offs among such varied objectives. We have demonstrated how adaptive slicing and orientation determination can be combined with multiobjective optimization to provide the capability to investigate trade-offs among time, finish, and accuracy. This work has been integrated into the Rapid Tooling Testbed.

☑ *Identify feasible concepts for 5-axis SLA machines and evaluate these concepts for their capabilities in building smooth surfaces and building around inserts.*
It is well known in the machining area that 5-axis machine tools are much more capable than 3-axis tools in producing parts with complex shapes. Imagine what is possible if SLA and other RP technologies adopt additional axes, or degrees-of-freedom. As a key element of our long-term vision toward Rapid Manufacturing, we are exploring this possibility. We have identified several feasible concepts and recently demonstrated a working prototype of one of these. This is exciting!

Infrastructure

☑ *Develop and begin to implement a five-year strategic plan.*
Our strategic plan was met with great appreciation from our industry members. Not only is it good to know where you are going, it is important to take a leadership role, which our strategic plan enables. We successfully implemented <u>all</u> aspects of our Year 1 plans. Our new research program is making incredible progress. We acquired a SLA-3500, which positions us at the forefront of RP technology. We have a new continuing education plan. We are cooperating with Tom Starr at the University of Louisville in rapid tooling, and have a collaboration plan with Phill Dickens at DeMontfort University in Great Britain. On to Year 2!

☑ *Gain international publicity for leading edge work using current lab resources.*
We were extremely visible at home and abroad this year. On three occasions members from our group presented to international audiences. Professor Colton delivered a paper on Design Rules for SL injection molding inserts at the 32nd CIRP international Seminar on Manufacturing Systems in Leuven, Belgium in May. Thomas Cedorge delivered a paper on the same topic at the 8th European conference on RP&M in Nottingham, England in July. Kent Dawson presented his ongoing research work on the Effect of RP Tooling on Final Product Properties at the Fourth Annual Time-Compression Technologies Conference & Exhibition in October in East Midlands Conference Centre, UK.

☐ *Fill membership to 15 companies and retain ten 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 10 active companies. Our recruiting at conferences and during company visits to Georgia Tech added two additional members, Ford Motor Company and Club Car, for a total of 12 members. A number of guest companies accepted our invitation throughout the year to attend the open member meetings. A strong recruiting effort was made during the August Technology Showcase with these and other interested companies, but all of their membership decisions had to be deferred until after the first of the year.

"I decided to attend GT because of the school's good reputation, its location, and the opportunity that I had to work in the RPMI. The exposure with new technologies is what I enjoyed most about the RPMI. My RPMI experience got me started working with HTML and web-based technologies, which got me started in my current role as a leader in leveraging knowledge and collaboration technologies globally within P&G. The grounding in web technologies was the most valuable part of my project. I have used the gained knowledge as part of the foundation on which I have now built my career."

Tom Kuhn
Procter & Gamble

Systems Manager

☑ *Increase existing RP&M capabilities to state-of-the-art RP&M technologies.*

A Sanders Model Maker II (MMII) was added in June. We use this machine primarily to support student coursework. The MMII builds parts by precisely spraying layers of a waxy material from 2 "ink-jet" heads. It extrudes a small bead of wax material to build, layer-by-layer, functional prototypes directly from CAD data.

In August, our SLA-3500 arrived. This was unit is intended to support continuing research using newer solid-state laser technology and materials. Additionally, the Windows NT-based operating system allows us to take advantage of our distributed environment research.

☑ *Implement and enforce a formal procedure for keeping RPMI project status, library resources and general information up to date on web site.*

Our design and implementation project page nears completion prior to the completion of this document. The pages are linked to the RPMI homepage, and certain proprietary information is hidden and only viewable through secure access.

Our new e-mail list server allows students, faculty and members to electronically discuss project progress, share new ideas, and transfer technology much more effectively than solely relying on our meetings. Most of our communication, outside of our regular meetings, now happens via e-mail and the web site (http://rpmi.marc.gatech.edu).

Students can continually update the status of their project. This allows the web pages to stay current and members to stay informed with projects so they can help provide assistance and direction when needed.

Beginning next year, status pages can be easily accessed from anywhere via the Internet.

Outreach

☐ *Pursue and win 3DSNASUG Excellence award.*

Our efforts not withstanding, we failed to enter this year's competition. However, based on our progress thus far, next year's entry will be a major submission.

☑ *Create, develop, maintain and present comprehensive outreach RP&M course for technical, industrial, medical and business audiences.*

We presented an RP&M fundamentals seminar in Mexico City, Mexico June 4 and 5. In its first offering, we attracted 25 participants. This response indicates at least two things: 1) more and more people all over the world need to learn about RP&M, and 2) our approach to delivering the course is broadening and is well-received.

The content of this course belongs to Georgia Institute of Technology and we continue to develop its content.

Now that we have our own RP&M course and own its content, we are able to offer it more frequently for broad industry audiences, have current materials for GT students, and are prepared to deliver customized courses to meet specific industry requests.

We will deliver a custom course for Technology Training Corporation next year and have been asked to provide others for Lucent Technologies, Schlumberger and Oreck Tooling Services.

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

We visited with and introduced over 20 Georgia industry representatives to the RPMI through lab tours and recruitment contacts. Among these were Scientific Atlanta, Ross Controls, Ingersoll-Rand, Goody Products, Snapper, NEC, GTE, Hewlett-Packard, Nordson Corporation, TLC Polyform Inc., Industrial Design Associates, Caterpillar, Inc., Yamaha, CIBA Vision, John Deere, Cummins Diesel, EZGO, Makita, BellSouth Mobility, Lockheed-Martin, Rand Technologies, AMITECH, Draftech and Brown & Sharpe.

☐ *Teach four short courses for industry*

Only three courses were actually taught for industry in 1999 – two for Lucent Technologies in their Holmdel, New Jersey Learning and Naperville, Illinois Performance and Education Centers, and one for Technology Training Corporation in Mexico City, Mexico headquarters. Two more courses are scheduled with Technology Training for 2000 and one course for Lucent.

☑ *Deliver six presentations at five RP conferences.*

This has been another banner year for presentations at conferences, universities, and industry. Fourteen conference papers were presented at six different conferences, including the NASUG, ASME Design Technical Conferences, the CIRP International Seminar on Manufacturing Systems, the European Conference on Rapid Prototyping and Manufacturing, the Solid Freeform Fabrication Symposium, the Annual Meeting of the American Ceramic Society, SPE ANTEC, the NSF Design and Manufacturing Grantees Conference, SME NAMRC. All of these conferences have significant RP&M content and we are making an impact!

☐ *Gain publicity for our work in six national RP, manufacturing or business publications*

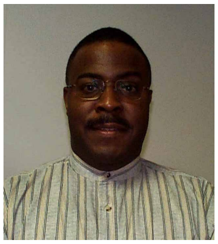
Unfortunately, only one activity made a targeted national publication. We look to improve on this short coming this year by identifying and addressing publishable quality research in the first quarter. This will enable us to get off to a faster start than last year.

Modern Mold & Tooling, December 1999 – "How do rapid tooling approaches stack up?" (an article written by Bill Durden that features research in RT at the RPMI).

☑ *Establish a new continuing education program based on RP&M.*

Our continuing education program consists of the two elements that have already been mentioned: our short course and our new Advanced RP&M Symposium. Each was carefully planned after extensively surveying industry. Through our program, we will reach a direct audience of at least 150 professionals per year, with an indirect audience much greater through a ripple effect. We are very excited by the potential impact of our education program!

Leverage



"In today's fast-paced competitive environment, industry realizes that it's not enough to possess and develop state-of-the-art RP&M technologies. You've got to be able to use them effectively. The RPMI's overall strategy involves integrating technology to match more closely to the objectives of industry through our well-defined projects. The major strengths of our program are just that. Through participation, our program is designed to provide the knowledge and skills to make this happen. The students who exit our program will be major contributors in developing and deploying future rapid prototyping and manufacturing technologies and processes."

Reginald D. Ponder
Director of Operations, RPMI

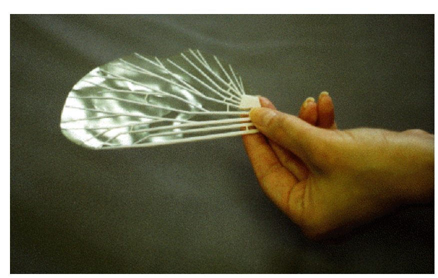
Our early successes heighten the groups' confidence. As we embark on the future trends of RP&M, our industrial application development, multidisciplinary research and deployment of educational solutions will contribute to industry advancement. The growth of RPMI's intellectual capital and the publicity surrounding its growth will promote itself. Now that we are into our fourth 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. 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, Asia and Central America. 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 accepted that new applications are often emerge from our newfound capabilities. Following are some examples of RPMI supported projects that have been making significant achievements.

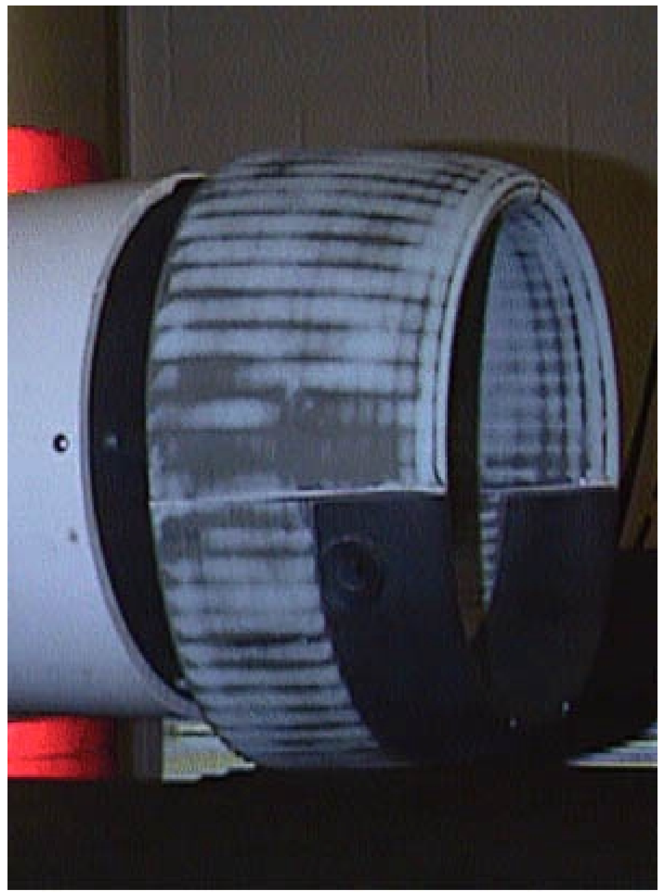
Over the years, the single most frequently cited contribution from the RPMI to industry is the GT Build Time Estimator - a software tool that estimates build times for parts produced on the SLA-250. We get emails from around the world about this tool. Most recently, we have had dozens of inquiries about its availability on the Windows PC platform. We are very pleased to announce that we have successfully ported it to Windows. The tool is available for download at no cost from our web site.

Robert Michelson of the Georgia Tech Research Institute (GTRI) is developing an electromechanical multimode (flying/crawling) insect with the help of our rapid prototyping technology. The mechanical insect, known as an "Entomopter" is based around a new development called a Reciprocating Chemical Muscle (RCM) that is capable of generating autonomic wing beating from a chemical energy source. Through direct conversion, the RCM also provides small amounts of electricity for onboard systems and further provides differential lift enhancement on the wings to achieve roll and, hence, steered flight. Stereolithography (SL) and Fused Deposition Modeling (FDM) techniques have allowed Michelson's design team to create intricate wing structures directly from computer models. Imagine an aircraft small enough to fit in the palm of your hand, yet able to fly into damaged buildings to search for survivors or onto battlefields to detect toxic chemicals, not to mention the limitless uses a small undetected flying "bug" would present for the intelligence community. The work has been featured in numerous publications, popular magazines, and television programs.



A new biomedical material used in cartilage replacement has benefited from some of the fabrication techniques used in the RPMI. Researchers are able to construct casting molds and dies from medical MRI (Magnetic Resonance Imaging) scans of actual human patients. The ability to fabricate the complex geometries found in nature quickly and to easily modify and iteratively revise the designs helps make the new developments feasible.

Building on the success of our earlier work with Aerospace molding techniques, Georgia Tech Research Institute AERO lab has several projects on going to produce synthetic jets and models of jet engine components. The fast turn around time of the process allows them to go through several iterations of scaled model designs in the time it would take to make one conventionally machined mockup. The knowledge gained here is of great value in the development of investment engine components in the shortest amount of time.



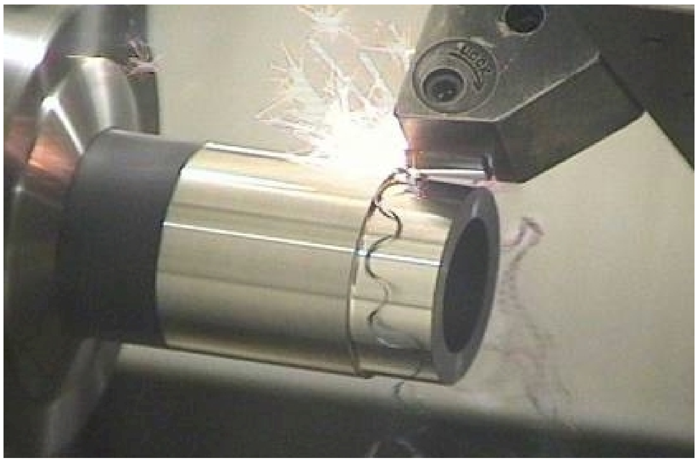
The entire model, pitot rake, and inlet plenum chambers were segmented and fabricated into six builds. After some initial testing, the AERO lab was able to determine a need to make another plenum chamber with a 30 degree arced slot. This would be the size of two of the previous plenum chambers. Benching time was minimized a lot through the use of SL. By utilizing the RPMI lab facilities, the AERO lab was able to save an enormous amount of time and cost.

