Calmac Manufacturing Corporation

New Refrigeration Cycle To Improve 100-Year-Old Technology

Refrigeration is one of the leading uses of electric power in the United States. The term "refrigeration" refers to air-conditioning for homes, businesses, and industry and the operation of refrigerators, freezers, and heat pumps. The technology most often used in refrigeration, the vapor compression cycle, is 100 years old, inefficient, and environmentally unsound. Since the 1980s, the refrigeration industry has faced pressure to improve efficiency and reduce emissions of the chloroflurocarbon (CFC) compounds used in vapor compression cooling. Attempts to decrease CFC emissions by using alternate compounds have typically made refrigeration devices less efficient.

Calmac Manufacturing, Inc., proposed a new, efficiency-enhancing twist on the old paradigm. It proposed an ejector expansion refrigeration cycle (EERC) to increase the efficiency of the cycle by recovering some of the unused energy in the compressed fluid. Calmac targeted a 10-percent reduction in energy used for air-conditioning and up to a 20-percent improvement for other, lower temperature applications over standard vapor compression refrigeration systems. Because Calmac lacked the internal funding resources to support such an ambitious, but risky, project, it turned to the Advanced Technology Program (ATP). In March 1993, ATP awarded $729,000 to Calmac to pursue the development of EERC technology. Unfortunately, scientific and technical failures prevented Calmac from successfully developing the EERC technology and, by the project's end in February 1996, the company had abandoned its efforts. Calmac did, however, advance the refrigeration industry's body of knowledge for modernizing the vapor compression process, and future industry efforts may potentially expand on the inroads made by Calmac.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)

No Stars

Research and data for Status Report 92-01-0007 were collected during October-December 2001.

100-Year-Old Refrigeration Techniques Are Obsolete

Vapor compression refrigeration systems use 23 percent of all electric energy in the United States. Add the millions of gallons of gasoline burned to power automobile air conditioners, and it is clear that any increase in efficiency could lead to tremendous societal benefits. Unfortunately, decades of attempts to improve the vapor compression refrigeration system by reducing chloroflurocarbon (CFC) emissions have not resulted in increased efficiency or reduced the environmental impact of the system. Typically, reductions in CFC emissions lead to decreased efficiency, requiring the use of more electric power as well as the emission of more environmental toxins from the electric-power-generation process.

Efficient, Cleaner Refrigeration Through EERC

Calmac developed an ejector expansion refrigeration cycle (EERC) process to improve the efficiency of vapor compression refrigeration by recovering energy typically lost during the process. Specifically, the EERC process uses the energy normally lost in the expansion process to help compress the gas entering the compressor. The

EERC expands the liquid refrigerant in two steps. The first step is through a specifically designed nozzle where the liquid is used to increase the pressure of the gas returning to the compressor. After this stage, the liquid refrigerant is collected in a receiver where it is metered into the evaporator by conventional methods.

Prior Success Indicates Goals Are Possible

Before applying for ATP funding, Calmac had expended significant internal resources to overcome prior EERC failures in the industry. For example, industry efforts to achieve EERC had not generated sufficient pressure within the ejector nozzle to enhance refrigeration efficiency. Calmac, however, had developed techniques to achieve a six-percent improvement in energy expended for refrigeration through the use of the EERC. That level of improvement was not high enough to make the technology cost effective, but, with further research and refinement, Calmac expected a 10-percent improvement for air-conditioning and up to a 20-percent improvement for other, lower temperature applications. Moreover, more efficient refrigeration would reduce both the size of the equipment needed in the process and the potential release of CFCs into the environment. When improvements reached the 10-percent threshold, cost savings would then be high enough to encourage original equipment manufacturers (OEMs) to use the EERC process. At that point, economic and environmental spillover could be achieved.

Limited internal funds had hindered efforts, however, to reach the commercially viable 10-percent improvement stage. Furthermore, given the previous failures to develop EERC technology within the industry, external funds through the private market were not available to Calmac.

Improved Refrigeration Efficiency Has Potential Spillover Benefits

Because refrigeration is used in almost every residential and commercial structure, and because it accounts for such a high percentage of the nation's consumption of electric power, improvements in refrigeration efficiency could result in lower overhead costs across many industries. In the commercial setting, cost savings could then be invested back into product development. In the residential setting, the decrease in money spent each month on electricity could free up spending for a host of consumer items or for personal savings. The potential spillover benefits supported Calmac's proposal to receive cost-shared funds from ATP. Therefore, in 1993, ATP awarded the company $729,000 to pursue further development of the EERC technology.

Unforeseen Obstacles Block Increased Efficiency and Commercialization

In the first 18 months of the project, Calmac engineers researched materials and engineering advances that had the potential to push the EERC above the 10-percent efficiency improvement threshold. The following six months were spent integrating these innovations into the EERC technology. At the start of the third year of the project, however, Calmac encountered unforeseen instability in the ejector's operation. Three sources of the instability were examined, but Calmac was unable to completely pinpoint and solve the problem. The specific operating parameters needed in the ejector for the EERC operation introduced inherent instabilities to the system outside this design window.

Calmac conducted research into the cause of the instability and generated extensive documentation of its findings. However, the company could not make the EERC operate efficiently for the equipment's complete range of operation.

Calmac encountered unforeseen instability in the ejector's operation.

Consequently, Calmac could not commercialize a component package for retrofitting older machines or for installation by OEMs because the costs were still prohibitive. When the ATP project concluded in 1996, Calmac decided not to continue its work on EERC.

Conclusion

ATP funded Calmac's effort to develop more efficient, more environmentally friendly refrigeration technology based on recovering the energy lost during the process.

However, scientific and technical failures prevented the company from achieving the performance goal needed to make the EERC technology financially viable.

Scientific and technical failures prevented the company from achieving the performance goal needed to make the EERC technology financially viable.

Nevertheless, Calmac's research did add to the body of knowledge of engineering processes related to refrigeration. In the future, that knowledge may save engineers time and money as they continue to search for more efficient refrigeration methods.

PROJECT HIGHLIGHTS
Calmac Manufacturing Corporation

Project Title: New Refrigeration Cycle To Improve 100-Year-Old Technology (Ejector Expansion Refrigeration Cycle (EERC))

Project: To improve the efficiency of refrigeration through an ejector expansion refrigeration cycle (EERC) that recycles energy normally lost during the process. If successful, this technology would benefit every consumer of electric power by making refrigerators, air conditioners, and freezers substantially more efficient and cost effective.

Duration: 3/1/1993-2/29/1996
ATP Number: 92-01-0007

Funding (in thousands):

ATP Final Cost	$ 729	62%
Participant Final Cost	448	38%
Total	$1,177	

Accomplishments: Although Calmac made some progress in developing more efficient, more environmentally friendly refrigeration technology based on recovering the energy lost during the process, technical problems prevented the company from achieving the performance goal needed to make it cost effective. Despite this failure, however, Calmac advanced the refrigeration industry's body of knowledge for modernizing the vapor compression process by identifying for the industry those EERC methods that would not work.

Commercialization Status: Calmac was unable to commercialize the EERC technology it worked to develop in this ATP-funded project due to scientific and technical failures.

Outlook: Calmac has abandoned further work on the EERC project, and there are no plans for commercialization at this time. In 2003, the outlook for this particular project is poor.

Composite Performance Score: No Stars

Number of Employees: 16 at project start, 65 as of December 2001

Company:
Calmac Manufacturing Corporation (formerly Inc.)
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Contact: Calvin D. MacCracken
Phone: (201) 569-0420

Research and data for Status Report 92-01-0007 were collected during October-December 2001.

Corning Tropel (formerly Tropel Corporation)

Improving Measurement Accuracy and Speed Using Optical, Noncontact Technology

Many precision fabrication industries, such as fuel-injector and bearing manufacturing, rely on precise measurement techniques to sustain dimensional accuracy. During the early to mid-1990s, the primary technologies used to measure surface forms, particularly complex surface forms, failed to keep pace with the growing need to improve speed and accuracy through in-process measurement of these surfaces. Accordingly, Tropel Corporation, one of the world's leading small optics companies, sought to meet this need by developing its unique noncontact, optical interferometric measurement technology. In 1995, the company applied for and received funding through the Advanced Technology Program (ATP) to develop this new technology. By project conclusion in 1998, Tropel had developed a laser interferometry measuring system for complex shapes that increased measurement speed by a factor of 10 to 20 times and improved dimensional measurement accuracy by 2 to 5 times more than the mechanical measurement. Through these research and development accomplishments, Tropel was able to commercialize its CylinderMaster™ machine. Since the project ended, Tropel has sold more than a dozen machines worldwide.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * *

Research and data for Status Report 95-01-0022 were collected during July - September 2001.

Existing Measurement Instruments Were Slow and Costly

Precision manufacturing has always required a great deal of dimensional accuracy. It relies on performing exact measurements of component surfaces during the manufacturing process. Methods used for this type of measurement before the mid-1990s were reliable, but painstakingly slow and costly, causing major bottlenecks that affected the productivity of industries such as automotive and bearing manufacturing. During this time, coordinate measuring machines (CMMs) and precision roundness gauges were the backbone of general-purpose shape measurement; however, these machines had several limitations.

When a large number of points are needed to characterize a surface, the data-acquisition time becomes prohibitive, and the accuracy of the data often deteriorates because of thermal and other drifts. Data acquisition was limited to a few points per second with CMMs. Moreover, these machines did not permit in-process measurement of surfaces, which would let machine operators measure a surface before a process and make any necessary changes before completing the entire manufacturing loop. The need for greater in-process testing to improve the quality of manufacturing processes drove the evolving industry's need to measure machined part dimensions at higher speeds, with greater accuracy, and at lower costs.

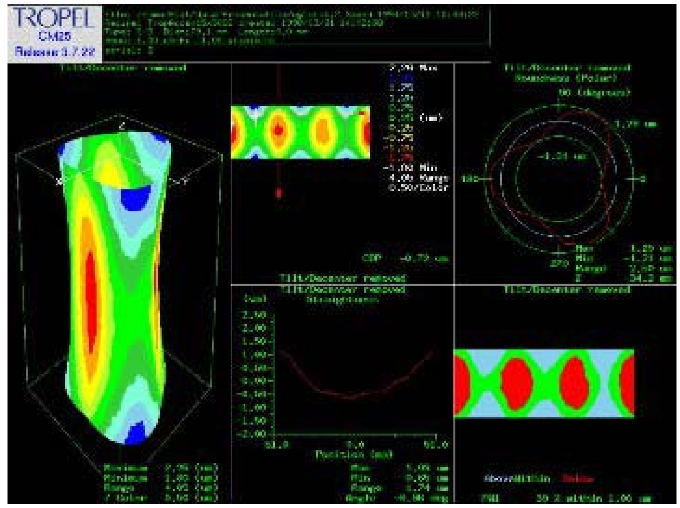
Particularly challenging to the precision manufacturing industry was the need to measure complex shapes, such as cylinders and cones, which had to be measured by physical contact. At the time, most manufacturers used CMMs to perform these measurements. CMMs move tiny contact probes around the surface and build up a set of measurement points that are used to ensure that the object measured is within certain dimensional tolerances. The process was slow, however, and could not be used for real-time control.