Future projects with the AERO lab required construction of highly detailed, very complex models of micro aircraft at actual scale (less than 2 inches). In order to construct such highly detailed models, AERO lab desires access to higher resolution SL technologies. SL seems to be a natural method for rapid construction of such micro-aircraft models given the required detail resolution. In concept these models will be nearly impossible to produce by any means other than an additive construction process, due to the incorporation of complex internal ductwork and micro scale.

This year, our history of achieving unparalleled accomplishments has earned us the honor of being entrusted to accommodate the National Center for Manufacturing Sciences' bi-annual "Industrial Roadmap for the Rapid Prototyping Industry", one of the industry's most highly regarded documents. The report has proven to be one of the most accurate and well respected predictors and RP & M guidebooks of our evolving industry. Our newfound affiliation with the NCMS Rapid Prototyping Technology Advancement project (NCMS-RPTA) made this possible. The RPMI and RPTA are cooperative affiliates working together to advance the use and development of RP technologies through collaborations among RP users and technology suppliers. The roadmap serves a multitude of manufacturing organizations as an indispensable tool for strategic planning of R&D and technology investments. Now, that's 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. Continuing the theme of ensuring value in RP, RT, and RM activities, two faculty (Nagesh Murthy in Management and David Rosen in ME) and their students teamed up to conduct an extensive best practices benchmarking survey. Bill Griffin and Atul Mandal (MGT), along with Chris Franck (ME), assisted with a lot of the groundwork, conducting early surveys and in-depth interviews of industrial RP&M experiences. This project has been so successful that SME has become a partner, sponsoring some of the survey mailings and lending their name as a survey supporter. That is leverage!



Machining has long been recognized as a rapid prototyping technology, but only if used carefully. We are leveraging an ongoing, state-of-the-art research activity in the Precision Machining Research Center at Georgia Tech to investigate the usage of machining as a rapid tooling technology. Faculty members Shreyes Melkote, Steven Liang, and Jon Colton are collaborating with Ciba Specialty Chemicals on a study of Ciba tooling board machinability and the subsequent injection molding. This type of leverage can only occur after organizations have successful track records. This is a great example of leverage and cooperation that we hope to continue.

The Industrial Design faculty and students are included in the five disciplines involved in RPMI laboratory activities. Industrial Design students have accomplished a variety of projects ranging from individual to group efforts since we opened in 1995.

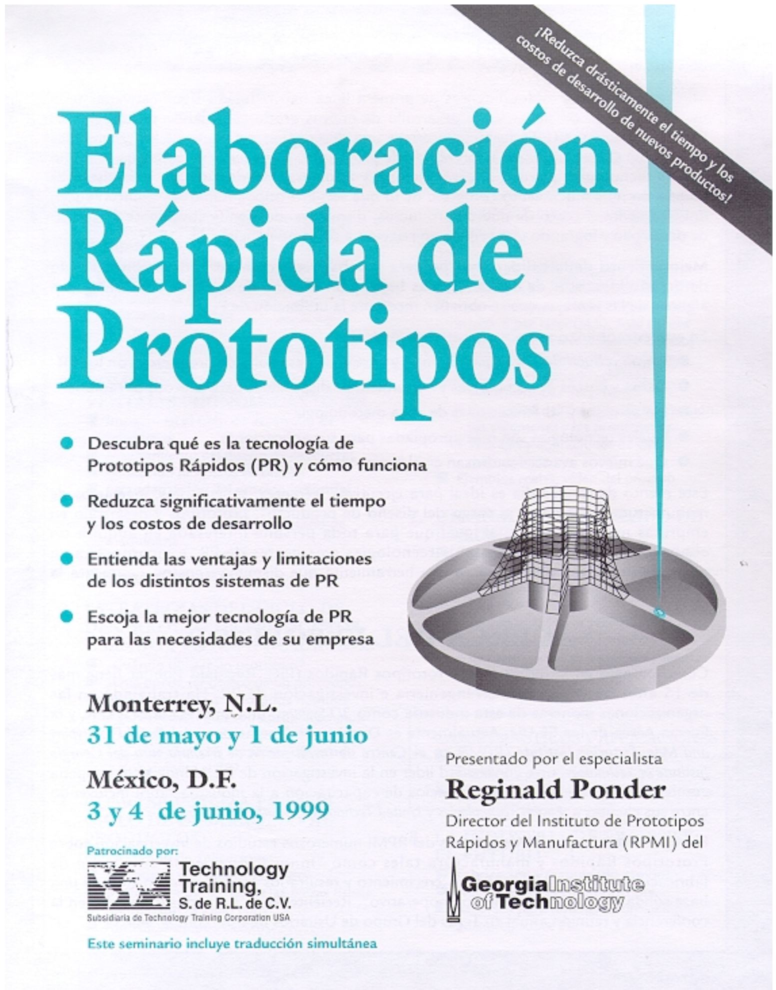
Project deliverables have included: product innovation, product interface and packaging, product visualization, potential customer/user analysis, competition analysis, global market research and business assessment, market gap analysis and trends, emerging materials and technology studies, competitive product analysis, technical performance assessment, rapid prototypes, product system analysis and product and systems animation. Recent research sponsors include corporations such as The Coca-Cola Company, Intergraph, Dell, Murray Bicycle, Xerox (Liveworks), Kawneer (Alumax), BioLab and Rheem.

Deploying Solutions into Education

We mentioned the successful deployment of our RP&M fundamentals course for Lucent and two-day RP seminar for Technology Training Corporation in the Accomplished Goals section. A short course for Lucent Technologies and a two-day seminar provided for multi-industry participants are two examples of solutions in educational deployment for this year. We delivered two SME/RPA content courses on RP&M fundamentals for the third and fourth times in June and September 1999 to Lucent.

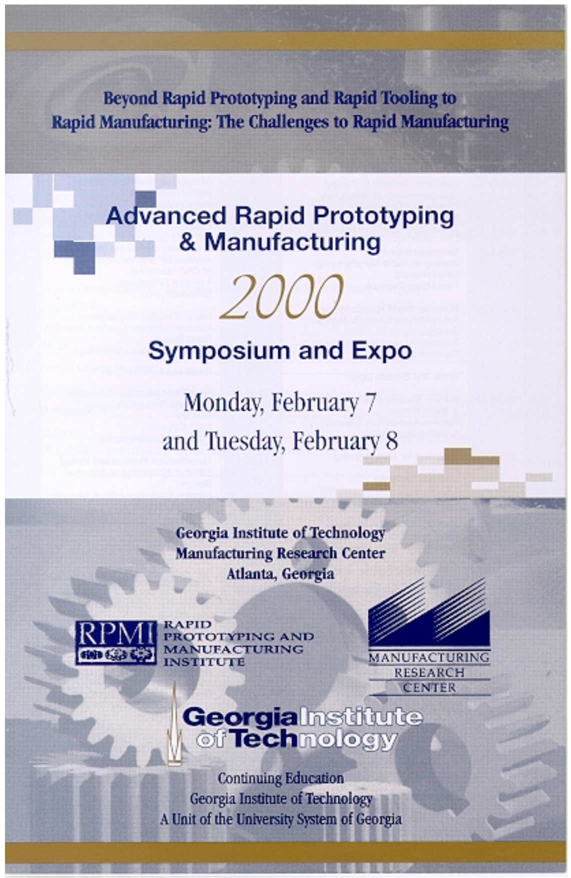
We own the content for the RP seminar and are able to offer the seminar more frequently for broad industry audiences, have current materials for GT students, and are prepared to deliver customized courses to meet specific industry requests. We are not limited to national organizations with our RP educational programs. We delivered an RP seminar in Mexico

City, Mexico in June. For its first offerings, we attracted 20 participants from prominent Mexican manufacturing organizations. There were representatives from Volkswagen, Evenflo, Siemens, and Hewlett-Packard among the audience. Georgia Tech was especially well received and feedback on this course was extraordinarily positive.



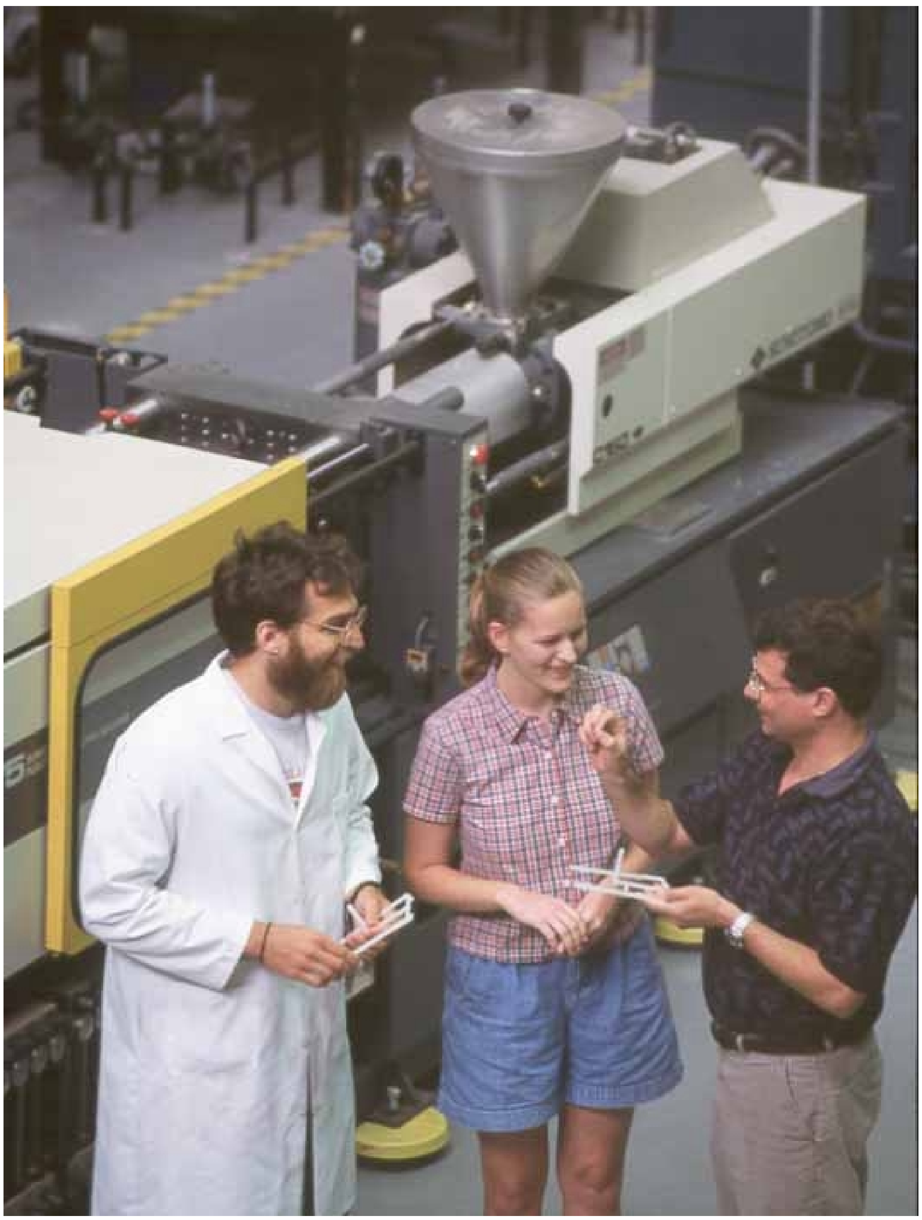
We hosted a technology showcase in August that attracted over 40 southeastern industry observers. Our seven invited presenters captivated the audience with newly developed prototypical technologies and processes.

A final example is our Advanced RP&M 2000: Symposium and Expo that is scheduled for early February next year. We anticipate reaching over one hundred and fifty interested participants who will gain knowledge in areas of rapid manufacturing, layered-based manufacturing technologies and visualizations tools. Additionally, invited exhibitors will display hardware, software and materials being slated for RP&M's future.



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 surface finish and machining have begun.



Project Overview Table

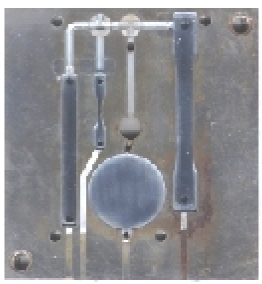
Current RPMI & Proposed Projects	Students	Faculty	Industry/Govt
Tooling Life			
Effect of RP Tooling on Final Product Properties	Kent Dawson	John Muzzy	C. Hull, B. Durden, S. Jayanthi
Experimental Methodology for Rapid Tooling	Vincent Rodet, Giang Pham	Jon Colton	Neil Enke, D. Feindel, L. Whitaker, G. Beldue, J. Malluck, C. Hull
Shrinkage - Compressive Failure	Ricardo Niedermeyer	Reggie Ponder	B. Durden
Molding in Machined Tooling Board	Efe Arkayin	Steven Liang	M. Kotnis, D. Moulton
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
Closed Loop Control of SLA-250/50	No student	Giorgos Hatzilias	
Heat Transfer Engineering & Evaluation	Alan P. Martin Steve Hoffman	John Muzzy	R. Pressley, M. Bellotti
Rapid Inspection and CAV			
New Method for Freeform Surface Registration	Tommy Tucker	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
Smooth SLA Surfaces			
Surface Coatings	Open	John Muzzy	C. Hull
RP&M Within Product Realization			
Best Practices Survey	Atul Mandal	Nagesh Murthy	D. Daruwala, J. Malluck
Rapid Tooling Testbed			NSF
Material & Process Selection	Marco Fernandez	Janet Allen	
RP Process Planning, Tool Design	Yong Chen, Shiva Prasad	David Rosen	
Ejection Mechanism Design	Sunji Jangha	David Rosen	
Tool Design Rules	Joe Crawford	Jon Colton	
Point-To-Surface Assignment During Registration	Andre Claudet	Tom Kurfess	
Metal Powder Injection Molding	UofL student	Tom Starr	
Distributed Computing Environment	J. Gerhard, A. Xiao, A. Gavrilovska, Yuan Chen	Farrokh Mistree, Karsten Schwan	
Other RPMI-Related Activities:			
Machining of Tooling Boards	Ruben Lanz	Shreyes Melkote	M. Kotnis
Laser Chemical Vapor Deposition	C. Duty, D. Jean, B. Furman	Jack Lackey	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 two polystyrene stereoisomers were compared and molded in three types of tools: H13 steel, specialized composite, and backfilled stereolithography (SL) tools.