Measuring Complex Shapes Requires New Technology

Even companies that had mastered methods for measuring simple, flat surfaces struggled to develop new methods for measuring complex shapes. Tropel Corporation, one of the world’s leading small optics companies, teamed with Cummins Engine to develop a new approach for measuring complex surfaces using optical, noncontact methods.

Particularly challenging to the precision manufacturing industry was the need to measure complex shapes, such as cylinders and cones, which had to be measured by physical contact.

Tropel proposed to investigate advanced optical interferometric methods for measuring complex machined surfaces that would allow in-process characterization of these surfaces. Interferometry had been used successfully for many years to accurately and rapidly measure simple shapes such as spheres and flat surfaces. Common optical systems, such as laser interferometry, worked well for simple surfaces because they were able to accurately create the optical wavefronts that conform to and, therefore, permit the measurement of such surfaces. However, more complex surface forms, such as cylinders and cones, could not be easily measured by these common optical components, because the components were unable to create the complex wavefronts (conical or axiconical) required to test such surfaces. Therefore, accomplishing accurate yet rapid measurements of complex surface forms was challenging. The complexity of the technology and the failures of other CMM manufacturers to develop new methods caused Tropel to seek support for its technology development efforts. In 1995, the company applied for and received ATP funding.



An example of the imaging capabilities that were possible using the CylinderMaster™ machine.

Tropel's unique approach used diffractive optics (DOs) to apply the multiplexing and noncontact advantages of laser interferometry to more complex shapes. The company planned to use DOs to produce complex wavefronts by applying the same lithography techniques that were common in the semiconductor industry for processing silicon wafers. DOs allow wavefronts to be designed or engineered with a nearly arbitrary shape from a software description. Thus, with DOs, interferometry could be used with a much broader class of surfaces, limited only by the ability to mathematically describe the desired wavefront or surface. It was predicted that replacing mechanical measurement systems with laser interferometry systems would improve the speed and accuracy of complex surface measurements.

Tropel Faces Technical and Business Barriers

The project's technical and business risks were particularly daunting for a company as small as Tropel. For example, major technical risks included the use of DOs for this type of measurement, since this technology was in its infancy at the time; the self-alignment and automatic operation elements of the proposed technology; and the fact that completing the dimensional measurements required analyzing large amounts of data.

Assuming technical success, the major business risk was that the techniques proposed were radically different from the existing ones, and no other equivalent technology existed. Tropel knew that there would be a long acceptance period before manufacturers and other end users would readily adopt these technologies.

The new technology increased measurement speed by a factor of 10 to 20 times and improved dimensional measurement accuracy by a factor of 2 to 5 times.

By project conclusion in 1998, Tropel had successfully improved measurement accuracies to the submicron level and had reduced measuring time to less than one minute. Tropel was able to develop a prototype, the CylinderMaster™, which measures shape and form, and Cummins performed tests on this prototype machine. However, as discussed earlier, the measuring machine used techniques that were very different from the techniques normally used at that time. Cummins was dissatisfied with the results of the new technology because the company had difficulty correlating measurements by the prototype machine with data obtained from existing instruments. Consequently, Cummins ended its participation in the ATP project at the testing stage.

Despite losing its strategic partner, Tropel continued developing the technology and was able to perform in-plant demonstrations. Additionally, the company disseminated its knowledge to others, allowing the University of North Carolina at Charlotte to use the machine for research purposes.

CylinderMaster™ Improvements in Speed and Accuracy Lead to Success

The new technology increased measurement speed by a factor of 10 to 20 times and improved dimensional measurement accuracy by a factor of 2 to 5 times.

These improvements allowed Tropel to find enough support for its technology to commercialize the CylinderMaster™ in 1998, shortly after the ATP project concluded.

Through this project, the company successfully developed the basis for its CylinderMaster™ product, which is now being used throughout the world.

Since then, Tropel (now Corning Tropel) has sold more than a dozen machines for $200,000 each. This success has allowed the company to establish a worldwide, three-year sales agreement with Carl Zeiss IMT for Tropel's metrology instruments business.

Conclusion

Manufacturing industries are constantly striving to improve the speed and accuracy of their processes. One major aspect involved in the process is the measurement system that is used to ensure that the parts produced are within the required dimensional tolerances.

Measurement techniques used during the time of this ATP project were fairly accurate, but painstakingly slow. To meet the need for a more precise and quicker method, Tropel sought ATP's assistance in developing its unique optical interferometric measurement technology based on diffractive optics. Through this project, the company successfully developed the basis for its CylinderMaster™ product, which is now being used throughout the world to improve the accuracy and speed with which complex shapes are measured in precision manufacturing plants.

PROJECT HIGHLIGHTS
Corning Tropel (formerly Tropel Corporation)

Project Title: Improving Measurement Accuracy and Speed Using Optical, Noncontact Technology (Noncontact Optical Metrology of Complex Surface Forms for Precision Industrial Manufacturing)

Project: To develop a unique optical interferometric measurement technology based on diffractive optics to enable high-speed, in-process, noncontact measurement of complex shapes, such as cylinders and cones, in a manufacturing environment.

Duration: 8/1/1995-3/31/1998
ATP Number: 95-01-0022

Funding (in thousands):

ATP Final Cost	$ 924	45%
Participant Final Cost	1,115	55%
Total	$ 2,039	

Accomplishments: Through this project, Tropel accelerated the development of its optical measurement technology and achieved important milestones leading to its technological successes. The company improved dimensional measurement accuracies to the submicron level and reduced measuring time to less than one minute. The project's accomplishments also enhanced the company's reputation as an innovative optical metrology company, and they experienced a 10- to 15-percent increase in revenue and employment.

Tropel received the following five patents as a result of technology related to the ATP project:

- "Diffraction management for grazing incidence interferometer"
  (No. 5,719,676: filed April 12, 1996; granted February 17, 1998)
- "Object fixturing in interferometer"
  (No. 5,684,594: filed April 18, 1996; granted November 4, 1997)
- "Fringe pattern discriminator for interferometer using diffraction gratings"
  (No. 5,724,137: filed June 27, 1996; granted March 3, 1998)
- "Interferometric measurement of toric surfaces at grazing incidence"
  (No. 5,889,591: filed October 17,1996; granted March 30, 1999)
- "Interferometric measurement of absolute dimensions of cylindrical surfaces at grazing incidence"
  (No. 5,777,738: filed March 17, 1997; granted July 7, 1998)

The developers of the technology made several presentations and wrote numerous papers explaining the technology. The following presentations and papers are a sampling:

- Kulawiec, A.W. and J.H. Bruning, "Applications of Diffractive Optics to Three-Dimensional Surface Form Measurements," 1996 Annual Meeting of the Optical Society of America, Paper TuH3, Rochester, NY, October 20-24, 1996.
- Kulawiec, A.W., J.F. Fleig, and J.H. Bruning, "Interferometric Measurements of Absolute Dimensions of Cylindrical Surfaces," 1997 Annual Meeting of the American Society of Precision Engineering, Norfolk, VA, October 5-10, 1997.

Commercialization Status: Before this ATP project, Tropel conceived of a cylinder-measuring instrument and had established a proof of concept. Through the ATP-funded project, the company was able to develop a prototype of the metrology instrument. In 1998, after the conclusion of the ATP project, Tropel successfully commercialized its CylinderMaster™ product. They have sold two to three CylinderMasters™ ($200,000 each) per year over the past five years and have established a worldwide, three-year sales and marketing agreement with Carl Zeiss IMT for Tropel's metrology instruments business.

Outlook: Currently, the technology is aimed at a specific, high-end, precision manufacturing segment. Tropel (now Corning Tropel) expects its CylinderMaster™ to experience limited growth over the next couple of years as the firm continues to develop an increased market for the instrument. Corning Tropel is seeking to expand the development of this technology by adding new capabilities that would be useful for process manufacturing, such as the ability to measure size and diameter, in addition to measuring shape and form. The company is exploring additional applications for its technology, such as fiber-optics packaging for the telecommunications industry.

Composite Performance Score: * * *

Number of Employees: 120 employees at project start, 260 as of September 2001

Company:

Corning Tropel
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Phone: (716) 388-3410

Subcontractors and Strategic Partners:

INTI Electronics
Cummins Engine

Research and data for Status Report 95-01-0022 were collected during July - September 2001.

Dana Corporation

Magnetic Pulse Welding Process To Decrease Vehicle Weight and Increase Fuel Efficiency

Looking forward in 1995, automobile manufacturers identified a potential shift in customer preferences to lighter weight, fuel-efficient automobiles; fuel-cell powered cars; and hybrid gas/electric vehicles. To make existing cars more fuel efficient and to meet the coming needs of alternatively powered vehicles, automobile original equipment manufacturers (OEMs) needed lighter components. These same OEMs, however, recognized that the 1995 generation of automobile components was manufactured as light as they could be using the existing technology. Therefore, improved efficiency could only be gained by using new, lighter weight materials, such as aluminum, and new manufacturing processes that reduced the use (and therefore the weight) of steel in welding. The Advanced Technology Program's (ATP) Focused Program, Motor Vehicle Manufacturing Technology, provided Dana Corporation with the necessary funding to develop technology to bond aluminum to steel without depositing additional metal at the weld site. Dana Corporation developed a functional magnetic pulse welding machine prototype to manufacture automobile parts that are two-thirds lighter. Once installed into vehicles, these lighter parts would result in increased fuel efficiency of 8 to 10 percent. Since the project ended in 1998, automakers have contacted Dana Corporation about using magnetic pulse welded materials in their vehicles.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

* * *

Research and data for Status Report 95-02-0055 were collected during October - December 2001.

Current Welding Technology Increases Component Weight

The challenge that the industry faced was how to join different metals together so that the assembled components had the desired stiffness, strength, and dimensional quality. Current manufacturing technologies that provided multi-metallic joints, such as the use of fasteners or adhesives, require additional implementation expense, such as processes and special design features, and may not achieve acceptable levels of strength and dimensional quality. Attachment processes are critical to performance in weight-reduction initiatives involving rotating assemblies, such as driveshafts. Minimizing forcing functions related to both the shaft's mass and dimensional quality necessitated a new assembly approach, especially when using large-diameter, thin-walled tubular components.

The welding method commonly used before this ATP-funded project deposited substantial amounts of additional metal onto the joint. This additional metal was critical to the integrity of the weld because it flowed into the materials to be joined, hardened, and formed into an intermolecular bond. While this bond was extremely strong, the added metal from each weld could increase the part's weight by up to 10 percent, thereby decreasing fuel efficiency.

ATP Funds Development of Magnetic Pulse Welding Process

In 1995, Dana Corporation submitted a proposal to ATP's Focused Program, Motor Vehicle Manufacturing Technology, to develop a novel technology for bonding aluminum to steel without depositing additional metal at the weld site. ATP awarded the company $2.0 million for a three-year research program. The company's proposed magnetic pulse welding process begins by subjecting preshaped aluminum and steel tubular stock to high pressure within precision die cavities machined directly from computer-aided design files. This process, called hydroforming, leads to more precisely fitting structural components, which require little overlap or fill material for the subsequent welding steps.

The welding method commonly used before this ATP-funded project deposited substantial amounts of additional metal onto the joint.

These hydroformed parts are then fitted loosely together. An inductor is utilized either internally or externally to create a rapidly switching magnetic field that causes one of the metallic components to form quickly and finally impact the other "stationary" metallic part with sufficient velocity and force to create a metallurgical bond. Implementation of this process would require new machinery capable of generating proper welds in complex geometric arrangements. Because of these project risks, automobile parts manufacturers had only studied the technology, but had not taken steps to develop it.

New Welding Process Promises Wide-Ranging Benefits

Dana Corporation envisioned that its new process would enhance manufacturing productivity through a simplified welding process that offered a reduction in manufacturing steps, materials, equipment, and personnel expenses. One predicted benefit to the original equipment manufacturers (OEMs) and automobile purchasers was a vehicle frame that was two-thirds lighter, which would result in an 8- to 10-percent improvement in vehicle fuel efficiency. Increased fuel efficiency, in turn, would reduce air pollution. Moreover, Dana Corporation's process could potentially reduce the energy consumed in joining components and eliminate the shielding gases associated with conventional welding, benefits that would further decrease air pollution.

If U.S.-manufactured vehicles became less expensive to manufacture, operate, and recycle, U.S. competitiveness could be enhanced, and domestic

Frames, side rails, cradles, stampings, space frames, and bumper reinforcements are a few examples of automobile products produced more efficiently due to the magnetic pulse welding process.

automobile companies would realize a higher market share. Moreover, the new technology could benefit other industries that need to efficiently join dissimilar metals. Combining hydroforming with magnetic pulse welding could result in nearly limitless possibilities to improve any industry that requires machined metal or welding. New lighter, stronger, and potentially more efficient structures could be created, and costs could be reduced. The strong potential for economic spillover made the project more attractive to ATP.

Dana Corporation Overcomes Project Roadblocks

During the project, Dana Corporation's team faced daunting technical roadblocks that threatened to derail the project. The prototype magnetic pulse welder, as originally designed, forged a new path for shop floor assembly power distribution and required a substantial risk assessment that took many months of the initial installation. The welding process utilized a rapidly changing magnetic field derived from the rapid release of high-voltage and high-current electricity through the welding circuitry. Concerns and design revisions addressed changes to the power distribution and insulation of the elements to prevent the potential of electrical arc-off that could compromise components of the equipment. The Dana Corporation team took nearly a year to resolve these safety problems, and, by October 1996, the machine was operating safely and more efficiently.

A second technical challenge was to determine the proper geometric relationship between the mating components to be welded. The weld angle, for example, ultimately determines a shape configuration that influences the design for hydroformed tube ends. The shape factor is important because precisely formed tubes allow strong, smooth bonds without the need to deposit additional metal on top of deformities. A challenge throughout the project was to understand the relationship between weld angle, part size, and power distributed to the weld surface. After much effort, Dana Corporation determined the appropriate parameters for particular tubes, created prototypes, and sent the prototypes to automobile OEMs for testing. A third technical challenge was to develop consistent metallurgical bonds.

OEMs are rethinking their automobiles' structures and powertrains to find cost savings and fuel efficiencies that were not thought possible before this project.

The goal was to create bonds strong enough that, even under extreme torque, the tube warped before the bond failed. The team achieved this goal; moreover, there was virtually no gross distortion associated with this welding process once the company refined the process. It could be used to join combinations of low-carbon steel, aluminum, and stainless steel in a variety of geometries.

ATP-Funded Technique Applies to Other Industrial Applications

Despite delays, Dana Corporation's advanced welding method has the potential to change entire industries. Dana Corporation engineers continue to work on production technology transfer in this post-project phase and, as of mid-2001, imminent commercialization was anticipated with a machine expected on the production floor by fourth quarter of 2002. Technical issues have been solved, a proof of concept has been developed, and automobile OEMs now recognize the value of magnetic pulse welding. When commercialization is achieved, the new welding process promises to deliver driveshafts that are straighter and lighter, experience less vibration, and enable new geometries that could change the configuration of automobile transmissions and undercarriages.

Dana Corporation's process is the most advanced of its kind in the industry. Automotive industry news indicates that BMW attempted to use friction welding to accomplish a similar result, but could not forge strong enough bonds in their bimetallic driveshafts. According to Dana Corporation executives, because of ATP's funding and the company's innovation, major automobile manufacturers are conducting studies on how to incorporate magnetic pulse welding into their production. Since the ATP project disproved the old paradigm that dissimilar metals could not be structurally welded, OEMs are rethinking their automobiles' structures and powertrains to find cost savings and fuel efficiencies that were not thought possible before this project.

While clearly important to the automobile industry, magnetic pulse welding has wider applicability. Bimetallic welding enables lighter structures in new shapes and allows for cost savings in a way that could revolutionize the design and manufacture of many kinds of metal-based products.

Conclusion

ATP funded the development of a new welding method to join dissimilar metals (something never before accomplished for productive structural shapes). Dana Corporation developed magnetic pulse welding and is poised to begin selling components into automotive production. Moreover, the company received four patents as a result of the ATP-funded project. The company had also filed several other patents that had not yet been granted when this project case study was compiled. Magnetic pulse welding has the potential to change the way many kinds of metal items are manufactured by making them lighter, assembled with greater dimensional accuracy, less expensive, and easier to assemble.

PROJECT HIGHLIGHTS
Dana Corporation

Project Title: Magnetic Pulse Welding Process To Decrease Vehicle Weight and Increase Fuel Efficiency (Advanced Welding Technology-A Phase Shift for Metallurgical Manufacturing)

Project: To develop a versatile manufacturing process (implemented by a new machine that combines a precision metal-forming step with an unconventional welding method that is capable of joining dissimilar metals) to build lower cost, lower weight aluminum and steel load-bearing structures, such as car and truck frames. The process requires precisely crafted and machined tubes of metal bonded by heat generated by a rapidly shifting magnetic field.

Duration: 9/10/95-9/9/98
ATP Number: 95-02-0055

Funding (in thousands):**

ATP Final Cost	$2,000	47%
Participant Final Cost	2,221	53%
Total	$4,221	

Accomplishments: Through ATP funding of this technology, Dana Corporation created a process for welding tubular steel to aluminum without depositing additional metal, overcame technical barriers to join dissimilar metals, enabled new geometries for automobile undercarriages, and maintained the potential to increase fuel efficiency and create a phase shift in automobile manufacturing.

Dana Corporation holds four U.S. patents as a result of this ATP-funded technology and has filed for several others still in the approval process. The patents granted are:

- "Molecular bonding of vehicle frame components using magnetic impulse welding techniques"
  (No. 6,104,012: filed June 14, 1996, granted August 15, 2000)

- "Method of magnetic pulse welding an end fitting to a driveshaft tube of a vehicular driveshaft"
  (No. 5,981,921: filed June 20, 1997, granted November 9, 1999)

- "Method for joining vehicular frame components"
  (No. 5,966,813: filed December 13, 1997, granted October 19, 1999)

- "Molecular bonding of vehicle frame components using magnetic impulse welding techniques"
  (No. 6,234,375: filed August 22, 1998, granted May 22, 2001)

Commercialization Status: Despite delays, Dana Corporation views commercialization of the technology as imminent. The only remaining barrier is to complete extensive durability testing at original equipment manufacturer (OEM) sites, something Dana Corporation expects will occur by the end of 2002. The big U.S. automakers, as well as European companies, have contacted Dana Corporation about using magnetic pulse welded materials in their vehicles. Moreover, the company is ready to provide component parts for fuel-cell or hybrid-electric cars, if and when they are produced in larger volume.

Outlook: The outlook for this technology is good. Safety-related concerns and other manufacturing difficulties delayed commercialization of this manufacturing process, but Dana Corporation has overcome these difficulties. If commercialization occurs as planned, the benefits to automobile manufacturers, automobile purchasers, other industries requiring metal components, and the U.S. economy as a whole could be substantial.

Composite Performance Score: * * *

Focused Program: Motor Vehicle Manufacturing Technology, 1995

Company:
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Contact: Bob Durand
Phone: (610) 371-7111

** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 95-02-0055 were collected during October - December 2001.

General Electric Corporate Research & Development

Mercury-Free Lighting Could Provide Environmental and Economic Benefits

In 1994, William Woodburn, then vice president of worldwide marketing for General Electric (GE) Lighting, made the following statement regarding the lighting industry: "What was a relatively stable industry dating back to Thomas Edison's invention, with innovations coming at an evolutionary pace, has accelerated into a revolutionary outpouring of new technology and new products." During the early 1990s, many companies engaged in research and development to create technologies that would lead to further innovation in this field. One impetus behind these initiatives was the need to create lighting systems that are friendlier to the environment, a goal that led companies to focus on developing mercury-free lighting technologies. Many of these efforts centered on an earlier innovation-fluorescent lighting. GE focused on developing mercury-free fluorescent lighting because it recognized the technology's potential economic and environmental benefits. Because the technical risks were too high for internal funding, given the required rates of return when compared with less environmentally friendly products, GE submitted a project proposal in 1993 to seek co-funding from the Advanced Technology Program (ATP). Although the company did not achieve its goal of developing mercury-free fluorescent lighting for existing sockets, it did advance the state of the art of mercury-free fluorescent lighting. GE also used the technologies developed during this three-year project to improve conventional fluorescent lighting. Moreover, the company published papers and gave presentations on the subject and received three patents for technologies related to this ATP project.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 92-01-0132 were collected during October – December 2001.

Mercury-Filled Products Burden the Lighting Industry

For more than 62 years, fluorescent lighting has been used in offices and homes as a low-cost, energy-saving power source. Fluorescent bulbs last longer, are more energy efficient than incandescent bulbs, and have reduced the load on power plants. But there is a downside, fluorescent tubes contain mercury vapor, a substance that is toxic. In the early 1990s, it cost $275 million annually to dispose of fluorescent tubes in an environmentally sound manner, greatly burdening the industry and its end users. In fact, during this period, several states enacted legislation to ban or limit the disposal of any products containing mercury.

Fluorescent tubes contain mercury vapor, a substance that is toxic. In the early 1990s, it cost $275 million annually to dispose of fluorescent tubes, greatly burdening the industry and its end users.

Two essential elements are involved in fluorescent lighting: plasma and phosphors. In a fluorescent tube, electrical energy is used to excite electrons in conducting plasma, which emits ultraviolet photons that then strike a phosphorescent layer on the inner surface of the tube, emitting visible light. Mercury is used in plasma because it converts electrical energy into relatively low-energy ultraviolet photons with a high level of efficiency.

Phosphor and Plasma Technology To Replace Mercury-Filled Systems

In 1992, GE proposed to use ATP co-funding to develop a lighting source that was more environmentally safe and as cost efficient as the original fluorescent bulb. GE pursued research to develop a low-pressure xenon-positive column discharge, which would excite the phosphor to create white light.

GE proposed to use ATP co-funding to develop a lighting source that was more environmentally safe and as cost efficient as the original fluorescent bulb.