Kent Dawson, a Ph.D. student in Chemical Engineering, is leading this investigation and is supervised by John Muzzy. When molded in backfilled SL and composite molds, both isomers exhibited an average of 17% lower ultimate tensile stress, comparable Young's modulus, and 20% lower ultimate elongation than parts produced from a steel mold. 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 also were found to be correlated. In flexural testing, both isomers produced in the composite mold exhibited an average of 19% higher flexural strength, 39% higher flexural modulus, and 27% lower ultimate flexural elongation than parts produced in the steel mold. Unlike the tensile tests, these differences were attributed to the increased degree of perfection on the surfaces 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 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.

Future work will attempt to predict the mechanical properties of certain injection-molded materials as a function of the mold material and molding conditions. New techniques, methods and materials will be used to exceed the material and thermal properties of current rapid molds, reducing the mechanical property differences between prototype and production parts. Additionally, the mechanical properties of more sensitive and industrially relevant polymers will be tested and compared. 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. We hypothesize that four failure mechanisms predominate: part shrinkage onto the core, thermal cycling of the mold, mechanical interlocking of the part and mold due to stair-stepping, and flow failure during injection.

Jon Colton is leading this project. Three Masters students completed their theses in 1999: Anne Palmer, Thomas Cedorge, and Yann Lebaut. The primary objectives of their work included investigating: geometric aspects that establish guidelines for geometric limits on feature sizes and ratios, surface roughness aspects leading to mechanical interlocking, and thermal aspects for quantifying mold shrinkage and evolution of cure during molding. These students demonstrated that SLA tools fail primarily due to thermal cycling, part shrinkage, and flow failures. In fact, it appears that pull-out failure exhibits a mechanical/thermal fatigue behavior based on a combination of thermal and shrinkage effects. These results are critically important since they explain what others have been experimentally observing, and bring some 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.

"Working at the RPMI provided exposure to advanced design tools and techniques. Communication with member companies showed me how they were being used to solve real world design problems. My experience has enabled me to make better design decisions."

Brian VanHiel
Mechanical Engineer

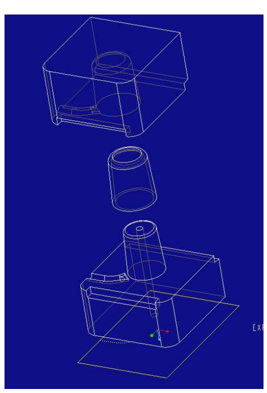
Nordson Corportation

Based on these successes, this project continues into 2000 with a new group of three students, Joe Crawford, Giang Pham, and Vincent Rodet. Their main objectives are to: computationally model ejection and pull-out failures, computationally model the injection process to better predict flow failures, experimentally study ejection timing issues. Ultimately, they plan to develop a standard test procedure that can be applied to new mold materials, tool designs, and part materials.

Shrinkage-Compressive Failure

Several research projects involving SL tool life are ongoing. Each focuses on understanding failure modes of SL injection molds by investigating many variables to predict tool life. The approach taken in this particular project requires shooting injection molded parts, in ABS and/or polystyrene, using SL mold inserts built out of four different SL resins in one simple cylinder geometry. The cylinder has four different diameters, depths and draft angles. The parting line is the plane of the core. The two four SL materials are SL7510 and Somos 7110. Additionally, SL5190 and SL5510 molds will be evaluated early next year.

In an effort to better understand SL tool failure, several mold inserts of each resin will be built and run until failure occurs. Using statistical analysis, average tool life for four SL materials tested will be determined as follows: 1) Test SL molds to find average life and standard deviation. 2) Apply regression analysis to data to determine average life vs. yield strength at ejection temperature in a direction perpendicular to layered plane to establish working curve. 3) Use working curve to map a selected SL material to a desired tool life using test geometry. 4) Correlate test geometry results to various SL tool test geometry to quantify factors used.



The part was designed as a test part to verify past and present SL tooling mold design rules and techniques being utilized at GT and within the great RT community. The cylinder has four different diameters, depths and draft angles.

To date using two solid SL molds in (Somos7110 and SL7510 material) produced the mixed results. Some preliminary results seem to suggest that shrinkage of SL mold inserts is greater than that of ABS and polystyrene injection molded parts. Additional experiments are being conducted to verify this finding. Revision of SL mold design will be relevant if these findings are proven.

Ricardo's responsibilities include being the resident Morgan Press "guru," helping other students learn how to use the machine and get trained in rapid tooling methods. He is conducting this project, under the supervision of Reggie Ponder and with the assistance of Giorgos Hatzilias. Future solid SL injection mold work will involve investigation of the following: determining ejection forces of undercuts, build style and SL material effects on tool failure, study of quick vs. slow ejection in a model material

"My research was valuable to me because I was able to work on a "real-world" problem. We had access to state-of-the-art technologies and received thorough training on this fabulous equipment. The meetings with the members allowed collaboration and insight as to how these technologies are used in a wide variety of industries. My graduate experience was very well-rounded and applied in comparison to other graduate students that worked on other projects in Materials Science."

Elizabeth A. Judson
Applied Ceramics

Project Manager

Tooling Board

Recent industry reports have demonstrated the general viability of rapid tool development for injection molding/forming via high speed machining of composite tooling board materials (e.g., Renshape® 2000 Express). Case studies have shown that this material is relatively easy to machine, yields good finish, and that 200-400 plastic parts can be shot in the tool before it exhibits appreciable wear. This project proposes to systematically study and identify the different types surface/sub-surface damage induced in the tooling board material by high speed machining, quantify the impact of the damage on the life of the rapid tool, and establish optimal cutting conditions to minimize the damage. A new student, Efe Arkayin, has started working on this project, advised by Steven Liang. We welcome Steven as a new RPMI faculty. This team will work closely with Shreyes Melkote and Ruben Lanz on tooling board machining (see page 27), and will coordinate with Jon Colton and students on the injection molding side.

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.

New method for Freeform Surface Registration and Metrology and Reverse Engineering Capabilities

These projects, supervised by Tom Kurfess, 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. Significant developments to date include:

- Least squares best fit registration methods to localize the measurement coordinate frame to the design coordinate frame for a range of geometric surfaces, including planes, conics, and even sculpted surfaces described by NURBS,
- Data reduction methods to reduce the analysis cycle times for the copious data generated by scanning equipment (rather than touch probe equipment),
- New point-to-surface assignment methods that drastically reduce the complexity of the least-squares best-fit registration methods, and
- Methods for recognizing patterns in scan data, such as common surface types (planes, conics, etc.) that aid data reduction and registration tasks.

Tommy Tucker and Andre Claudet are two Ph.D. students researching these topics. Tim Lloyd, a Masters student who graduated in spring 1999, developed new methods for recognizing patterns in scan data. As Tommy and Andre complete their Ph.D.'s, we can expect significant, new metrology methods and codes that promise to outperform leading commercial codes! Assisting them beginning this year is James Nichols, a new Masters student. His work will involve a benchmarking study of commercial metrology and reverse engineering codes.

In fact, a particularly exciting development is the formation of a new inspection company, called Applied Metrology, Inc., that was spun off from Georgia Tech by Tom Kurfess. Look for a major announcement regarding Applied Metrology's software products in early 2000.

"My experience with the RPMI has been a very enriching one. I think that one of the key benefits of a group like the RPMI is the practicality of the research problems. For instance, my particular project was created to fill a need from some of the member companies. This realism serves two purposes. For the member company, it provides a solution to a problem that they may not have time to thoroughly investigate. For me, it affords the opportunity to connect academic research to industrial problems yielding an increased understanding of the nature of problem solving in the 'real-world'."

Sunji Jangha
GRA, RPMI

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 new graduate student who will start on this project, 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.

Dimensional Accuracy in Rapid Prototyping of Ceramics using Injection Molding

A new method of ceramic prototyping has been derived from traditional low-pressure ceramic powder injection molding and solid epoxy tooling produced overnight by stereolithography. By combining these technologies, it is possible to produce functional ceramic prototypes in one week, avoiding the long lead-times and high costs of traditional tooling for ceramic molding. However, a significant challenge arises in ceramic molding – that of large, anisotropic shrinkage.

Beth Judson worked with her advisor, Tom Starr, to address the part dimensional problems that result from large shrinkages. The result of not accounting for anisotropic shrinkage is the inaccurate prediction of final dimensions. In ceramic injection molding this problem is magnified when compared to plastic injection molding because the shrinkage is an order of magnitude higher. Beth's research identified three processes and mold design factors that influence the final geometry: the powder loading factor in the feedstock material, the mold opening direction and the mold fill pattern. Initially identified using an alumina ceramic system, these factors have been confirmed with a second material - zirconia ceramic. Results from this work are summarized below:

1. When the part had isotropic geometry and gating, the shrinkage was more isotropic.
2. Shrinkage was higher in directions normal to flow than in the flow direction, and shrinkage in the flow direction (length shrinkage) decreased as the flow length increased:
   - For alumina, length shrinkage was 9.4% for short flows, 8% for long flows
   - For zirconia, length shrinkage was 15% for short flow lengths, 14.5% for long lengths.
3. Dimensional accuracy was improved by gating in the center of the part. Similarly, center gating reduces variations in accuracy.
4. The thickness and width shrinkage were consistent along the length of the part, and did not show significant anisotropy.

A generalized anisotropic shrinkage model has been developed based on these results. Furthermore, this model is independent of material type, enabling it to be applied to other ceramics, and even to metal powder injection molding. Beth graduated with her Ph.D. in May. We hope to continue this project with a new student in the near future.

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.

Assessing RP/RT Usefulness in Product Development

Rapid prototyping is a key factor in reducing the cost and time to market associated with new product development. This means that design flaws can be detected, corrected and the new design tested again much faster than was previously possible. Unfortunately a lot of the time and cost savings associated with RP are often lost due to the use of processes that are incompatible with the type of information needed by the designer at any given point in the product development process. A common example is using a relatively expensive SLA model to check the overall form of a proposed design when a concept model costing much less and built in a fraction of the time would have provided the necessary information.

The goal of this research is to improve the selection of prototyping techniques to reduce the costs and cycle times associated with product development processes. Chris Franck, as part of his Masters work advised by David Rosen, has proposed three measures of ***value*** associated with rapid prototyping technologies. By quantifying the value of various prototyping technologies for at particular stage in a design process, the idea is that the designer can make a better choice among these technologies. **Value** is defined as a comparison of the **benefit** (the amount of useful information generated) and the **cost** (resources used) associated with creating the prototype.

The major result is the completion of these value models and the embodiment of a selection decision method in a web-based software tool. Four case studies were performed at RPMI member companies (NCR, Kodak, Lucent, and 3M) to verify the usefulness of the value model and software tool. In all cases, our value model provides guidance on selecting prototyping technologies that was at least as good as that actually used in the companies. This is a promising result indeed! Certainly, we have not captured all aspects of rapid prototyping, but we have shown that with a modest amount of information on technologies and design requirements, good guidance can be provided on selecting appropriate technologies. The web-based selection tool will be posted to our web page.

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 are researching different methods through literature search and site visits to RPMI member companies. A comprehensive survey has begun of RP and RT technology usage in Fortune 500 companies and selected smaller companies. Surveys for both engineers and managers have been prepared. A particularly noteworthy accomplishment is the cooperation and endorsement of SME in this survey. After completion of the survey, a comprehensive report will be compiled on RP/RT technology usage, highlighted with case study and backed up with extensive data. We hope that with SME's cooperation, this report will be widely disseminated.

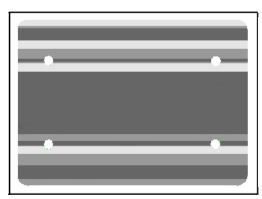
Rapid Tooling Testbed

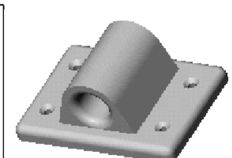
The product realization process, driven by market factors, is changing dramatically. Increased competition is forcing product realization to become faster, enabling shorter time to market. At the same time, globalization, core-competencies, outsourcing, etc. are changing the structure of the product 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 are now two years into this project; progress has been terrific!

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.

A tremendous amount has been accomplished in the first two years of this project. Present work is focused on three primary decisions, resource selection, mold design, and fabrication process design, and on information modeling to support those decisions. A new selection decision formulation has been developed to match target values of attributes, which is necessary when trying to select materials and RP/RT processes that will yield production representative parts. This new formulation will be used for resource selection. Amy Herrmann led this work and recently graduated with her Masters degree. Marco Fernandez is a new graduate student who will continue Amy's work.