This discharge would replace the mercury gas discharge used in existing fluorescent lamps. GE's plan was to develop the two essential parts of the lamp: 1) the mercury-free discharge to produce the ultraviolet light and 2) the quantum-splitting phosphor that would convert the ultraviolet light into acceptable visible light. To replace the mercury, it was necessary to find a low-pressure plasma source that was comparable to the high efficiency level of mercury (roughly 65 percent) and was compatible with existing phosphors.

The difficulty was to create a mercury-free product that could be used immediately in current socket structures, since GE anticipated there would be low market penetration for a product that used new socket structures. Therefore, the company decided to concentrate its efforts on developing commercial phosphors and on lowering the amount of mercury in its current fluorescent lights, rather than creating a new mercury-free product. The technical risks for this project were too high to allow GE to use internal funds because other, less environmentally friendly products could produce a higher rate of return. The potential broad benefits to the economy and the environment from this project, however, could be significant.

Partnerships Contribute to Technical Success

GE's alliance with ATP gave the company access to rich resources throughout the life of the project and allowed GE to gain the support of valuable university subcontractors to perform some of the research. For example, the California Institute of Technology studied circuit topologies in an effort to develop a ballast prototype to contain the mercury-free light. (The ballast starts the lamp and then regulates the electric current that flows into it.) The University of Wisconsin helped in assessing plasmas as ultraviolet light sources. Access to the expertise at these universities proved invaluable to the research.

GE achieved spin-off benefits related to the development of quantum-splitting phosphors. The completed work on quantum-splitting phosphors led to an increased interest among universities.

Through ATP, GE met another ATP award recipient, Photonics Imaging, which manufactures plasma flat panel displays (PFPDs). A technology overlap existed between GE's primary path in this project and Photonics Imaging's primary path in developing PFPDs. GE's path involved low-pressure xenon-positive column discharge and an efficient phosphor used to create white light. Photonics Imaging's path was aimed at an intermittent atmospheric-pressure discharge in a gas mixture containing xenon, which excites phosphors to create red, green, and blue pixels. Through discussions regarding similar uses of phosphor technology, the companies shared knowledge that proved valuable to both efforts.

GE Encounters Technical Difficulties, but Realizes Spin-Off Opportunities

GE was able to achieve operating conditions under which a direct-current xenon discharge reached approximately two-thirds of the efficiency and output of a conventional fluorescent lamp. Unfortunately, the research team was not able to achieve its goal of a candidate discharge (low-pressure xenon-positive column) that was highly efficient at a high-discharge power density.

However, GE achieved spin-off benefits related to the development of quantum-splitting phosphors as well as technologies that can be used in any type of fluorescent lighting. The completed work on quantum-splitting phosphors led to an increased interest among universities and within GE to further develop such phosphors. GE is currently pursuing additional research and development efforts in this area.

The following technologies developed through this ATP project can be used in any type of fluorescent lighting:

- Lifelong, low-pressure cathodes, which led to higher lamp efficiency, lower ballast costs, and better performance from lamps that are frequently switched. These cathodes are used in a range of applications, from basic lighting to electron microscopes and plasma cathode electron guns.

- Electronic ballasts, which have advantages over conventional electromagnetic ballasts, including smaller size, lower weight, higher efficiency, and faster starting and dimming capability. This cheaper, more efficient method of applying power electronics to improve traditional fluorescent lighting eliminates flickering and reduces the acoustic noise associated with fluorescent bulbs.

- Electromagnetic shielding of ballast, lamp, and phosphors, which led to higher efficiencies by protecting the power system from spikes in energy and from the heat of the lamp.

Conclusion

Through the research performed during this project, GE made advances in the design and production of quantum-splitting phosphors. Although GE was not able to develop a mercury-free fluorescent light that is as efficient as mercury filled lights, the technologies developed have been used to improve conventional fluorescent lighting. For example, oxide quantum-splitting phosphors are being used generically in conventional fluorescent lights and in the development of miniature lamps.

PROJECT HIGHLIGHTS
General Electric Corporate Research & Development

Project Title: Mercury-Free Lighting Could Provide Environmental and Economic Benefits (Mercury-Free Fluorescent Lighting)

Project: To demonstrate the feasibility of developing an environmentally safe, cost-competitive fluorescent lamp source that is as efficient as the currently used mercury-filled fluorescent lamps.

Duration: 5/10/1993-5/9/1996
ATP Number: 92-01-0132

Funding (in thousands):**

ATP Final Cost	$1,336	40%
Participant Final Cost	2,044	60%
Total	$3,380	

Accomplishments: Through the ATP funded project, GE made improvements in the design and production of quantum-splitting phosphors. Although the company did not develop efficient mercury-free fluorescent light, the technologies developed have been used to improve conventional fluorescent lighting. GE also accomplished the following:

- Achieved a breakthrough in getting quantum-splitting phosphors to work in everyday chemicals (oxide-based) that are regularly used in manufacturing
- Published several technical papers and gave presentations regarding the mercury-free fluorescent lamp program and research that was conducted during the project
- Received the following patents for technologies related to the ATP project:
  - "Quantum splitting oxide phosphor and method of making"
    (No. 5,571,451: filed January 3, 1995, granted November 5, 1996)
  - "Determination process for determining if quantum splitting phosphors are obtained and novel compositions"
    (No. 5,788,883: filed February 28, 1997, granted August 4, 1998)
  - "Mercury-free ultraviolet discharge source"
    (No. 5,866,984: filed November 6, 1997, granted February 2, 1999)

Commercialization Status: GE was not able to commercialize the technologies that were developed under this project. The company is continuing to work to develop a commercial phosphor, however, and is concentrating its efforts on lowering the amount of mercury in existing fluorescent lights.

Outlook: While a clear path does not seem to exist for replacing mercury-filled fluorescent lighting with a mercury-free product, the research and development conducted during this project has led to further development in fluorescent technology. GE continues to improve its ability to measure phosphor-quantum efficiencies and to assess new candidate phosphor material, working toward its goal of developing a quantum-splitting phosphor that can be manufactured.

Composite Performance Score: *

Company:
General Electric Corporate Research & Development
One Research Circle
Niskayuna, NY 12309

Contact: Dr. Timothy Sommerer
Phone: (518) 387-6440

Subcontractors:
California Institute of Technology
University of Wisconsin

** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 92-01-0132 were collected during October – December 2001.

Ingersoll Milling Machine Company

Octahedral Hexapod Design Promises Enhanced Machine Performance

In the field of advanced machine tools, enhanced performance is seldom achieved without greater design complexity, reduced operational flexibility, and higher costs. These drawbacks have stalled innovation in the U.S. machine tool industry, where most research and development (R&D) efforts focus on incremental improvements to conventional machines. Ingersoll Milling Machine Company developed its octahedral hexapod prototype, which promised superior accuracy, stiffness, and speed, as well as lower prices, shorter delivery times, simpler assembly, and greater accessibility. Further development of the octahedral hexapod tool concept had the potential to boost U.S. status in a competitive international market and to bolster smaller manufacturing companies by meeting their need for high-precision machine tools at an affordable price. However, because the industry viewed Ingersoll's prototype as a radical design and its continued development as too high risk to fund, the company sought and received funding from the Advanced Technology Program (ATP).

Since 1996, when the project ended, sales of the octahedral hexapod machine have been limited to three laboratories. However, Ingersoll's R&D during the ATP project laid the foundation for eventually bringing the octahedral hexapod to maturity. Moreover, the company's efforts have resulted in additional research by two-dozen machine companies that are currently investigating this machine tool.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

*

Research and data for Status Report 92-01-0034 were collected during October - December 2001.

Manufacturing Industry Needs More Precise Tools

The machine tool industry depends heavily on stacked-axis computer-numerical-control (CNC) machines, which achieve a specified position and orientation of the spindle by controlling individually as many as six positioning axes (X, Y, Z, roll, pitch, and yaw). The CNC commands up to six separate movements, each performed independently, whose combined effects produce a target position. However, the stacked-axis machine architecture generates cumulative error. This occurs because inexact positioning on one axis dislocates the positioning of the spindle on the next axis, which multiplies the imprecision with each subsequent adjustment. In addition to this design shortcoming, the traditional stacked-axis machine requires a massive granite foundation for stability. This results in a cumbersome unit that takes up considerable factory floor space and is difficult to transport.

The manufacturing industry desired a more precise tool. The development of a high-precision, low-cost machine tool became imperative for small companies' ability to enhance the quality of U.S. products. Moreover, innovation was vital for the United States to improve its position in the machine tool industry (the nation lagged behind Japan and Germany in a competitive market, with domestic manufacturing companies importing $1.6 billion in machine tools in 1991).

The Octahedral Hexapod Offers Promise

In 1987, a radical concept caught the attention of engineers at Ingersoll. Eventually called the octahedral hexapod, this novel design creatively employs the Stewart platform concept, most commonly known for its application in flight simulators. The Stewart platform, a floating base supported or suspended by six actuators, is familiar to several generations of pilots (it was the basis for the design of the Link flight simulator).

The octahedron, a regular geometric shape of eight equilateral triangles, is built on an octahedral frame and a Stewart platform actuation, the hexapod. Machining operations take place within the octahedral frame, and the struts, or the pods of the hexapod, directly translate the force generated during the machining operation to the six vertices of the octahedral frame. The shape has such stiffness that when a load is applied, the frame responds by distributing the weight of the load evenly throughout the shape, eliminating much of the bending because of the shape's stiffness. Furthermore, the six axes are in simultaneous movements rather than the independent sequential movements experienced with the CNC machine. Hence, the shape of the octahedral hexapod tool would offer six times the machine stiffness and five times the position accuracy of the traditional CNC machines.

Under the ATP award, Ingersoll planned to use a laboratory prototype octahedral hexapod machine (which they had constructed prior to the ATP project with their own funding) to develop detailed baseline data on the performance of the design. Then they would try various enhancements to improve and measure machine precision. The results would be used to design a future class of commercial machines based on the octahedral hexapod concept.

ATP Provides Early Catalyst for R&D Proliferation

As indicated by the numerous predicted uses of the octahedral hexapod, this technology has the potential to substantially impact a wide range of manufacturing industries across the supply chain. However, the risk of funding research for such a radical design was too high for either machine tool companies or their manufacturing clients. Moreover, if Ingersoll absorbed the cost of the extensive R&D required to fully develop the octahedral hexapod, it would have to subsequently increase the cost of its machine tools by at least 20 percent. This cost escalation would put their products in a range that would be prohibitive for many smaller companies, such as those who provided parts for the automobile industry.

The concept demonstrated the potential to evolve into a machine tool that offered double the accuracy at a selling price and life cycle cost that was 30 percent less than that of the best existing technology. Therefore, ATP awarded cost-shared funding to Ingersoll.

Project Slowly Overcomes Technical Obstacles

With a prototype of the octahedral hexapod as a starting point, Ingersoll set out to design and develop several applications to achieve the machine tool's maximum potential for improved accuracy and precision. Though the design concept itself was in place, other components essential to achieving these performance objectives needed to be developed.

This technology has the potential to substantially impact a wide range of manufacturing industries.

A key step of this process was the development of a computer control system and accompanying software that were capable of processing the complex algorithmic calculations necessary to command the parallel movement of the hexapod's six struts. To direct these complicated six-axis moves in real time, the processor requires a calculation power equivalent to that of several fast PCs combined. Additionally, the software needs to compute error as well as offset data, thermal deviations, and compensation formulas. During the project, Ingersoll worked with software suppliers GE Fanuc and Siemens to incorporate software algorithms into a central control system, taking important strides toward the full computerized alignment envisioned for ideal accommodation of the octahedral hexapod. Ingersoll was able to begin the development of the system during the ATP project. However, the development and programming of such a system proved to be extensive and time-consuming, demanding R&D beyond the timeframe of the ATP project.

Ingersoll also faced the challenge to develop a calibration system that would guarantee high-level accuracy, enabling the machine tool to manufacture parts repeatedly within specified tolerances. Because of its design, the octahedral hexapod concept did not lend itself to conventional inspection techniques. Therefore, before it could be commercialized, Ingersoll needed to develop a turnkey calibration method that could be performed more quickly and efficiently than the existing labor-intensive procedure. To this end, the company worked to implement a self-calibration system that would allow machines to check their own performance and correct any detected inaccuracies.

In addition to these tasks to install control and calibration systems, Ingersoll encountered obstacles in developing the supporting electronic and mechanical components of the octahedral hexapod machine tool. However, the company maintained steady and productive R&D efforts throughout the ATP project, continuing to demonstrate promise for eventual commercialization and revealing more and more possible applications.

Sustained R&D Points to Commercialization on the Horizon

At the conclusion of the project in 1996, the technology components of the octahedral hexapod were well understood; however, six years later, the machine tool was still in development. While several fully functional hexapods exist, researchers must improve their accuracy, streamline the production process, develop standards, and solve small but important mechanical problems before pursuing full-fledged commercialization. Based on the interest generated by Ingersoll's original prototype, there are currently about two-dozen companies that have invested R&D funds in hopes of bringing the Ingersoll hexapod to market.

> ***The company maintained steady and productive R&D efforts throughout the ATP project, however, six years later, the machine tool was still in development.***

Ingersoll has sold three octahedral hexapods, one each to the National Institute of Standards and Technology (NIST), Lockheed-Martin's research facility, and Aachen University. Because Ingersoll's current goal is the evaluation of production techniques rather than sales, only a national laboratory, a large corporate research facility, and a university have purchased hexapods. Octahedral hexapods are custom-made because Ingersoll has not developed a protocol for high-volume, quick, and affordable manufacturing. Future research will address production problem areas, such as computer control systems and struts, which together account for 75 percent of the machine tool's cost. Other research will focus on simplifying the hexapod's design, since reducing the number of machine parts could lower costs by an estimated 40 percent.

Calibration, control, and thermal compensation issues persist as roadblocks to commercialization, reducing the octahedral hexapod's ability to repeatedly manufacture parts within specified tolerances. Using an octahedral hexapod purchased from Ingersoll, a project at NIST's Manufacturing Engineering Laboratory, supported in part by ATP intramural funds, is addressing these problems by setting common performance-evaluation procedures and developing measurement methods to achieve high positioning accuracy.

Scientists at NIST have focused on implementing a built-in metrology system and an enhanced machine controller that simplifies performance-enhancing modifications in software or hardware. Ingersoll has improved thermal compensation techniques by using laser feedback that senses and eliminates deviant length changes of the hexapod's struts. Additional post-project research will determine the optimal machine configuration and the most advantageous strut length given a particular working envelope size (the work area).

Researchers Identify Multiple Uses for the Octahedral Hexapod

As researchers assessed the mechanical and electronic specifications for the octahedral hexapod, they discovered the versatility and flexibility of this machine tool. Engineers at Ingersoll predict that the hexapod could become a general manipulator for various tasks or a universal carrier for several end effectors, such as milling heads, coordinate measuring machine probes, and turning tools. These engineers anticipate that current R&D efforts will lead to the octahedral hexapod's role in numerous applications, including the following:

- Mold and die industry uses, such as contouring large surfaces and machining dies for precision sheet-metal forming
- The machining of high-value, low-volume, high-complexity components, such as titanium for use in military aircrafts
- The machining of lighter metals and materials

- Precision assembly technology; for example, delicate welding in an automotive assembly line and in aerospace and aircraft production

Conclusion

Dennis Bray, vice president of engineering at Ingersoll, reports that the current configuration of the octahedral hexapod would not have been designed without ATP funding. The ATP project allowed Ingersoll to tackle a number of the deficiencies identified in the original prototype and to bring the hexapod closer to full-scale development. Additionally, ATP funding helped to validate the unconventional concept and design of the octahedral hexapod, convincing other machine tool companies of its worth and generating further investment in its R&D. Although commercialization of the octahedral hexapod machine tool has stalled, Ingersoll continues to research methods to improve accuracy, streamline the production process, and develop the ability to manufacture parts repeatedly within specified tolerances, with reasonable production costs.

PROJECT HIGHLIGHTS
Ingersoll Milling Machine Company

Project Title: Octahedral Hexapod Design Promises Enhanced Machine Performance (Octahedral Hexapod Machine Development Program)

Project: To demonstrate a revolutionary new design for high-precision, multi-axis machine tools based on an octahedron frame and a Stewart platform actuator.

Duration: 3/1/1993-2/28/1996
ATP Number: 92-01-0034

Funding (in thousands):

ATP Final Cost	$ 1,864	53%
Participant Final Cost	1,635	47%
Total	$ 3,499	

Accomplishments: Ingersoll has sold three octahedral hexapod machine tools, one each to NIST, Aachen University, and Lockheed-Martin's research facility, to be used for further R&D. The company performed several demonstrations of its prototypes to potential clients such as Boeing Corporation and the U.S. Air Force. These demonstrations created interest and generated constructive feedback.

Ingersoll received the following patent for its work:

- "Octahedral machine tool frame"
  (No. 5,392,663: filed November 9, 1993, granted February 28, 1995)

Commercialization Status: Due to the need for additional research, Ingersoll has not been able to fully commercialize the octahedral hexapod. However, the company has sold three of these machine tools, generating $6 million in revenue.

Outlook: The outlook for the octahedral hexapod is clouded. At this point, researchers at Ingersoll have been unable to combine accuracy and the ability to manufacture parts repeatedly within specified tolerances with reasonable production costs. This has stalled the commercialization of the octahedral hexapod machine tool. However, several companies continue to research the octahedral hexapod tool concept.

Composite Performance Score: *

Company:
Ingersoll Milling Machine Company
707 Fulton Avenue
Rockford, IL 61103

Contact: Dr. Dennis Bray
Phone: (815) 987-6891

Research and data for Status Report 92-01-0034 were collected during October - December 2001.

M&M Precision Systems Corporation

World's Most Accurate Gear-Measurement Machine

Automobile transmissions, submarine screws, and helicopter rotors can all be made quieter, smoother running, and more efficient with enhanced gear precision. By the 1980s, American gear-measurement instruments were beginning to lag behind the accuracy of gear-manufacturing technology, and the gear-measurement market shifted toward foreign-made instruments that had a higher level of accuracy. In 1994, M&M Precision Systems Corporation, in collaboration with Pennsylvania State University, submitted a proposal to the Advanced Technology Program (ATP) to develop a highly accurate gear-measurement machine. ATP awarded co-funding for a three-year project, and M&M subsequently successfully developed gear-measurement technology that was more than five times more accurate than existing U.S. gear-measurement tools. The technology was later commercialized, which increased the U.S. share of the global gear-measurement machines market to 50 percent and led to a resurgence of confidence in the accuracy of American gears.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* *

Research and data for Status Report 93-01-0191 were collected during October – December 2001.

Gear Precision Inaccuracy Harms U.S. Gear Industry

Gears have been used for centuries and are critical mechanical elements in the operation of a device that requires a transfer of motion and power to enable rotation. A mainstay of civil and military engineering, gears are in virtually all motor vehicles, aircraft, machine tools, and military combat vehicles. One of the constants of the industry is that as gears become more exact, their operation becomes smoother, quieter, and more efficient As gear-manufacturing technology became more complex, however, it was more difficult to perform gear measurements with the degree of accuracy required; thus, precision in gear manufacturing began to suffer. Partly as a result of this declining precision, the U.S. gear industry began to suffer, and German firms began taking more dominant control of the world market.

M&M Proposes World's Most Accurate Gear-Measurement Machine

No single company or organization had the capabilities or could afford the investigation required to research and identify the problems with gear-measurement machines. Therefore, M&M teamed with Pennsylvania State University to study current gear-measurement technology, to identify and eliminate weaknesses, and to create the world's most accurate gear-measurement machine.

ATP Funds Development of New Technology

Recognizing that the future of both the U.S. gear and gear-measurement industries depended on improvements, ATP funded the research and development of new gear-measurement technology.

M&M teamed with Pennsylvania State University to create the world's most accurate gear-measurement machine.

Awarded in 1994, the ATP grant provided a fresh start to the industry-an opportunity to reassess the technology, correct existing problems, and develop breakthrough technologies to enhance the precision of gear measurement. Moreover, the potential for

M&M's 3500-series machine has automatic software-driven correction, rotary axis motion, and new control technology.

far-reaching economic spillover was high. The technology would impact the nation's 350 gear and gear-related component manufacturers.

M&M Addresses Technical Issues

First, M&M engineers had to correct errors inherent in the operation of gear-measurement machines. Gear-measurement machines typically rotate the gear and compare the specimen with precise measurements taken from the appropriate gear mold. Gear-measurement machines cannot hold a specimen perfectly still, which causes errors in the final measurement. To solve this problem, M&M developed algorithms for the computer correction software that adjusts measurements for errors caused by the gear-measurement machine itself. Second, M&M tried to incorporate a linear motor into the gear-measurement machine to enable "on-the-fly" operation. Typically, gear-measurement devices set the gear in one place, take a measurement, move the gear to another fixed spot, and take another measurement. This is a time-consuming process, and M&M sought to improve the speed of gear-measurement machines by taking laser measurements as the gear rotated. Unfortunately, linear motors did not run smoothly enough to allow accurate measurements, and the gear-measurement machines resulting from the project did not have the desired on-the-fly measurement capability. In the years following the ATP project's completion, however, linear-motor technology advanced to the point where the second generation of M&M gear-measurement machines now has this capability.

ATP Project Leads to Technology and Knowledge Spillover

What began as a partnership with Pennsylvania State University evolved into a coalition of several universities. After the ATP project, M&M entered into cooperative research agreements with professors and laboratories at the University of North Carolina, Ohio State University, and the University of Toledo. Not only do these alliances generate new innovations from the academic labs, but they also train students to enter industry fully prepared to operate in, and improve upon, cutting-edge technology. According to Dean Hawk, M&M's ATP principal investigator, gear-measurement software technicians typically are not productive for the first four to six months of their tenure in the industry because they must climb a steep learning curve. Recently hired graduates of the collaborating universities, however, are capable of stepping in and being productive from day one.