SLA rapid tools act differently from conventional steel tools and must be designed somewhat differently. Based on Kent Dawson and Anne Palmer's work in rapid tooling, a set of mold design rules are 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. Under Fabrication Process Design, Aaron West developed a method for selecting favorable values of SLA process variables to achieve build goals of accuracy, surface finish, and build time. He graduated in Spring 1999. The CAD models on this page show results from his work.

Tool Design Rules

Jon Colton is leading this research thrust. The goal is to characterize polymer injection molding in support of the molding process design activity. We will use this knowledge to develop a set of rules that designers can use when designing SLA mold inserts, to assure that they will produce a specific number of quality parts (e.g., 50) without damage to the mold.

A prerequisite for good experimental studies is state-of-the-art experimental equipment. Thanks to the good work of Anne Palmer, the graduate student conducting the experiments, we now have an insert mold base with flexible cavity size and ejector pin pattern, and with a data acquisition system integrated with transducers for indirect cavity pressure measurement, in-cavity melt temperature, screw position and velocity, and hydraulic pressure.

The two major types of experimental mold inserts focused on this year were a multi-feature insert and a single feature insert. The multi-feature inserts were used to determine major trends in the stereolithography tooling process. A variety of draft angles, aspect ratios, and height ratios were explored. The single feature inserts were used to examine the process on a more detailed level. Here, the project has been split into three major areas consisting of thermal, surface roughness, and geometrical aspects. With the single feature, some of the confounding data can be eliminated from certain aspects of the experiments. This single feature was a rib of the mold material that forms a v-shaped plastic part. Resulting mold design and process rules are summarized in the table below.

Experiment	Factor	How to Produce a Greater Number of Parts Before Failure of a Feature
Multiple Feature: Draft Angle	Draft Angle	Larger draft angles.
	Processing Conditions	Lower injection velocities.
Multiple Feature: Ratio and Angle	Height Ratio	Smaller height ratios.
	Aspect Ratio	Inconclusive findings.
	Draft Angle	Larger draft angles.
Individual: Feature	Height Ratio	Smaller height ratios.
	Aspect Ratio	Inconclusive findings.
Individual: Draft Angle	Draft Angle	Larger draft angles.

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.

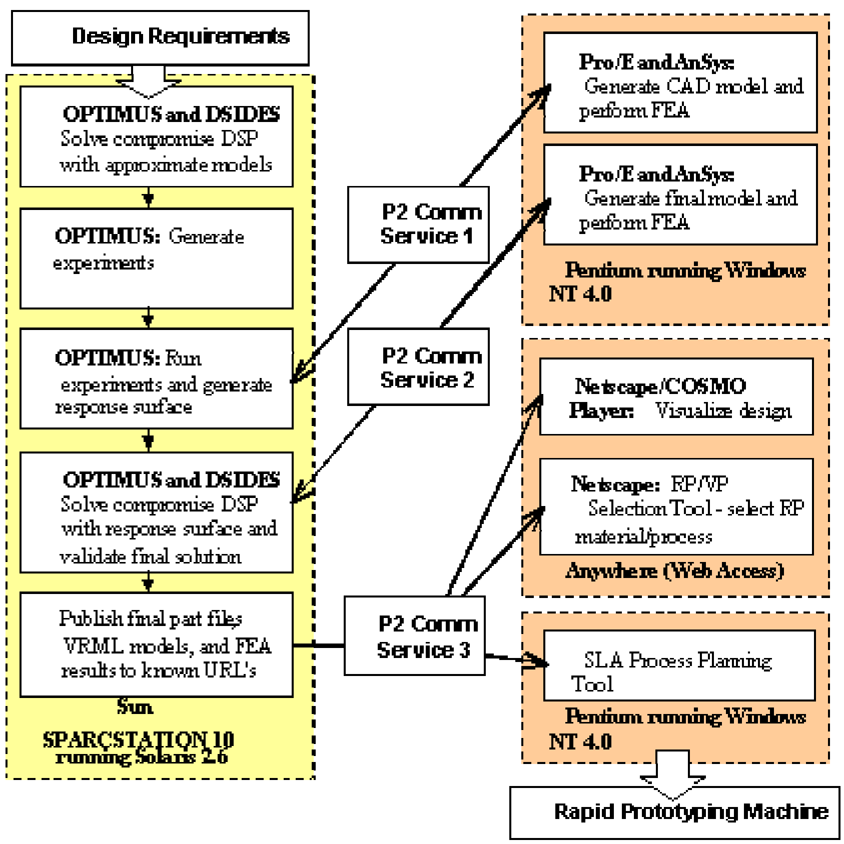
Determining whether an SLA machine can meet a set of tolerances on a part is often difficult. To achieve a set of tolerances as closely as possible, relationships between part geometry, tolerances, and process variables must be understood quantitatively. We have developed an empirical model for SLA accuracy, 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. For stainless steel powders, the part seems to de-bond from the mold easily. However, closer examination reveals a thin layer of mix 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-set 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.

Distributed Computing Environment

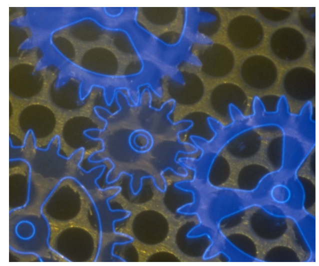
The goal is to develop the distributed computing environment that enables the RTTB to function across the web. As required by the NSF Initiative, the RTTB must support distributed design and fabrication. It should be possible to search for materials and manufacturing processes on the web. Designers in 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, and applying the Sandia PRE system. PRE provides a platform and operating system independent communications framework for enterprise integration and product realization. The PRE framework defines common data and application interfaces to enable rapid and easy integration of distributed tools, which in turn makes stand-alone software tools reusable components. The framework provides a set of core services that enable wrappers to be written for distributed computing: a service to create and manage data objects, a distributed file manager, a conversion broker, a registration and location service, and a security service. The latest version of PRE is being developed using Java-RMI. Farrokh Mistree leads this effort.

The College of Computing Distributed Labs work, led by Richard Fujimoto and Karsten Schwan, focuses on high performance distributed computations. Several technologies will be developed 1) Foundations, Shared Event Formats, and Objects. 2) Distributed Architecture Managers: we will develop mechanisms that support the creation and management of the environment at cooperating locations and of specific processes performed at those locations so that design, planning, and fabrication components can be "plugged in" and jointly executed easily. 3) Distributed Optimization and Fabrication Architectures: we will develop a framework for the establishment, management, and growth of distributed optimization and fabrication by applying these distributed simulation technologies. We are currently experimenting with distributed finite element analysis across a network of PC's using the COC distributed environment.

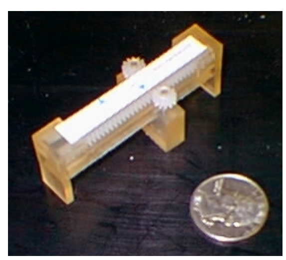
Alternate Applications of Stereolithography

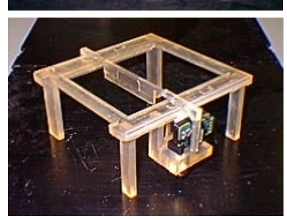


Overall, this project area is concerned with extending the suite of applications of SLA machines, particularly in the fabrication of functional assemblies and mechanisms. In short, it is our contribution to the emergence of rapid manufacturing. A major motivating factor is the growing realization that the future success of layer-based fabrication processes is for applications that take advantage of the unique capability of these layer-based technologies. 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.

In order to achieve functional assembly fabrication and smooth surfaces, the SLA machines themselves will require additional functionality. We will investigate the use of additional degrees of freedom in the operation of SLA machines, working up to 5-axes of motion. If successful, such a result brings us much closer to our long-term objective of *rapid manufacturing*. All of the projects under this Alternative Application heading are being run as one large project. The project began in October 1998. See the web page: http://rpmi.marc.gatech.edu/project.

Building Around Inserts





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, with his advisor David Rosen, is leading the investigation into these issues. Many difficult issues arise 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,

"What I most enjoyed about my research in the RPMI was the opportunity to use cutting edge technology in an environment that drew from both the academic and industrial expertise present at Georgia Tech. This experience not only sharpened my research and presentation skills, but also developed my project and time management abilities. These are all qualities I am still benefiting from in my career with Schlumberger."

Joel McClurkin
Project Engineer

Schlumberger

and methods to recoat the SLA vat with inserts sticking above the resin surface. Alok is currently developing an SLA simulation environment for testing building-around-inserts concepts. Shown in photos on the previous page are several devices that have been fabricated in our SLA-250 by building around inserts. The ultimate product to be built in this manner is a working model of an SLA-250. We are finalizing its design as this Report goes to press. We are planning to build an SLA-250 model in one build of our SLA-250, with about 20 inserts ranging from gears to electric motors to printed circuit boards to optics devices, including a laser and galvanometer. Look for an update on this project on our web page: http://rpmi.marc.gatech.edu/projects.

"Rapid Prototyping is actually an additive fabrication (AF) process, limited only by the materials available and our imaginations. By leveraging the RPMI resources, we are learning how to best apply AF to meet 3M needs."

Larry Whitaker
Engineering Specialist

3M

5-Axis SLA

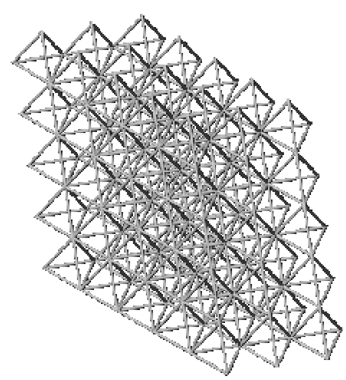
In order to achieve functional assembly fabrication and smooth surfaces, SLA machines will require additional functionality. We are investigating the use of additional degrees of freedom in the operation of SLA machines, investigating 5-axis of motion or more. Conventional RP machines have three degrees 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 are being taken to provide additional DOF's. The first involves modifying the mechanical subsystem to provide platform motions beyond simple elevation. The second involves adding additional capabilities to the optics system.

Tom Kurfess, Imme Ebert-Uphoff, and David Rosen are supervising this project. Imme and her student, Brad Geving, are investigating alternative mechanical and optical subsystem configurations. Tom Kurfess and Chad Moore, a Masters student working with Tom, are focusing on the development of a suitable machine controller. Alok Kataria is also involved in this project, contributing process-planning methods for our machine designs.

The group has settled on SLA machine design with eight DOF's, having added two galvanometers for additional capability in the optics subsystem, with these galvanometers mounted on a XYZ gantry robot. A prototype machine was demonstrated in Fall 1999, which was capable of drawing laser strokes on the gantry robot's metal base. Basically, the machine is undergoing tests and calibrations; we are not concerned at present with actually solidifying SLA resin, we are testing out the machine's kinematics, errors, and controls. But this is a tremendous success for such a short time frame. In 2000, we intend to complete tests of the machine's capabilities for accuracy, controllability, and ability to draw around inserts. Updates and animations will be posted on our web page as successes are achieved.

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? Investigating potentially promising applications is the purpose of this project. We are identifying the unique capabilities of layer-based, additive fabrication technologies. Then, we want to identify 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. David and Vincent, a new graduate student, are investigating the usage of truss structures to design structures with very high stiffness-to-weight ratios. A high-speed robot arm is the potential application. Different truss elements, and various ways of combining them, serve as our design primitives. While rigid structures are interesting, things get particularly exciting when these structures are intended to move. This is the second aspect of the project: miniature robot arms composed of modified "trusses" that are intended to have small deflections under control signals. Imme and Jacob, another new graduate student, are investigating these compliant trusses for use as miniature, flexible robots. We envision building both rigid and compliant trusses with embedded actuators and sensors using our abilities to build around inserts.

"My graduate experience at Georgia Tech is fully complemented by the great opportunity I had to interact with knowledgeable faculty, students and industry members through the RPMI. This made the learning process a lot more challenging and fulfilling and helped me get an all-around perspective of the various fields of my interest."

Ruben Lanz
GRA, RPMI

Closed Loop Control of SLA

While Stereolithography is mature, it still remains an open loop system. By open loop, we mean that the SLA continues to build, without knowing how well it is actually performing. By "closing the loop" the SLA would be able to monitor and control the process in real time. This would uncover new SL capabilities while at the same time refine existing ones. With on-demand knowledge of process parameters like degree of cure, stiffness, thickness, and layer bond strength, newer generations of SLA's could potentially optimize laser scan speeds, laser power, layer thickness, depth of cure, and critical exposure.

Various non-contact measurements are being investigated by Giorgos Hatzilias to explore the feasibility of such a technique. The project's preliminary feasibility study was given the initiated with the goal of uncovering sufficient work worthy of a student project.

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. Experimentation will test heat transfer using SL models to determine correlation of data between SL 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 is affected by the following factors:

- Build orientation
- SL resin type
- Part thickness

Joint co-op students Alan Martin and Steven Hoffman will be co-supervised by Professor John Muzzy and Reggie Ponder.

Smooth SLA Surfaces

Surface Coatings

Prototypes produced by stereolithography (SL) have "stair-step" surfaces as a result of the layered SL build process. This pattern leads to a rough surface that reduces the utility of the SLA prototype. To counteract this surface roughness, one idea is to somehow fill in the spaces between stair steps using a liquid or powder coating. A subsequent post-processing step could be used to coat a SLA part, and then process that coating. Powder coating provides a means for adding polymer similar to the SLA substrate. Electrostatics can temporarily hold the powder coating on the surface until the coating melts and wets the surface. This liquid resin should preferentially fill in the "stair steps", thereby smoothing the surface. In addition, a second material system, liquid UV coatings, will also be investigated. John Muzzy is supervising this project. We are attempting to identify and hire a student for this project.

Other RPMI Related Activities

Machining of Tooling Boards

In contrast to SLA based rapid tooling approaches, high speed machining is often used to fabricate tools for short runs or for prototype parts. This project will investigate the machinability characteristics of CIBA tooling board materials, specifically the CIBA-Express epoxy tooling board materials. Since these materials can machine faster than aluminum, they hold tremendous promise for rapid tooling applications where speed is critical.

Shreyes Melkote and his student Ruben Lanz are taking the lead on this project. The objectives of this project are to:

- Develop an understanding of how process conditions and tool-related factors (geometry, wear) affect machining.
- Investigate the effect of material properties on machining, particularly the glass transition temperature of the tooling board.
- Compare and contrast with CNC machining of aluminum tooling.
- Investigate the life of injection molded tools machined from tooling board by studying subsurface characteristics, particularly damage caused by machining, and their relationships to tool failures.

Rapid Manufacture of Composite Structures

NASA has sponsored a first phase of work to investigate the feasibility of creating new methods for building large composite structures more quickly than current methods allow. Long lead times and high labor contents characterize current composite manufacturing processes. This makes it difficult to produce parts quickly. Jon Colton led this research to develop the science underlying the rapid production of composite structures. This scientific understanding will be reduced to practice in a demonstration device that will produce a part on the order of 12" by 12" by 12".

The developed machine system builds a part layer by layer with continuous curing and consolidation, making traditional curing methods unnecessary. Each part layer, which has been prestaged to provide a desired degree of cure, moves under a heat gun and a roller for curing and consolidation. The heat gun initiates the cure in the part layer, partially curing it and making it tacky enough for the next layer to stick to it. The cure continues to advance as each layer is placed. Testing was performed by fabricating three-layer parts and performing tests on single strips of towpreg to determine how temperature and time affect the degree of cure. The material was IM7 carbon fiber/977-3 epoxy towpreg, prestaged in a tunnel oven to an approximate 30% degree of cure. Results showed that the machine system can continuously cure and consolidate parts. The cure was advanced to any level up to 100% degree of cure with an air temperature of 380ºC. Temperature was the most significant factor affecting degree of cure. The design of the machine system allows for the addition of components for the fabrication of arbitrarily shaped parts and for different curing methods.

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 as shown below. 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 1999 Financial & Budget Report

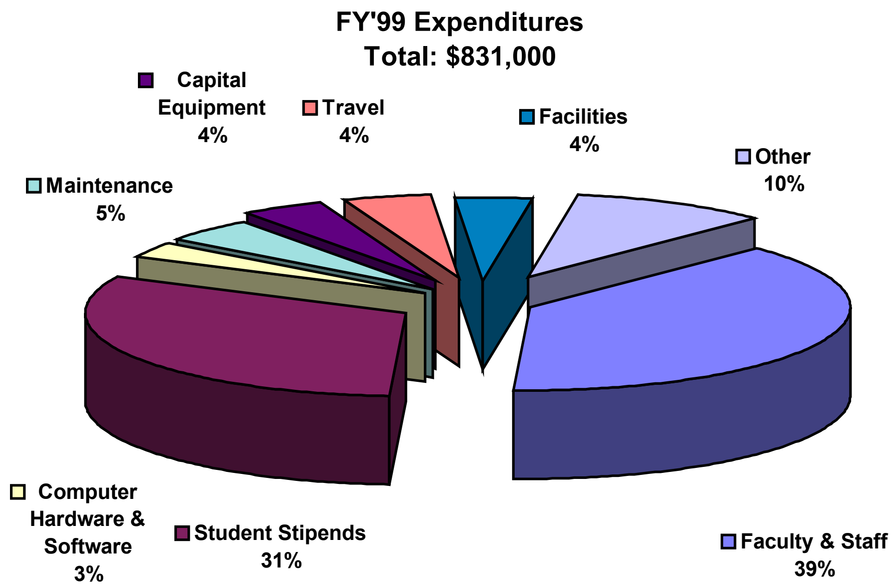
Our finances in the RPMI are managed very conservatively. In the university structure, we have no provision for deficit spending, and we are not able to borrow funds. Therefore, we must always manage our funds to maintain a surplus to cover unexpected expenses or reductions in funding.

The RPMI continued to operate on solid financial ground in fiscal year 1999 (ending June 30, 1999), and the outlook remains healthy.

Expenditures

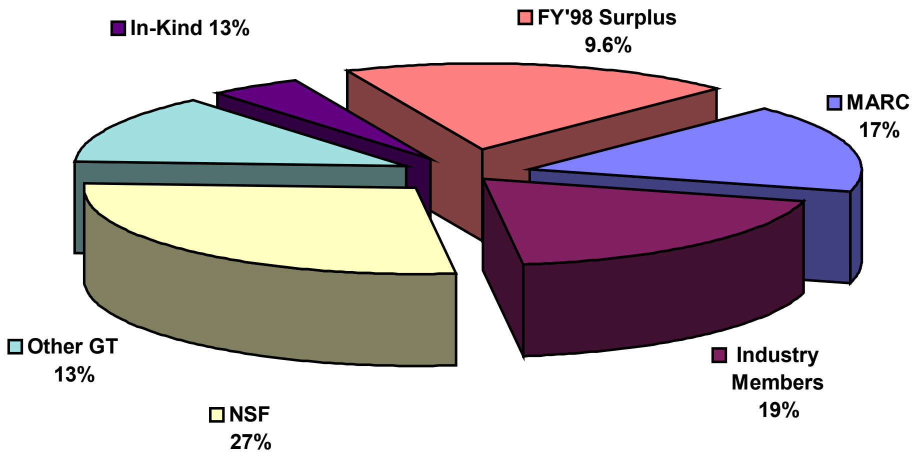
The largest single area of expenditure was for student stipends totaling $247,000 compared to $168,000 in FY '98. These expenditures were necessary to support the vast projects launched in 1999. Faculty and staff salaries in FY'99 increased by $54,000 to $246,000. This for the most part was due to the transition period while the RPMI was being restructured. Expenses for RPMI faculty and staff salaries reflect the now full-time commitment of the lab manager, the director of operations and our administrative assistant.

Other significant expenses include capital equipment, which decreased in FY '99 to $57,000,



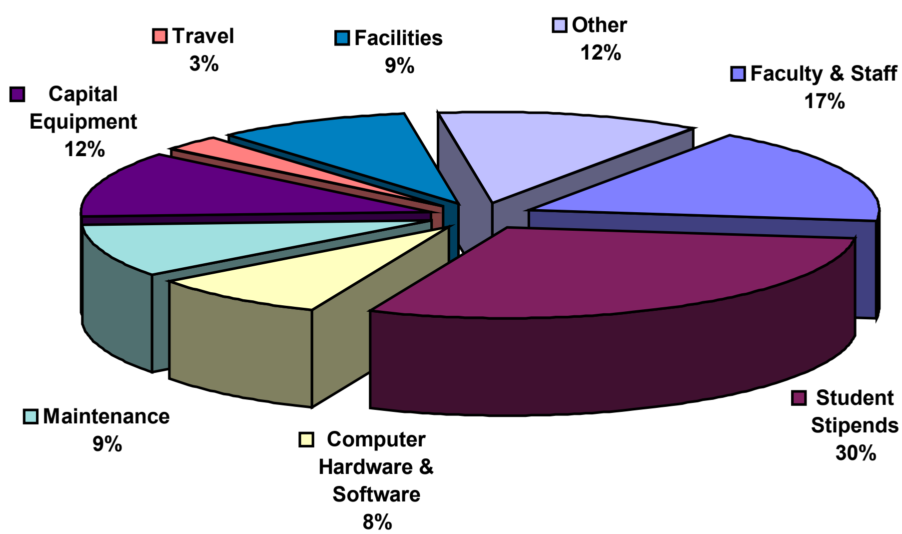
which was $17,000 less than the previous year. This is due to the completeness of FY'98 capital equipment purchases for project requirements. Other significant expenses include machine and software maintenance, which reduced slightly to $36,000 compared to last year's total of $58,000. "Other" RP&M-related expenses include expenses for project material and supplies. Other RP&M-related expenses increased by $6,000 to $61,000.

FY'99 Funding
Total: $988,000



For fiscal 2000, expect proportional increases in most categories to reflect our increased number of students and newly launched projects. Capital equipment budget will increase by $39,000 to $96,000 to accommodate payments for the newly acquired SLA-3500. Travel increases by $2,000 to $37,000 to support industry case study research and international conferences. Total budgeted expenditures for FY '00 are $855,000. The only real reductions are in project-related expenses where we're only budgeting $18,000, a decrease of $4,000, software maintenance from $36,000 to $20,000 and an $8,000 decrease from $41,000 in computer hardware repairs.

FY'00 Budgeted Expenditures
Total: $855,000



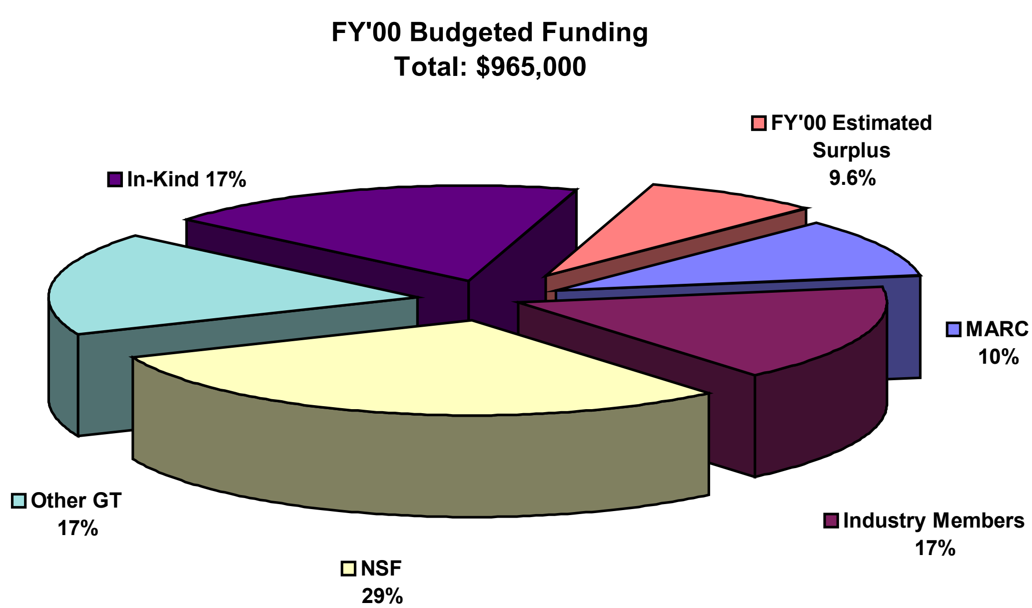
Funding

Membership dues in FY '99 decreased to $220, 000 from $248,000 the prior year. "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 RPMI members and non-members for hardware, software, materials and supplies in support of the RPMI laboratory.

In FY '00, research sponsored by NSF is helping to support more than 43 per cent of the total RPMI activity. Several of our students are now funded through this program. 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. Other special donations and a small amount of dues still uncollected from FY'00 make the dues expected total $274,500. Of course, an increase in the number of members could increase this amount by a maximum of $75,000. (We currently have 12 members, 15 is our limit.) Contributions in-kind from 3D Systems increased membership dues significantly for FY'00. Total in-kind contributions are $270,000, which are attributable to the real cost of items donated.

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.



The cumulative surplus at the end of FY'99 reduced to $157,000. This is an important cushion that we plan to continue to grow. For FY'00 with the encouragement of our members, we've established a $150,000 minimum goal for our surplus. It would be used in the event of a major loss of funding, or might be used for a strategic purchase. Our goal is to maintain and support existing and future research projects while maintaining the established surplus.

In 2000 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.

Photo courtesy of 3D Systems, Inc.

Outlook for 2000

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 1998, we have restructured the leadership of the RPMI and hired two key staff people. We have further clarified the roles of all positions within the RPMI and fine-tuned our operations to better serve our constituents.

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, Reggie Ponder (Operations) and David Rosen (RPMI), 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 1999.

1999 Committee Members List

<u>Operations</u>

Chair:	**Marc Bellotti**
Members:	**Darius Daruwala, Bill Durden, David Feindel, Chuck Hull, Dave Rosen, and Larry Whitaker**

<u>Technology</u>

Chair:	**John Malluck**
Members:	**Gary Beldue, George Hatzilias, Suresh Jayanthi, Larry Navarre, John Malluck, Reggie Ponder, Doug VanPutte, Larry Whitaker**

<u>Operations</u>

Chair:	**Chuck Hull**
Members:	**Doug VanPutte, Reggie Ponder, Dwight Williams**

<u>Executive</u>

Chair:	**Doug VanPutte**
Members:	**Marc Bellotti, John Malluck, Chuck Hull, Reggie Ponder, Dave Rosen**

"Baxter Healthcare Corporation, which is represented by the Corporation's Advanced Engineering Design Center, has been a member of the RPMI for several years. Our key reason for membership is to participate in applied research which we would not have the time or resources to manage ourselves. We feel this allows us to remain on the leading edge and to gain competitive advantage in our RP and Fabrication Operations."

Marc Bellotti
Director, Fabrication and Product Development

Advanced Engineering Design Center

Baxter Healthcare Corporation

Operations Committee Year-End Report

Marc Bellotti from Baxter Healthcare has served his second term as Chairman of the Operations Committee. Marc and his group built on the screening and portfolio-planning foundation established last year. The result is a balanced portfolio of research projects, which meet the needs of industry members as well as the academic community.