Conclusion

As a result of this ATP project, M&M brought its 3500-series machine to market in 1998. The machine's most important innovations were automatic software-driven correction, rotary axis motion, and new control technology. The 3500-series machine measures spaces between gear teeth to within 0.22 uncertainty microns and provides an entire tooth profile to within 1.3 microns. This represents improvements over prior capabilities of 78 percent and 74 percent, respectively. The 3500-series machines developed through this project helped M&M to gain approximately 50 percent of the world's market share for gear-measurement machines and to increase its U.S. market share to 70 percent in the years after the project concluded. According to an M&M executive, more accurate gears enabled the U.S. automobile industry to increase the quality of its transmissions. Moreover, in the defense industry, U.S. submarines and aircraft are now the quietest in the world, in part because of their more precise gear operation.

PROJECT HIGHLIGHTS
M&M Precisions Systems Corporation

Project Title: World's Most Accurate Gear-Measurement Machine(Advanced Gear-Measurement Technologies to Achieve Submicron-Level Accuracies)

Project: To create a new generation of gear-measurement machines, which were necessary to enhance the accuracy of American-made gears, to create smoother running transmissions, and to maintain market share for gear-measurement machines within the United States.

Duration: 4/1/1994-3/31/1997
ATP Number: 93-01-0191

Funding (in thousands):

ATP Final Cost	$1,950	64%
Participant Final Cost	1,093	36%
Total	$3,043	

Accomplishments: This ATP project led to a revolution in gear-measurement technology and innovations in motor-powered transportation transmissions that were not possible before the project. By starting over and aiming to design the perfect gear-measurement machine, M&M achieved submicron-level accuracy in gear measurement. This ATP-funded project generated the following new technologies and process improvements:

- Automatic computer-controlled error-correction software
- Rotary-axis technology, enabling smoother and faster gear measurements
- New control technology, enabling a smoother, more precise gear motion during measurements

Commercialization Status: Before this ATP project, no U.S.-based company had the ability to measure gears to less than one-micron accuracy. Because this measurement inability created uncertainty about the precision of U.S.-manufactured gears, U.S. industrial customers turned to foreign companies for both gears and gear-measurement systems.

The error-correction software and control mechanisms developed by M&M during this ATP project were later commercialized into the 3500-series measurement machine. The 3500-series machine measures spaces between gear teeth to within 0.22 uncertainty microns and provides an entire tooth profile to within 1.3 microns, an improvement over previous capabilities of 78 percent and 74 percent, respectively.

The 3500-series machines helped M&M gain approximately 50 percent of the world's market share for gear-measurement machines and to increase its U.S. market share to 70 percent. Additionally, the technology had an immediate impact on the 350 gear and gear-related component manufacturers within the United States. The many improvements developed during M&M's ATP project have been incorporated extensively into automobile transmissions, submarinescrews, and helicopter rotors.

Outlook: The prototype machine developed through this ATP project continues to be the gear-measurement industry's "gold standard." The newest generation, which made its debut at gear shows in Detroit and Germany in late 2001, includes linear motors for on-the-fly measurement, in addition to the improvements already made through the ATP-funded project. These machines should continue to dominate the gear-measurement industry, allowing quieter, smoother running transmissions and gear assemblies for the foreseeable future.

Composite Performance Score: * *

Number of Employees: Seventy-seven employees at project start, 70 upon completion of status reports.

Company:
M&M Precision Systems Corporation
300 Progress Road
West Carrollton, OH 45449

Contact: Dean Hawk
Phone: (937) 859-8273

Research and data for Status Report 93-01-0191 were collected during October – December 2001.

Perceptron (formerly Autospect, Inc.)

Laser Ultrasonics to Improve Automotive Painting Process

Whether the hue is sports-car red, school-bus yellow, or sleek black, the automotive painting process has frustrated manufacturers for years. Of all automotive manufacturing processes, painting has historically been the most costly ($345 per vehicle in 1995) and arguably the most painstaking, involving 13 discrete steps. Moreover, the slightest inaccuracy can cause corrosion, adhesion, and poor finish, requiring that the auto body undergo a costly repair process. Existing paint-thickness-measurement systems could only measure dry paint, so by the time controllers detected errors and made proper adjustments, paint-booth operators had often coated up to 100 more units. To remain competitive, U.S. automotive manufacturers needed an accurate and reliable non-contact method for online paint-thickness measurement, and in 1995, Autospect proposed to develop a new wet-paint-thickness measurement system using its existing laser ultrasonics (LU) method.

Autospect suggested that three significant benefits would accrue to the industry: savings of $683 million annually for the Big 3 auto manufacturers (Ford, General Motors, and DaimlerChrysler), improved vehicle quality, and lower volatile organic chemical emissions. Due to the technical risk, direct funding from the Big 3 was unavailable; they did, however, commit to participating in the project's process integration stage. In 1995, Autospect was awarded $1.8 million in cost-shared funding from the Advanced Technology Program (ATP) to develop a wet-film-measurement (WFM) system. By the end of the ATP project in 1998, Perceptron had successfully produced a prototype LU WFM system for a DaimlerChrysler test site. Though the prototype WFM system has proven its value and technical viability, Autospect (now Perceptron, which acquired Autospect in 1997) encountered severe financial difficulties in 1998 that have forestalled its ability to commercialize the technology.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
*

Research and data for Status Report 95-02-0005 were collected during October - December 2001.

Measurement Techniques Fail to Simplify Painstaking Painting Process

In the early 1990s, the painting process represented a disproportionate amount of the total automobile manufacturing costs and labor requirements, requiring several expensive materials and 13 discrete steps to coat a bare-metal auto body with a high-quality finish. Additionally, painting errors were frequent and costly, and the paints and solvents used posed a threat to the environment. Consequently, there was increased pressure from both consumers and environmentalists to produce high-quality finishes through efficient methods.

For example, a 1994 Delphi study indicated that 50 percent of consumer appeal and satisfaction derives from factors directly or indirectly related to the automobile's paint job, such as appearance, durability, and resistance to scratching. Further, amendments to the 1989 Clean Air Act limited the discharge of volatile organic chemicals (VOCs), thereby requiring automotive manufacturers to consider the environment by more efficiently using paints and solvents.

Before the ATP project, existing paint-thickness-measurement methods failed to help automotive manufacturers address these concerns or to reduce the high cost of painting each vehicle. At the time, non-contact-measurement techniques were not reliable outside the laboratory, so magnetic-inductance methods, including the Elcometer and the Fischer Scope, were the only available paint-measurement technologies. Both of these methods were extremely time-consuming. After each coat (i.e., the electrocoat, primer, base coat, and clear coat), manufacturers had to wait for the coat to dry and then had to remove the test vehicle from the assembly line for inspection of the coat at 60 to 80 points on the car's surface.

Fifty percent of consumer appeal and satisfaction derives from factors related to the automobile's paint job.

With these costs, manufacturers could only afford sampled quality control, measuring approximately 1 to 3 cars per day, or about 1 out of every 500 vehicles. Moreover, the slowness of the quality control contributed to poor feedback response time. By the time quality control detected a problem and made proper adjustments, up to 100 vehicles had passed through the defective painting production line. Manufacturers had to repair all vehicles with defective paint coatings by using one or both of the low bake repair (LBR) and high bake repair (HBR) processes, at a cost of $600 to $1,200 per vehicle in 1995. In some extreme cases, the manufacturer had to completely scrap the vehicle. At the time of the ATP project, 15 percent of all vehicles required HBR, putting a massive strain on overall automotive production budgets.

Autospect Proposes a More Efficient Coating Process

To address the problems that riddled the automotive painting process, Autospect proposed to develop a wet-film-measurement (WFM) system that would provide non-contact inspection and online measurement. This process would eliminate the need for an operator and would allow manufacturers to measure every vehicle, thus reducing the time it took them to detect and respond to problems in the coating process. Thickness and distribution information would feed back immediately to logic controllers that controlled paint flow to sprayers, reducing the number of vehicles that passed through the process after error detection from up to 100 units to just 1 to 2 units. With accumulated feedback data, manufacturers could correlate wet-film-build measurements with flow-control methods so they could predict future behavior and develop more precise systems.

Reduced paint use and reduced defects would save $683 million annually for the Big 3 manufacturers and would lower costs and improve quality for consumers.

Autospect envisioned a non-contact WFM system that included a precise and reliable instrument for the online measurement of paint thickness and that provided closed-loop feedback in real time for the painting process. The proposed system would function in the hostile environment of the factory paint booth, withstanding paint splatter, temperature and humidity fluctuations, and exposure to evaporated solvents, without performance degradation.

Broad-Based Benefits Extend to the Environment and Consumers

The proposed WFM system also promised broad-based economic benefits. The automotive industry would reap significant advantages, as demonstrated in Autospect's cost-benefit analysis. Before the ATP project, 106 of the 168 paint production lines in North America used Autospect's existing QMS-I and QMS-BP products. Thus, the company's equipment assisted in the production of nine million vehicles annually. The average cost of paint required to coat a vehicle was $345. Unfortunately, up to 60 percent of the paint was wasted due to inefficient production processes. Therefore, a measurement system that reduced excess paint could lead to savings of up to $200 per vehicle. Conservatively estimating that its WFM system would save $50 in paint per vehicle, Autospect projected an annual savings of $360 million for its existing customer base. Because figures indicated that 15 percent of all vehicles required HBR at a cost of at least $600 per vehicle, a system that prevented painting defects could save Autospect's customers another $323 million annually. Thus, reduced paint use and reduced defects resulting from the company's WFM system would save $683 million annually for the Big 3 manufacturers and would lower costs and improve quality for consumers.

Autospect also expected that consumers would benefit from improved vehicle appearance as well as from reduced repair costs related to low-quality paint coats that easily scratch and corrode. Autospect identified the environment as another beneficiary, since a more efficient painting process would lead to lower VOC emissions. Further development of a WFM system could provide advantages to other industries in which the painting of large surfaces is expensive and environmentally hazardous, such as the aerospace and coil-coating industries. Finally, Autospect itself would benefit by tapping into a potential market of $500 to $750 million, increasing its engineering leadership by 5 to 10 employees, and strengthening its position to provide best-in-class measurement and control for the U.S. automotive industry.

WFM Technology Supported by Industry But Lacks Funding

Despite the many potential benefits, Autospect recognized the high risk involved in developing a breakthrough product. Measurement systems that appear promising from a theoretical standpoint often fail to realize the flexibility and ruggedness required for the factory floor. Thus, as a small company with about 10 employees and limited internal research funds, Autospect could not single-handedly undertake such a project. Without additional funding, Autospect would need to scale back its goals and focus on small, incremental development.

Although unable to find private funding, Autospect secured the support of the entire industry for cooperative development and feedback. The Big 3 auto companies committed to participating in the project's process integration stage. Painting-robot manufacturer Fanuc, paint shop manufacturer Haden, and automotive paint suppliers PPG and BASF agreed to help, and PPG also offered the use of its Flint Applications Facility for product testing. Confident of the importance of WFM technology to the automotive industry, Autospect applied for and was selected to receive $1.8 million in cost-shared funding from ATP's 1995 motor vehicle manufacturing technology-focused program competition.