With the help of Dr. David Rosen, who served as the faculty/student representative for operations, the committee was able to re-establish our charter as a context for planning a balanced portfolio. All new proposals were reviewed and presented to the membership. The new proposals were screened for technical merit, academic fit and enterprise value. 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
- Alternative Applications
- Rapid Inspection and CAV
- RP&M Within Product Realization
- Other RPMI Related Activity

Students were recruited for each of the new project areas with the result being that all qualified projects were resource loaded for the coming year.

Following the selection process that was established last year has proven to be both efficient and effective. With the needed process in place and the portfolio balanced, Marc will be passing the baton to Bill Durden from Durden Enterprises who was elected the new Chairman of Operations at the fall meeting. Marc will continue along with Dave Rosen and the Committee to support Bill in the coming year.

Technology Committee Year End Report

John Malluck from Lucent Technologies chaired the Technology Committee from 1997 through 1999. He and his committee continued the work outlined in their 98 agenda. They were successful in acquiring new and strategically appropriate lab equipment. Under John's leadership, the committee focused on fully utilizing technology purchases in support of both existing and newly launched RPMI research projects.

John and his committee had ample financial resources to use for project support equipment and set out to further develop lab resources. The SLA-3500 Stereolithography apparatus was acquired to sustain newer solid-state material research and enhance operation system development. A Sanders Model Maker II was added to further support student research capabilities. A Morgan press was installed in the lab to facilitate student understanding of the molding process and to support rapid tool research projects. In addition, a Benchman tabletop machining center was added to support rapid machining of molds inserts and other prototyping needs. Several PC workstations were incorporated as well.

Next year, with newly elected chair Larry Whitaker of 3M, we're planning fewer major purchases, as our budget would suggest. We already are well equipped for most of what we're doing now. Utilization levels suggest existing lab equipment is at comfortable operational margins; however, these levels are very dependent upon RP&M research involvement in newly launched and continuing projects.

Membership Committee Year-End Report

The Membership Committee made a significant effort to add new members to the RPMI and maintain the existing members during 1999. Two new members were added during the year: Ford Motor Company and Club Car. While the RPMI lost four members at the end of 1998, all members present at the beginning of the year were retained. The recruitment of new members was done by identifying companies and making contact with them through a variety of efforts. These efforts include contact through attendance at RP&M conferences, company visits to the RPMI lab, and the hosting of a Technology Showcase. The main effort to retain the existing members was to determine if their RP&M needs were being served by their participation in the RPMI by conducting a membership survey.

The RPMI membership was again surveyed in 1999. The purpose is to learn what motivations each company has to participate in the institute, and to understand how their

"The largest value to date that we've received from being affiliated with the Georgia Tech RPMI is knowing that we are helping direct the research efforts of college students that will directly affect how new products are developed using rapid prototyping technologies. We are also creating new challenges and opportunities for them and for ourselves. This is exciting!"

Dwight Williams
Business Director

DSM Somos

experience with the RPMI meets these 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 motivations:

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

"Membership in the RPMI affords a company the opportunity to leverage a modest amount of funding together with other companies to sponsor important RP&M research at Georgia Tech. Together with the other members, research projects can be selected to develop technology that is pertinent to improve the understanding and deployment of RP&M in each company. "

Douglas VanPutte
Industry Liaison, RPMI

The results of the survey showed that the highest motivation of the member companies is to stay current in rapid prototyping and manufacturing, and that they are generally satisfied that the RPMI is serving that role. The second highest motivation is to augment the members own R&D in rapid prototyping and manufacturing applications, and the third highest motivation is to network with other companies involved in rapid prototyping and manufacturing. The members were somewhat less satisfied that RPMI met their needs in these latter two areas, although the scores were still well above average.

These top three motivations are the same as they were for the 1998 survey. The members were more satisfied that the RPMI is helping them keep current in 1999 than they were in 1998.

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 RP&M 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 RP&M 2000: Symposium & Expo

The RPMI will present a forward-looking two-day RP&M symposium on February 7-8, 2000 at Georgia Tech. The symposium program will feature three sessions:

- *Realizing Rapid Manufacturing,*
- *Unique Applications Using Layered Manufacturing Technologies*
- *Visualization: Physical and Virtual*

A person recognized as a spokesperson for the RP&M industry will chair each session. Ms. Elaine Hunt, Clemson University, will chair the *Realizing Rapid Manufacturing* session followed by Mr. Ken Johnson, NCMS who will chair the *Unique Applications Using Layered Manufacturing Technologies* session. Mr. Brock Hinzman, SRI International, will chair the third and last session, *Visualization: Physical and Virtual*. Each session is geared to present a view of the RP&M future and will present some of the challenges that must be met to move the industry forward into the new millennium.

Mr. David Howard from Ford Motor Company will present the symposium keynote address, *Journey to Rapid Manufacturing*. After the third session, a panel composed of the symposium speakers will attempt to answer questions and address issues about the future of RP&M contributed by the attendees. Dr. Phill Dickens, De Montfort University, will provide the session wrap-up presentation by discussing *Rapid Manufacturing--Near or Far*.

RPMI Member Meetings

RPMI Members Meeting, February 2-3, 1999

The first meeting at Georgia Tech of 1999 was the first to implement the new two-day meeting schedule. On the first day, the students presented detailed status reports on all of the active RPMI projects in the following categories: Rapid Tooling, Rapid Tooling Test Bed, Alternate Applications of SLA, Alternate SL Applications and Smooth Surfaces, RP&M within Product Realization, and Other RPMI Projects. Each of the project category presentations was followed by a question and answer period. The meeting ended with many favorable comments from the attending members concerning the new meeting format for the first day. The main purpose of the business meeting on the second day was to look briefly at what was accomplished in the previous year and look ahead at the activities planned for the new year. The first item on the agenda was to distribute copies of the 1998 Annual Report to the attendees. Doug VanPutte, RPMI Industry Liaison, reviewed the major changes in the report from the previous year. In addition, he reviewed the completion performance (71%) of the goals set by the RPMI staff for 1998. Doug followed this discussion with a review of the 1999 meeting schedule. After a report on the ExCom meeting on the previous day, Doug turned over the meeting to Reggie Ponder, RPMI Operations Director.

Reggie discussed the RPMI plans for participation in the 1999-RP&M events. He also discussed the desire of the RPMI to place co-ops and interns from the RPMI at the industry member sites during 1999. After a discussion on plans for GA Tech undergraduates, Reggie passed the meeting on to David Rosen, Director of the RPMI.

David discussed the RPMI plans to recruit additional graduate students to fill all the vacancies in the industry proposed project slate. David went on to discuss the 1999 project selection plans and the importance of full industry participation in the activity. David finished his portion of the meeting with a proposed set of project status meetings at industry sites, and turned over the meeting to the RPMI Industry Chairs.

The RPMI Industry Chairs, Chuck Hull, 3D Systems, Marc Bellotti, Baxter, and John Malluck, Lucent, each in turn presented the outlook for the coming year for each of their committees.

RPMI Members Meeting, May 25-26, 1999

This meeting followed a similar format as the February meeting; a two-day format with research project reviews on the first day and a business meeting on the second day. All six categories covered in the February meeting were also reviewed on the first day at this meeting. In some cases, the students presented their final project report before graduation and all assigned projects showed good progress since February. The day ended with a barbeque outing at the Durden homestead.

On the second day the major items discussed were the continuing education survey results, a year-end project status report, and the new project development process for the forthcoming year. Doug VanPutte reviewed a survey conducted by the RPMI to determine the direction for a new RPMI sponsored symposium. While the survey responses were less than expected, they were generally favorable to the Rapid Manufacturing theme chosen by the staff.

David Rosen began the year-end project report by recapping the major accomplishments of the graduating students. A chart was distributed which summarized the RPMI project portfolio. Each project was then evaluated by the group to determine the continuing interest by the industry members.

Marc Bellotti, Operations Committee chair began the new project process by summarizing the newly received project opportunity statements, followed by a presentation by the project champion of each proposed project. This was followed by grouping the proposed projects in the existing project portfolio and a solicitation of industry champions for each project. Each project team was challenged with producing a more detailed project description, as a resource for identifying student, faculty, and capital needs to carry out the project.

RPMI Members Meeting August 24-25, 1999

The normal two-day agenda was modified for this meeting. The focus of the first day was changed from project reviews to a Technology Showcase and concurrent sessions for recruitment of new graduate students and new industry members. The Technology Committee, headed by John Malluck, invited six speakers to discuss new technology topics in

RP&M. The showcase featured speakers from DTM (Christian Nelson), Graphic Manufacturing Solutions (Terry Peters), 4-Dimensional Volumetric (Bob Andrews), Los Alamos (Gary Lewis), Molecular Geodesics (Keith Oslakovic), SRI International (Brock Hinzmann), and U. of Rhode Island (Brent Stucker). Introduced by John Malluck, each speaker spoke about new RP&M technology being developed by his company or institution. The consensus of the attendees, including the speakers, was that the technology showcase was very informative and worthwhile.

The concurrent recruitment sessions were successful in presenting an overview of the RPMI and the benefits of being a part of the organization as either a student researcher or an industry member. A social presented by the RPMI followed a very fruitful day.

The business meeting on the second day covered the proposed RP&M symposium update, a proposed cooperative RPMI affiliated program, a status of the RPMI current and future year expenses, and a discussion of the research thrust and project plans for the coming year.

Doug VanPutte revealed that the RPMI was going to establish a new RP&M symposium in February 2000. Organized by Reggie Ponder and three session chairs (Elaine Hunt, Clemson, Brock Hinzmann, SRI International, Ken Johnson, NCMS), the symposium proposed content as presented on the RPMI web page was very favorably reviewed by over 50 respondents to a survey. Based upon the results of the survey and the good attendance at the SFF conference at the University of Texas, Austin, the new symposium was given the "green light" to proceed.

"RPMI has successfully managed to integrate the rapid prototyping industry needs with its research objectives. The quality of work coming out of this institution is outstanding and will help promote the growth of the young RP industry."

Suresh Jayanthi
Manager, Applications Development & Customer Support

DSM Somos

Reggie Ponder passed out a draft of guidelines for a Cooperative Affiliate of the RPMI. After spirited discussion, the proposal was tabled due to a number of unanswered issues that required further investigation.

Reggie then presented the RPMI finances. He reminded the group that funding would have to be actively sought to replace the RTTB funding from the NSF, which is in its last year.

David Rosen gave a short presentation on the RPMI research vision and our current and proposed projects. A handout of all the current and newly proposed projects was distributed and the members were asked to rank the projects on three criteria: Enterprise value, technical value, and compatibility. The results of the ranking were later presented by David Rosen and Marc Bellotti and would later be used as a guideline to staff and fund the projects.

RPMI Members Meeting, October 26-27, 1999

The last meeting of the year was again presented on the previously established 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 semester. Tours of the 5-Axis SLA lab set-up and the Laser Chemical Vapor Deposition lab set-up were the most notable highlights of the day.

The last business meeting of the year began with a status report on the Advanced RP&M Symposium 2000 by Doug VanPutte, year-end status reports by the committee chairs, and a review of the project portfolio by Dave Rosen. These reports were followed by two presentations. Tom Kurfess presented the new software capabilities of his new software company, Applied Metrology, Inc., and Kent Dawson gave a report on his attendance and paper presentation at the Time Compression Technologies conference in the UK. Prior to the close of the meeting, new committee chairs from industry were elected by the members. They included Bill Durden, Durden Enterprises, as Operations chair, Larry Whitaker, 3M, as Technology chair, and Dave Feindel, Kodak, as Membership chair.

2000 Meeting Dates, Locations & Agenda

Mon.-Tues., February 7-8, 2000	Georgia Tech, Atlanta **Advanced RP & M 2000: Symposium & Expo**
Weds., February 9, 2000	Georgia Tech, Atlanta **Business Meeting and Project Reviews**-New Committee Chair agenda and New Member Recruitment
Thurs.-Fri., April 27-28, 2000	Georgia Tech, Atlanta **Business Meeting and Project Reviews**-Critical Reviews of projects, New Proposal Generation, and Year-End Project Completions
Thurs.-Fri., June 15-16, 2000	Georgia Tech, Atlanta **Business Meeting and Facility Tours**-New Project Development, Technology Transfer, Project Selection, and Strategic Planning
Thurs.-Fri., October 19-20, 2000	Georgia Tech, Atlanta **Business Meeting and Technology Showcase**-Committee Chair Nominations, Financial Review and Project Reviews
March 6-10, 2000 Member November 28- December 1, 2000	Periods reserved for **Project Reviews** at GA Tech or at Sites

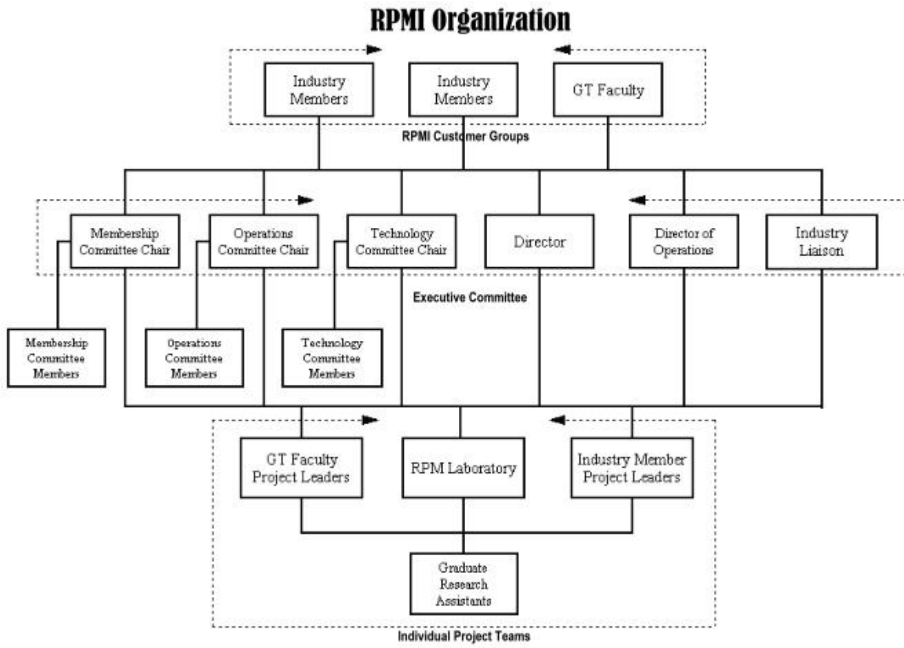
Structure of the RPMI

During 1998, the RPMI underwent a significant restructuring, with Tom Graver leaving the RPMI to join the Environmentally Conscious Design and Manufacturing (ECDM) initiative at Georgia Tech. Reggie Ponder moved in to assume many of Tom's responsibilities as Director of Operations, with Giorgos Hatzilias replacing Reggie as Laboratory Manager. Doug VanPutte was hired as our Industry Liaison with responsibilities for member relationships, outreach, and meetings. David Rosen became RPMI Director. Although many pitfalls could have arisen, the RPMI has continued operating smoothly and successfully as our successful year demonstrates!