Laser Ultrasonics Can Improve Efficiency and Reduce Costs

In accordance with its plan, Autospect explored three potential measurement techniques. After eliminating other non-contact methods, such as an alternating current impedance method and a method using micro-strip microwave resonators, Autospect turned to laser technology to develop the ideal technique for wet-film measurement. Extensive research indicated that laser ultrasonics (LU), a non-contact ultrasound technique, was most promising in terms of repeatability, measurement sensitivity, practicality, and cost.

Autospect valued the LU method for its simplicity. It requires only three square feet of paint booth space and three main components: two lasers and an interferometer. To measure wet-paint thickness, the first laser produces a very short pulse to generate ultrasound on the painted surface. The absorption of this light causes a temperature rise in the paint film, inducing a density gradient in the material and thereby producing an ultrasonic acoustic signal. Thus, the short laser pulse is analogous to a quick hammer strike to a bell. The second laser detects the minute ultrasonically induced motions (about 0.1 nanometers) on the paint surface. This detecting laser light is reflected off the surface and coupled into the interferometer, which strips away and measures the surface vibrations. The resulting spectra provide raw data for analysis, as film thickness has an inverse relationship to resonant frequency.

In addition to saving paint booth space, which costs about $100,000 per square foot, the LU method has many other advantages. The system can measure all automotive body coatings, both wet and dry. Its measurement is extremely fast and does not require calibration, even for new paint materials. Since laser light can be fiber-optically coupled to the paint booth, a manufacturer can place sensitive equipment far away from the spray area, thereby eliminating splatter disturbance and vibration problems. The LU method also provides advantages on the factory floor because the measured parametric frequency of the ultrasound is not affected by changes in intensity of the signal, which is a parameter susceptible to many environmental conditions. Finally, and perhaps most importantly, the LU system can be multiplexed; that is, 250 or more sensors in multiple locations can make measurements that feed to one set of equipment, allowing for the measurement of every vehicle in a plant by a single system.

Successful Prototype Proves System's Technical Feasibility

By the end of the ATP project in 1998, Autospect (hereafter referred to as Perceptron, which acquired Autospect in 1997) had successfully developed a WFM system and had achieved positive results from in-plant testing at PPG's Flint facility. Perceptron engineers Jeffrey White, Frederick LaPlant, and John Dixon coauthored a paper with PPG engineers Donald Emch and Vince Datillo that discussed the LU WFM technology. The paper, titled "Non-Contact Real Time Film Thickness Gauge," won the Best Paper Award at the 1998 International Body Engineering Conference.

Shortly after the close of the project, Perceptron sold a prototype system to DaimlerChrysler and installed it at the company's Windsor Assembly Plant, creating an alpha test site. Tests at the Windsor facility continued to prove the system's technical feasibility. Perceptron initiated its eight-stage product development process and planned its next step to pursue sales of the WFM system to each of DaimlerChrysler's eight plants. In 1998, Perceptron set target sales at 4 systems by 2000 and another 8 in 2001, with the hope of ramping up sales to 12 annually by 2002.

Financial Difficulty Halts Perceptron's Commercialization Effort

Equipped with a clear-cut business plan, Perceptron aimed to move forward to commercialize the LU WFM technology. However, the company began to experience the effects of the automotive industry's 1991 to 1993 slump and its stagnant sales from 1994 to 1997. The company's stock, which had peaked at just under $40 a share and had held steady there during 1996 and 1997, dropped to about $20 per share in the second half of 1998. Since then, Perceptron has not been able to recover, with its stock continuing to fall to around $5 per share between 1999 and 2000. In 2001, its shares decreased further and as of fall 2001 were valued at $.03.

Because of these severe financial difficulties, Perceptron has focused on survival strategies, and product development of the new WFM technology has become a low priority. Perceptron has managed to invest more than $1 million of its internal funds since the close of the ATP project, working with DaimlerChrysler to fine-tune the prototype and to convert raw thickness and distribution data into useful feedback information. Perceptron estimates that the system will require three years of product development before full-scale commercial release becomes feasible. At this time, the company is unable to pursue that development due to its financial position. Perceptron engineer Mr. White confirmed that the company is open to the possibility of a transfer of the technology to another company, but expressed doubt that any other automotive suppliers are in a position to take on the risk or the investment.

The WFM system has also sparked interest from the aerospace industry and coil-coating manufacturers, who are currently considering investments in the development of the WFM technology for their applications.

Industry Resistance Presents Another Barrier to Commercialization

In addition to the lack of available funds to commercialize the WFM system, industry resistance has presented another unforeseen challenge. Mr. White explained that because automotive painting is such a fragile and expensive process, manufacturers worry that constant adjustments to spray flow and other parameters will only compound the problems. Even though the existing process is error-laden, manufacturers hesitate to alter it until a new system demonstrates proven quality control elsewhere. While the DaimlerChrysler prototype exhibits superior measurement, researchers need to perform further testing and complete research to convert raw data into useful feedback before proving the WFM system's capability for total closed-loop feedback control.

Conclusion

As a result of the ATP project, Perceptron successfully developed a WFM (wet-film-measurement) system based on its LU (laser ultrasonics) technology. The company affirms that this advance would not have occurred without ATP's support. Despite the system's excellent technical outlook, however, Perceptron has not been able to fund commercial development because of severe financial difficulties and industry resistance. If Perceptron regains financial strength, it plans to resume commercialization efforts. In consideration of its present situation, the company expresses its willingness to negotiate a technology transfer to another company.

PROJECT HIGHLIGHTS
Perceptron (formerly Autospect, Inc.)

Project Title: Laser Ultrasonics To Improve Automotive Painting Process (Wet Paint Thickness Measurement System)

Project: To develop a non-contact method for online measurement of wet-paint thickness to enable a high-quality, time-efficient, and cost-effective painting process for the automotive industry.

Duration: 9/15/1995-9/14/1998
ATP Number: 95-02-0005

Funding (in thousands):

ATP Final Cost	$1,800	81%
Participant Final Cost	421	19%
Total	$2,221	

Accomplishments: Perceptron successfully developed the technology for a wet-film-measurement (WFM) system using its laser ultrasonics (LU) technology; tested the system at PPG's facility in Flint, Michigan; and installed a prototype for further development at DaimlerChrysler's Windsor, Ontario plant.

Company engineers received the Best Paper Award at the 1998 International Body Engineering Conference for a paper discussing the ATP technology titled, "Non-Contact Real Time Film Thickness Gauge."

Perceptron received the following patents for technologies developed during the ATP project:

- "Method and system for processing measurement signals to obtain a value for a physical parameter" (No. 6,092,419: filed November 21, 1997; granted July 25, 2000)
- "Method and system for measuring a physical parameter of at least one layer of a multi layer article without damaging the article and sensor head for use therein" (No. 6,128,081: filed November 27, 1997; granted October 3, 2000)

Commercialization Status: Although Perceptron sold a prototype WFM system to DaimlerChrysler after the close of the project, the company has ended its commercial development efforts due to severe financial difficulties caused by the auto industry's weakness in the early and mid 1990s.

Outlook: Currently, Perceptron's weak financial status and the industry's resistance to the new technology prevent the commercial development of the WFM system. However, the prototype system has demonstrated technical success and holds promise for future commercial development and improvement of the automotive painting process. The WFM system has also sparked interest from the aerospace industry and coil-coating manufacturers. These industries are currently considering investments in the development of the WFM technology for their applications.

Composite Performance Score: *

Number of Employees: (figures are for the Autospect division only) 10 employees at project start, 15 as of December 2001

Focused Program: Motor Vehicle Manufacturing Technology, 1995

Company:
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Research and data for Status Report 95-02-0005 were collected during October - December 2001.

Philips Laboratories

A Novel Microminiature Light Source Technology

Companies located in the Pacific Rim dominated the market for miniaturized circuitry and lighting applications from the 1980s to the early 1990s. During that time, U.S. firms fell far enough behind that they had trouble keeping a foothold in the marketplace. In 1993, Philips Laboratories applied for Advanced Technology Program (ATP) support to research a method to use microcavities as small as 1 mm in the company's microlamp research and to develop a prototype for industrial and consumer applications. Philips' proposed research would focus on creating electrodeless microlamps as well as microlamps with both conventional and thick-film electrodes. Toward the end of the ATP-funded project, Philips focused mainly on thick-film tungsten electrodes in 1-mm cavities, since these showed the most promise. All research and knowledge from the ATP-funded Philips Laboratories project was transferred to Philips Lighting after the close of the project in order to facilitate microlamp commercialization. Ultimately, Philips Lighting could not commercialize the product at prices low enough to compete with microlamps already on the market, so the company abandoned plans to bring a product to market.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
*

Research and data for Status Report 93-01-0045 were collected during October - December 2001.

Pacific Rim Firms Dominate the Market

Between the late 1970s and the early 1990s, miniaturization emerged as one of the most significant design trends for consumer and military products. Companies with strong technical competencies in miniaturization processes, such as precision machining and micromachining, gained considerable competitive advantages in the marketplace. These companies, largely based in Japan, used their strong miniaturization capabilities to design and manufacture electronic and optical products that were higher performing, lighter, and more rugged than those made by companies who lacked miniaturization expertise. The progress by Pacific Rim-based companies negatively impacted the health and stability of the electronics industry in the United States, which, as of the early 1990s, had not developed a comparable level of competency in miniaturization.

Moreover, because miniaturization technology significantly impacts the manufacturing, machining, lighting, and display industries, companies based in the Pacific Rim maintained a significant advantage in those industries. In 1993, however, Philips Laboratories developed a research project to use miniaturization technology to create a small, powerful, efficient lamp for lighting and display options.

U.S. Firms Must Improve in Order To Compete

By the 1990s, microlamps manufactured outside the United States were coming to market in automobile lighting, projection televisions, and backlights for laptop computers. However, the U.S. lighting industry had not been able to capture the benefits of miniaturization. These microlamps were generating significant revenue for non-U.S. businesses. For example, the automotive headlamp market was $389 million annually in 1993 and was expected to grow to $496 million by 1997. The projection television and laptop computer marketplaces, while smaller overall, were experiencing even more rapid growth. Without improved miniaturization capabilities, U.S. manufacturers could not produce lamps that were small enough, bright enough, cheap enough, or capable of being viewed at a wide enough angle to capture market share from the Asian companies.

Technical Benefits of the Proposed Technology

Philips Laboratories proposed to develop ultra-miniature light sources that were less than 1 mm in diameter, which would be significantly smaller than the Japanese-produced 5-inch lights, the smallest available at the time. This radically new approach would use microfabrication techniques to generate very small sealed cavities in transparent substrates. Those cavities, when created and activated properly, would serve as the ultra-small light sources. The sealed cavities would be formed by etching and wafer-bonding techniques that were already established within other industries.

Miniaturization emerged as one of the most significant design trends for consumer and military products.

The more difficult aspects of the proposed technology involved investigating the emissive properties of electrical discharges within the sealed cavities in both an inert state and when filled (also known as "dosed") with different materials. One of the expected advantages of the miniature cavity was its ability to sustain much higher pressures because of its small size. The cavity was expected to withstand several hundred atmospheres of pressure; and since light output (lumen) efficiency increases at higher pressures, the ultra-small light sources would be highly efficient. Moreover, the smaller size would enable wider viewing angles and more light sources packed onto a substrate, making the light more visible and of better quality.