The RPMI organizational structure is shown in the figure below. Over the past 1.5 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. Over the past year, two additional faculty have been added to the RPMI: Janet Allen is a Senior Research Scientist in ME and Steven Liang is an Associate Professor of ME. Regarding students, we have had a great recruiting year, hiring 11 new students. Our research program is now fully staffed! 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 2000, we enter the RPMI's sixth year in existence, and the second 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 a good start 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. In particular, our Generalized SLA, Building Around Inserts, and Design For Additive Fabrication projects are all aimed at positioning the RPMI for a future when affordable, high-accuracy rapid manufacture technologies become available. 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 2 plan is presented below. We have a good start on each element of this plan and look forward to achieving our objectives. In doing so, we believe we will be living up to the title of this Annual Report: ***Orchestrating the Path to RP&M's Future***.

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

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?

Goals for 2000

Education

- ☐ *Develop and initiate a 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 in 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 component of continuing education research.*
- ☐ *Achieve project links with Environmentally Conscience Design for Manufacture focused on achieving the manufacturing goals of the Georgia Strategic Research Alliance .Infrastructure.*

Research

- ☐ *Develop injection molding process design guidelines that maximize SL 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 at Georgia Tech.*
- ☐ *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.*
- ☐ *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 reporting by making information ever more readily available to members.*

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.*

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	Guest Lectures
	120+/yr	
CAD/CAM	Through academic courses and	**National Organizations**
	projects, and Industry Short	SME RPA
	Courses	
Metrology		3DNASUG
Practice		ASME
RT, RP Methods		**State**
RT, RP Processes and Standards		EDI
Rapid Inspection and Metrology		

Year 1 - 1999

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

Year 2 - 2000

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

Year 3 - 2001

Research	Deliver significant metrology and rapid inspection results. Demonstrate true rapid CAV methods and tools. Contribute to metrology standards. Reassess and refocus the rapid inspection effort. Harden the generalized SLA technology ("5-Axis SLA") to enable its commercialization. Demonstrate rapid manufacturing capabilities (vs. rapid prototyping). Refocus the rapid tooling effort. Is it still relevant? Continue working toward rapid manufacturing from a management and economics perspective.
Strategy	Begin implementation of new strategic plan from previous year.
Education	Host a major continuing education event.

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

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

Sundiata Jangha, An Ejection Mechanism Design Method for Rapid Injection Molding Tools

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

Journal Papers - 1999

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, submitted, 1999.

Choi, W., Kurfess, T. R., "Dimensional Measurement Data Analysis Part I, a Zone Fitting Algorithm," *ASME Journal of Manufacturing Science and Engineering*, in press, February 1999.

Choi, W., Kurfess, T. R., "Dimensional Measurement Data Analysis Part II, Minimum Zone Evaluation Design," *ASME Journal of Manufacturing Science and Engineering*, in press, February 1999.

Colton, J.S., and LeBaut, Y., "Thermal Effects on Stereolithography Injection Mold Inserts," *Polymer Engineering and Science*, accepted for publication, 1999.

Hemrick, J., Starr, T., and Rosen, D., "Release Behavior for Powder Injection Molding in Stereolithography Molds," *Journal of Materials Processing Technology*, submitted, 1999.

Lynn-Charney, C.M. and Rosen, D.W., “Accuracy Models and Their Use in Stereolithography Process Planning,” accepted in *Rapid Prototyping Journal*, 7/99.

Palmer, A.E., and Colton, J.S., "The Effect of Feature Geometry on Stereolithography Tooling," *Polymer Engineering and Science*, submitted for publication, 1999.

West, A.P. and Rosen, D.W., " A Process Planning Method for Improving Build Performance in Stereolithography," submitted to *Computer-Aided Design*, 1999.

Conference Presentations - 1999

Cedorge, T., LeBaut, Y., Palmer, A.,. and Colton, J.S., "Design Rules for Stereolithography Injection Molding Inserts," (1) Proceedings of the 1999 North American Stereolithography Users Group Conference, Orlando, May 17-20, 1999, (2) Proceedings of the 32nd CIRP International Seminar on Manufacturing Systems, 219-228, Leuven, May 24-26, 1999, and (3) Proceedings of the 8th European Conference on Rapid Prototyping and Manufacturing, 193-209, Nottingham, July 6-8, 1999.

Conner, C. G., DeKroon, J. P., and Mistree, F., "A Product Variety Tradeoff Study for a Family of Cordless Drills," ASME Design Automation Conference, Las Vegas, Sept. 12-15, 1999.

Dawson, E.K. and Muzzy, J.D., "The Effect of Rapid Tooling on Final Product Properties," Proceedings of the 1999 North American Stereolithography Users Group Conference, Orlando, May 17-20, 1999.

Gerhard, J.F., Duncan, S.J., Chen. Y., Allen, J.K., Rosen, D., and Mistree, F., “Towards a Decision-Based, Distributed Product Realization Environment for Engineering Systems,” ASME Computers in Engineering Conference, Las Vegas, Paper DETC99-CIE9085, Sept. 12-15, 1999.

Herrmann, A. and Allen, J.K., "Selection of Rapid Tooling Processes and Materials in a Distriburted Design Environment," ASME DFM Conference, Las Vegas, September 12-15, 1999, Paper Number DETC99/DFM-8930.

Jangha, S. and Rosen, D., “An Ejection Mechanism Design Method for Stereolithography Tools,” Proceedings Solid Freeform Fabrication Symposium, Austin, TX, pp. 219-228, August 10-12, 1999.

Judson, E. and Starr, T.L., “Dimensional Accuracy in Rapid Prototyping of Ceramics Formed by Injection Molding Using Rapid Tooling”, Symposium on Innovative Processing and Synthesis of Ceramics, Glasses and Composites, American Ceramic Society Annual Meeting, April 25-28, 1999.

Lynn, C.M. and Rosen, D.W., "SLA-250 Parts vs. Geometric Tolerances: Quantitative Results," 1999 North American Stereolithography User Group Conference, Orlando, May 17-20, 1999.

Palmer, A, and Colton, J.S., "Design Rules for Stereolithography Injection Molding Inserts," Proceedings of ANTEC '99, Society of Plastics Engineers, 4002-4006, New York, May 2-6, 1999.

Rosen, D. W., Allen, J. K., Colton, J. S., Kurfess, T. R., Mistree, F., Starr, T. L., Fujimoto, R. M., and Schwan, K., “A Rapid Tooling TestBed for Injection Molding,” NSF Design and Manufacturing Grantees Conference, Long Beach, CA, Jan. 5-8, 1999.

Tucker, T. and Kurfess, T., “Issues in Rapid Prototyping Metrology,” Technical Papers of the North American Manufacturing Research Institution of SME 1999, Berkeley, CA, May 1999.

West, A., and Rosen, D., “Process Planning Based on User Preferences,” Proceedings Solid Freeform Fabrication Symposium, Austin, TX, pp. 67-76, August 9-11, 1999.

West, A. and Rosen, D. W., "A Process Planning Method for Improving the Build Performance in Stereolithography," Proceedings 1999 ASME Computers in Engineering Conference, paper #DETC99/CIE-9124, Las Vegas, 1999.

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.

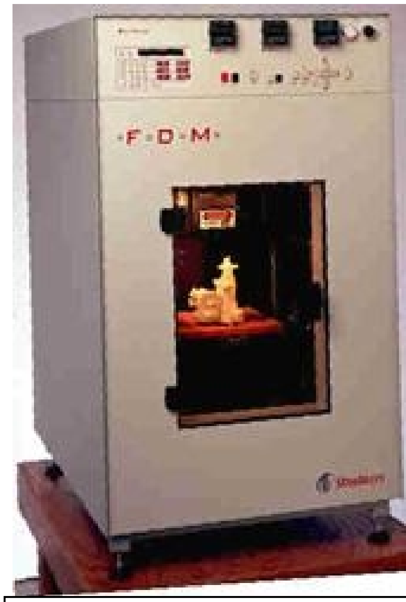
- Interchangeable vat for rapid and easy resin exchange
- Multiple polymers available
- Zephyr™ Recoating System
- Easily builds multiple identical or unique parts simultaneously
- Unattended build operation

'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



'Photo courtesy of Stratasys

FDM 1650

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

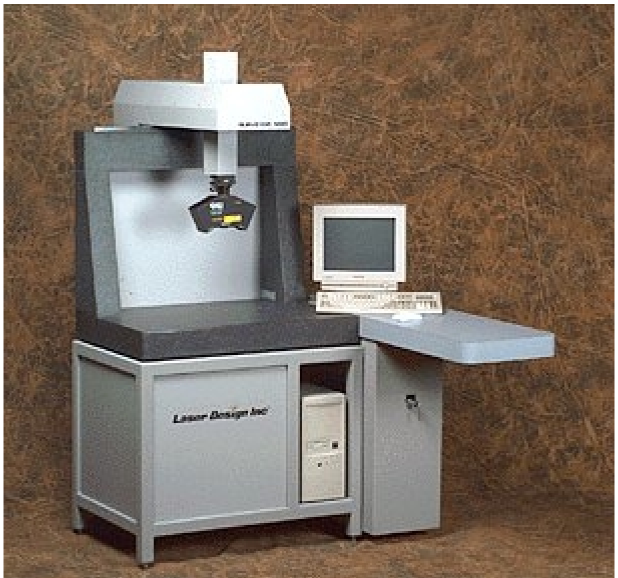


Photo courtesy of Laser Designs, Inc.

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.

- 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
- Precision ground chrome-plated stanchion rods
- 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

Computer Equipment:

(UNIX Platforms)
- One Octane Server with Risk 195 from Silicon Graphics, Inc.
- One Indigo 2 Work Station with Risk 200 from Silicon Graphics, Inc.
- One Sparc 4 Communication Server by Sun Microsystems
- Two O2 Work Stations with Risk 175 from Silicon Graphics, Inc.

(WINDOWS Platforms)
- One PC Server with a 486DX200 processor and 64 MB of RAM
- One PC Work Station with a 486DX33 processor and 16 MB of RAM
- Two PC Work Stations with P-Pro 200 processors and 64 MB of RAM by Gateway 2000
- Two PC Work Stations with P-100 and P-200 processors and 72 and 80 MB of RAM
- Two PC Work Stations with Pentium-S processors and 16 MB of RAM
- Two DELL PC Work Stations with dual P2 400 MHz processors and 256 MB of RAM
- Three DELL PC Work Stations with P2 450 MHz Processors and 256 MB of RAM
- One DELL PC Work Station with P3 550 MHz Processors and 256 MB of RAM
- One Hewlett Packard Work Station with a 150 MHz Processor and 24 MB of RAM
- Two GIM Work Stations
- (Intranet/Internet Connectivity)
- One T-1 Internet Connection
- 16 Port Passive Ethernet Hub
- Cisco 752 ISDN Router
- One 33.6 Dial In Modem
- Four US Robotics 28.8 Modems
- Computone Terminal Server
- One Hewelett Packard ScanJet 4C Scanner
- One Hewelet Packard Laser Printers
- One SLA Internet-Modified Camera
- One Silicon Graphics Networking Digital Camera
- One Kodak ds DC50 Digital Zoom Camera

Software

CAD and Geometric Software

- Allegro
- AutoCAD rel.14
- CATIA
- IGRIP
- Imageware Solution rl. 7.0
- RPM ver. 8.0
- MAESTRO 1.9
- MiniLab Statistical Software
- Pro-Engineer* ver.19
- QuickSlice ver. 4.2
- Raindrop Geomagic Studio
- SDRC IDEAS
- Solaris Works 96/97
- SolidWorks98*
- Solidview 1.02/2.0/3.0
- StlView
- Stratasys Inc.
- 3D C-Mold Quick Fill
- COSMOS-FEA

Other Software:

- COREL 50
- Cold Fusion
- Dreamweaver
- Freehand 8
- Flash 3
- IRIX Applications ver. 6.2/6.3/6.4
- LabView
- Live Works-Meeting Disk 4.5
- MS Front Page
- MS Office 97
- MS Project 98
- MS Visual C++
- MS Visual Basic Professional Edition
- MS Visual Studio 97
- PC Medic 97
- PkZip
- QuikCam
- RP and MS Resource Guide
- Virus Scan Security Suite
- WebSite Professional
- Windows 95/NT Workstation & Server
- WsFTP_95 LE

Library Resources

Books:

Automated Fabrication – Improving Productivity in Manufacturing, Marshall Burns. PTR Prentice Hall, 1993

Injection Molding Handbook, 2e. Donald V. Rosato. International Thompson Publishing, 1995

Introduction to Materials Science for Engineers, 3e. James Shackelford. McMillan Publishing Co, 1992

Mold Engineering. Herbert Rees. Hanser Publishers, 1995

Plastic Injection Molding…manufacturing process fundamentals. Douglas M. Bryce. SME – Society of Manufacturing Engineers, 1996

Rapid Prototyping - principles and applications in manufacturing, Chua Chee Kai, Leong Kah Fai. John Wiley and Sons, Inc., 1997

Rapid Prototyping & Manufacturing. Fundamentals of Stereolithography. Paul F. Jacobs, Ph.D. SME-Society of Manufacturing Engineers, 1992. {10 copies}

Rapid Prototyping and Tooling. A Practical Guide. David Atkinson Strategy Publications Ltd., UK, 1997

Rapid Prototyping Technology: A Unique Approach to the Diagnosis and Planning of Medical Procedures, Society of Manufacturing Engineers, 1997

Standards & Practices of Plastics Molders, The Society of Plastics Industry, Inc, 1993

Stereolithography and Other RP&M Technologies. Paul F. Jacobs. SME - Society of Manufacturing Engineers, 1996 {10 copies}

Brown & Sharpe: Handbook of Metrology. International Reference Edition

Renishaw Product Catalog Issue 2

Prototyping Technology International '97. UK & International Press, UK. {2 copies}

Proceedings :

- Annual Eugene C. Gwaltney Manufacturing Symposium. Georgia Institute of Technology, Atlanta, GA
- Second Gwaltney: October 24-25, 1995 {6 copies}
- Third Gwaltney: October 1-3, 1996
- Fourth Gwaltney: October 1-2, 1997 {3 copies}
- Annual UAS FDM Users Group
    - 1997: July 13-15, Prior Lake, Minnesota
    - 1998: July 12-14, St. Paul, Minnesota
- Conference Proceedings At ANTEC, Society of Plastics Engineers
    - 1998: Volume 1, April 26-30

    - 1998: Volume 2, April 26-30
    - 1998: Volume 3, April 26-30
    - 1999: Volume 1, May 3-7
    - 1999: Volume 2, May 3-7
    - 1999: Volume 3, May 3-7
- International Conference of Rapid Prototyping (ICRP). Dayton OH, University of Dayton –RPDL: Rapid Prototype Development Laboratory.
    - Second ICRP: June 23-26, 1991
    - Third ICRP: June 7-10, 1992
    - Fourth ICRP: June 14-17, 1993
    - Fifth ICRP: June 12-15, 1994
- First National Conference on Rapid Prototyping: June 4-5. 1990
- North American Stereolithography User Group Annual Conference and Meeting – Proceedings
    - 1995: March 12-16, Tampa, FL
    - 1996: March 10-13, San Diego, CA {2 copies}
    - 1997: February 15-20, Orlando, FL {3 copies}
    - 1998: March 1-5, San Antonio, TX {3 copies}
    - 1999: May 17-20, Orlando, FL {3 copies}
- Rapid Prototyping and Manufacturing. Dearborn, MI SME: Society of Manufacturing Engineers, RPA: Rapid Prototyping Association
    - 1996: April23-25
    - 1997: April 22-24 {2 copies}
    - 1998: April 20-22
- Rapid Prototyping in Europe and Japan. Japanese and World Technology Evaluation Centers (JTEC) SME & RPA.
    - Volume I. Analytical Chapters. March 1997
    - Volume II. Site Reports. September 1996
- Solid Freeform Fabrication Symposium (SFF). University of Texas, Austin.
    - 1990:August 6-8
    - 1991:September
    - 1992:August 3-5
    - 1993:August 9-11
    - 1994:August 8-10
    - 1995:September
    - 1996:August 12-14
    - 1997:August 11-13
    - 1998:August 10-12
    - 1999: August 9-11

Magazine and Publication Subscriptions:

- Composites Technology {1996/1997/1998}
- Manufacturing Engineering {1996/1997/1998}
- Molding Systems {1998}
- Polymer Engineering & Science {October 1997}
- Pro/NEWS {partial 1997/1998}
- ProE {partial 1995/1996/1997/1998}

- Prototyping Technology International {partial 1997/1998}
- Rapid News. Time Compression News. {partial 1996/1997/1998}
- Rapid Prototyping Journal {partial 1996/1998}
- Rapid Prototyping Report: The newsletter of the desktop manufacturing industry. {1993/1994/1995/1996/1997/1998}
- Rapid Prototyping, SME: Society of Manufacturing Engineers. Quarterly {Second Quarter 1995}

Training Packets:

- Composite Injection Mold Tool Training Manual, March 23-24, 1998 {Ciba Specialty Chemicals}
- Fundamentals of Rapid Prototyping and Applications in Manufacturing, John F. Miller (Chrysler), with cooperation from Tom Sorovetz (Chrysler), Tom Myeller (Prototype Express), Bob Flint (ProtoTech Engineering). SME/RPA {5 copies}
- Rapid Guide To Rapid Prototyping (booklet), Terry Wohlers, 1996
- VISTA (Maestro) Help Packet

Reports:

Bibliography of Rapid Prototyping – Technical Resources 1995-1996

A Comparative Study of Rapid Prototyping Processes. Jason W. Pratt 10/19/93

Global Trends in Software for Rapid Prototyping. Michael Wozny, Rensselaer polytechnic Institute. RP&M '97, Dearborn, MI 4/22-24/97

"Innovation in Rapid Manufacturing Education" – A Report on the First Year of the RPMI – January 1997 {3 copies}

Laser Engineered Net Shaping (LENS). Michelle Griffith, Sandia National Labs. RP&M '97, Dearborn, MI 4/22-24/97

New Developments in Production Quality Rapid Tooling. Jim Williams, Paramount Industries. SME RP&M '97. 4/23/97

Optimizing the Use of Stereolithography Photopolymers – Special Focus on Maintaining Appropriate Conditions for the use of Epoxy Photopolymers in a Stereolithography Laboratory. DuPont Company, Somos Solid Imaging Materials Group. 2/14/97

A Procedure to Estimate Build Time for Stereolithography Machines. Kamesh Tata/Dave Flynn

Prototyping Technologies in Industries. Technology Park Malaysia Minister of science, Technology & the Environment with UNDP. 12/7/1995

Rapid Prototyping Original Equipment Manufacturers' (OEM) Update Report

1996: Fourth Quarter, Society of Manufacturing Engineers

1997: Progress Reports from the "RP&M '97" Conference {2 copies}

1997: Progress Reports from the AUTOFACT '97 Conference {2 copies}

1997: Progress Reports from the "RP&M '98" Conference {2 copies}

The Road To Manufacturing: 1998 Industrial Roadmap for the Rapid Prototyping Industry June 30, 1998

Rapid Prototyping Journal. Special Internet Conference Issue. Volume 2, Numbers 2,3,4, 1996

Rapid Tooling for Injection Molds – Composite Tooling/Machined Tooling Comparison. Steven Willis, Plynetic Express. RP&M '97 Dearborn, MI 4/22-24/97

SL Rapid Tooling Enables Time To Market. Jeffery Heath, Xerox Corporation. RP&M '97, Dearborn, MI 4/22-24/97

State of the Industry – Worldwide Progress Report

Rapid Prototyping 1995-96 Worldwide Report

1997 Worldwide Progress Report – Executive Summary

A Step-by-Step Evaluation of Building as Investment Cast Plastic Injection Mold. Douglas A. VanPutte/Larry E.André.

Class & CIMS II Reports:

Current Applications of Simulation in Manufacturing – State of the Art Report for CIMS II, Elinor Bracho, Celena Evans, Haichuan Zou, 2/27/97

Design and implementation of Hypertext Tutorials as a means of Training in a Dynamic Environment. Charles W. Gillespie III, TEX 8500, Spring 1997

E"C" VAN Inc., State of the Art Report. Lan Cao, Haripriya Karanam, Florian Scwarz, Minzhi Shi, ME 6791 (CIMS II), 2/27/97

A Method for Designing Rapid Inspection Processes Using the Pahl and Beitz Design Method. Joel E. McClurkin, ME 6170, 12/19/96

Production Integration – State of the Art, Triple C. Inc. March 1997

State of the Art Report – 3D Modeling, Kimberly Haynes, Mathew Kelton, Albert Loichinger, Stelios Michaelides, Kyle Smith, ME 6791 (CIMS II), 2/27/97

Rapid Prototyping: State of the Art of Stereolithography and Fused Deposition Modeling, Tian He, Alpeshkumar Marurya, Bonnie Tseng, Daisuke Yano, ME 6791 (CIMS II), 2/27/97

State of the Art of Stereolithography. Ken Hamall, Kevin Kamphius, Rick Yamada, Imran Yusuf, ME 6791 (CIMS II), 2/15/96

State of the Art of 3D Modeling. Benedikt Heidenreich, Andreas Lolling, Joel McClurkin, Jason Shiroshi, ME 6791 (CIMS II), 5/9/96

Wearable Computers – State of the Art Report, Eric Schmenk, Erik Roberts, Jose Martinez, Michelle Rarey, Casey Swearingen, June Wei, ME 6791 (CIMS II), 2/27/97

Technology Forecast on Ink-Jet Head Technology Applications in Rapid Prototyping. Alejandro Carrion, ISYE 6777. 3/20/97

Videos:

- Acu-Gage Systems, A Division of Ocean Industries
- Advances in CNC. Manufacturing Insights, SME: Society of Manufacturing Engineers 27 minutes
- AutoSimulations: Where Simulation Defines Reality. Corporate Overview and Automod Demo
- CDI Computer Services: Visualization Reel. 11/14/94. {3 copies}
- CGI: Capture Geometry Inside. Demonstration of the reverse engineering system that captures INTERNAL and external part features. Approx 6 minutes
- CIBA Polymers. The Ureol Mass Casting System. CIBA Tooling Paste.
- Concept Modeling. Mfg. Insights, SME: Society of Manufacturing Engineers. 24 minutes.
- CYBERMILL 842 – 5 Axis. B3
- Digital Design 93/94
- FaroArm and AnthroCAM Demo Video. 10:15 minutes. {2 copies}
- Fused Deposition Modeling. Stratsys. 9 minutes. {2 copies}
- Hasbro Safety Video 1997
- KODAK Precision Plastics {2 copies}
- A Link between Virtual and Physical Prototyping. Clemson University, May 1995. 7.5 min. & 5 min.
- Laminated Object Manufacturing for Direct Investment Casting. Helisys, Inc.
- LOM: Laminated Object Manufacturing (NTSC) 1015/2030. Helisys, Inc. {2 copies}
- ModelMaker / Replica & ModelMaker on Future File 04/22/97
- Moldmaking with Materials from Dow Corning Corporation. 35:26 minutes. 9/16/97
- Rapid Injection Mold Tooling. Mfg. Insights, SME: Society of Manufacturing Engineers. 26 minutes.
- Rapid Prototyping. 3/8/95? {3 copies}
- Rapid Tooling, Rapid Parts. Mfg. Insights, SME: Society of Manufacturing Engineers. 40 minutes.
- Technology Today. The FOM Story
- The SLS Process and Functional Prototyping 1995. DTM Corporation.
- Skull News Release. Dow Corning Corporation. 4:20 minutes. 2/20/97
- "The Solution". Morgan Press. 13 min. {3 copies}
- 3D Systems: Corporate Video: Good Morning American, American Airlines
- 3D Systems: "Wining the Race". 15:45 minutes
- 3D Systems: 12 Innovative Solutions. 9 minutes. 9/26/97 {2 copies}
- Virtual Manufacturing: Simulating Reality. Manufacturing Insights, SME: Society of Manufacturing Engineers

Information Bins – Companies and Articles

- 1 bin Ciba-Geigy Information
- 1 bin DTM SLS Information
- 1 bin Factory Simulation Information
- 1 bin Workstation Companies: Information
- 1 bin 3D Modeling
- Autodesk Mechanical Desktop
- Folder Camax/Camand – Computer Aided Manufacturing for Performance Driven Companies
- Folder Imageware
- Folder Integraph

- RaPiD/CAST takes the guesswork out of casting design
- Folder SolidWorks
- Folder SURFCAM
- 1 bin Rapid Prototyping Equipment Manufacturers
- folder BPM Technology, Inc.
- CGI – Capture Geometry Inside
- Folder Cubital
- Folder Helisys
- Laser Design
- Folder Sanders Prototyping Equipment
- 1 bin RPMI Equipment Companies
- 1 bin RPMI Members
- 1 bin RP Papers
- 1 bin RP Reports
- 1 bin Phamphlets, Magazines, Articles
- 1 bin Workstations Company Information
- 1 bin Simulation Factory
- folder 3D Systems
- folder Stratasys

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 encouraged.

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 ________________________ ____. 2000.

Member's Mailing Address:	_______________________________________ (Name of Member Company)
_________________	Signature: ________________________________
_________________	Printed Name: _____________________________
_________________	Title: ____________________________________

Direct questions to: Reggie Ponder, Director of Operations, 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 Academic 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.