Philips' Research Project Promises Cost and Environmental Advantages

Philips determined that there were three areas of potential broad-based benefits that could flow from a successful project. First, given that the Pacific Rim countries' miniaturization skills clearly dominated the world market, any effort to bring market share back to the United States had the potential to create significant economic benefits through increased domestic manufacturing jobs and decreased reliance on imports.

Furthermore, the innovation Philips proposed could also reduce the cost of the ultra-miniature light sources produced in Japan. For example, before the ATP-funded project began in 1994, the typical cost of processing a 5-inch substrate for these light sources, through a sequence of integrated circuit fabrication steps, was $100. Since the proposed microlamps were smaller than their Pacific Rim counterparts, and the manufacturing process was simpler, the cost of processing the 1-mm ultra-miniature light source would be approximately 10 cents per lamp, a 99.9-percent decrease in the cost per lamp.

Philips Laboratories proposed to develop ultra-miniature light sources that were less than 1 mm in diameter.

The second broad-based benefit from Philips' proposed innovation was the impact that would accrue to many downstream U.S. industries. If the proposed technology were successful, the new range of U.S.-manufactured ultra-miniature light sources would be of interest to the lighting, automotive, consumer electronics, and professional equipment industries within the United States. However, in order to remain focused and to have a better chance of success, Philips decided to limit its miniaturization project to research for lighting and display applications.

The third potential benefit of the new technology was environmental. Philips' proposal would create lighting sources that used far less mercury than any lights available on the market. Because even small amounts of mercury in cast-off lamps leech into the soil and pollute large areas, there is a recognized need to reduce mercury usage. If successful, the project would enable effective lighting sources with a significantly lower risk of environmental pollution.

Philips Seeks Public Funds To Help Develop Technology

Despite these potential benefits, substantial technical and business challenges prevented Philips from funding the research internally. In 1990, several years before submitting their ATP proposal, Philips had conducted a preliminary investigation into this new technology. Their research suggested that the fabrication, dosing, and sealing of microcavities were possible for these ultra-miniature lighting sources. The technical risks lay with conducting a full-scale examination of the physical phenomenon of generating specific types and strengths of light within very small cavities. The research project called for full investigation of a large variety of discharges in order to minimize the amount of mercury necessary for lighting. In addition, the microcavity walls would need to be engineered precisely to prevent distortion and loss of energy that would adversely affect lumen efficiency. The microcavity engineering risk was substantial because U.S.-based lighting industry knowledge in 1993 was based on assumptions from lighting results in much larger cavities. Putting the physics and models to practice within a 1-mm cavity, however, was significantly more difficult.

The project's business risks were formidable given the complete industry domination by companies based in the Pacific Rim. The cost of manufacturing labor was significantly less in Japan than in the United States. Therefore, savings from a successful project would have to be significant enough to make up for the labor cost disadvantage if U.S. companies' microlamps were to compete in the global marketplace. ATP, satisfied that Philips met the technical criteria for funding, awarded the company cost-shared funds in January 1994.

Project Focuses on Three Types of Lamps

As part of its process to create an ultra-miniature light source, Philips studied light emission within three forms of lamps: the electrodeless microlamp, the electroded microlamp with conventional electrodes, and the electroded microlamp with thick-film electrodes.

Electrodeless Microlamp

Philips had fabricated sealed cavities in quartz substrates prior to the start of the ATP-funded project. They believed a similar process could be developed for glass, sapphire, and other substrates. The process used to fabricate the miniature cavities involved four steps. First, a masking layer is deposited on the wafer substrate and is patterned. Second, the quartz substrate is then etched through the openings in the cavity. Third, the cavity is filled with a dosing material. Finally, another wafer, in which similar cavities have been etched, is aligned with the initial wafer and bonded to it in the appropriate ambient gas using fusion-wafer bonding. This process forms a sealed cavity that contains the dosing material and the gas. As a result of the company's research during this ATP project, Philips succeeded in fabricating sealed cavities that contained a dose of mercury and argon gas. Such cavities can be excited with radio frequency or microwave power, thereby creating a discharge microlamp. The microlamp, however, did not produce commercial-quality light. Therefore, Philips continued its research with electroded microlamps.

Electoded Microlamp with Conventional Electrodes

Philips determined that the scientific and technical issues related to these electroded microlamps were more difficult than the electrodeless microlamp, but the potential for efficient lighting was greater. During the process of incorporating the electrode into the sealed cavity, careful steps needed to be taken to ensure that contamination did not occur within the cavity. If contamination did occur, the microlamps would not operate properly, if at all. Furthermore, the temperature within the sealed cavity, when excited by a current, had to be regulated to prevent evaporation of the vapors inside and to prevent the electrodes from melting.

The cost of manufacturing microlamps within Philips Lighting was too high to effectively compete with other products on the market.

After developing several designs and prototypes, Philips was able to create three electroded microlamps. The first was an electroded, high-pressure mercury microlamp and the second was an electroded high-pressure mercury microlamp that contained arcs of just 1 mm. The 1-mm arcs made the second microlamp well-suited for projection applications. A third microlamp was developed with electrodes located on one side, a design that enabled the microlamp to be illuminated using low electrical current. As a result, small apparatuses that require low-wattage light could incorporate this microlamp.

Electroded Microlamp with Thick-Film Electrodes
In order to create microlamps for use in a wider array of lighting applications, Philips also researched electroded microlamps with thick-film electrodes. In its proposal to ATP, Philips indicated that tungsten would be a good electrode candidate because of its high melting point, good conductivity, and electron-emission properties. The key step in the formation of the tungsten thick-film electrodes would be the deposition of tungsten films on quartz substrates without significant warping, cracking, or peeling. Philips simultaneously investigated several different techniques to achieve these requirements, including low-pressure chemical vapor deposition, plasma-enhanced chemical vapor deposition, laser ablation, and sintering of tungsten paste. At the conclusion of the ATP-funded project, Philips Laboratories scientists and engineers had developed an impressive research file on the emissive properties of tungsten thick-film electrodes.

Cost Pressures Limit Commercialization

The entire body of knowledge developed during this ATP-funded project was transferred to Philips Lighting, a separate company that would work to make the final adjustments on, and commercialization of, the thick-film electroded microlamps and conventional electroded microlamps. Ultimately, however, the cost of manufacturing microlamps within Philips Lighting was too high to effectively compete with other products on the market. Philips Lighting management decided in 1998 not to market any of these products commercially, but to retain them for future internal research and development activities.

Project Knowledge Is Disseminated

Though Philips Lighting's management decision ended plans to bring products resulting from this ATP-funded research to market, the research conducted at Philips Laboratories was made available to other interested parties through a number of knowledge-dissemination channels. Three patents were granted for knowledge directly related to this ATP project, and applications were submitted for nine others. Moreover, an article was submitted for publication to the professional journal, Applied Physics Letters, and presentations were made at four industry symposia.

Conclusion

ATP awarded Philips $1.43 million in cost-shared funds to pursue miniaturization technology for microlamps. The research project examined electrodeless microlamps and microlamps with traditional and thick-film electrodes. Tungsten thick-film electroded microlamps showed the most progress, and Philips Laboratories developed a large body of research on this technology. All knowledge was transferred to Philips Lighting for commercialization after the end of the ATP-funded project in 1997. However, the cost of tungsten thick-film electrodes was still too high for commercialization, and no products resulted.

PROJECT HIGHLIGHTS
Philips Laboratories

Project Title: A Novel Microminiature Light Source Technology

Project: To develop techniques to produce microminiaturized, high-pressure discharge lamps using etched cavities in quartz or sapphire wafers for lighting and display applications.

Duration: 2/15/1994-2/14/1997
ATP Number: 93-01-0045

Funding (in thousands):**

ATP Final Cost	$1,432	28%
Participant Final Cost	3,576	72%
Total	$5,008	

Accomplishments: As a result of this ATP project, Philips successfully achieved several broad objectives, which in the future could lead to the development of microminiature, high-intensity discharge lamps. These successes include the development of an electrodeless microlamp and the development of an electroded microlamp fabricated with conventional electrodes. Philips also developed tungsten films as thick as 20 microns with minimal warping, cracking, or peeling by using a plasma-enhanced chemical vapor deposition process. This process is pivotal to the future development of electroded microlamps fabricated with thick-film electrodes. In addition, Philips acquired significant knowledge from this project, which led to the granting of five patents and the publication of several articles. Patents for technologies related to the ATP project include:

- "Microlamp incorporating light collection and display functions"
  (No. 5,574,327: filed June 7, 1995, granted November 12, 1996)

- "Flat panel light source for liquid crystal displays"
  (No. 5,808,410: filed June 7, 1995, granted September 15, 1998)

- "Gas discharge lamps fabricated by micromachined transparent substrates"
  (No. 5,965,976: filed December 19, 1997, granted October 12, 1999)

Commercialization Status: Because manufacturing costs remained too high, commercialization of this breakthrough technology has not been initiated. However, Philips and the industry are ready to provide the technology and its related products when a scale-up need arises.

Outlook: As the demand for microminiature light sources increases, so will the need to provide a scaled-up production method. As a result, the outlook for this microminiature light source technology is promising, especially due to the lighting, automotive, consumer electronics, and professional equipment manufacturers' continuous search for methods to increase product efficiencies. In addition, the knowledge spillover from this ATP project is extensive. By May 2001, 32 additional patents had been spawned from the initial 5, evidence that the market is very interested in the technology that resulted from this project and that there could be demand for microminiature lamps in the near future.

Composite Performance Score: *

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** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 93-01-0045 were collected during October - December 2001.

Sheffield Automation (formerly Giddings & Lewis)

Enhanced CMMs To Improve Manufacturing Processes

Competitive manufacturers have shifted their focus from post-process defect detection to real-time, in-process defect prevention. In 1992, existing coordinate measuring machine (CMM) technology, which was used for quality control purposes, failed to meet the demand for real-time, highly accurate measurement, because the machines had to be located in climate-controlled rooms. Giddings & Lewis proposed to bring CMMs to the factory floor to improve process efficiency and product quality. These process improvements would result in fewer errors, thereby decreasing the levels of scrap, down time and the associated potential for large financial losses for the manufacturers.

The company applied for and was awarded cost-shared funding from the Advanced Technology Program (ATP) for a two-year project to develop and place an optical fiber multi-degree-of-freedom laser measurement system right on the CMM. This system would be capable of measuring error components within the machine during the manufacturing process on the factory floor so that corrective actions could be taken immediately, thus improving quality and speed.

Working with researchers at the University of Michigan, Giddings & Lewis sought to develop both a laser optical system to monitor positional deviation of CMMs caused by thermal expansion and an adaptive compensation system to account for those errors in real time. Persistent problems with thermal drift rendered the prototype system incapable of adaptive thermal compensation, so the full technology was never developed. However, the company used this knowledge to develop its Atlas, Discovery, Endeavor, and ProGage factory-floor CMMs.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)

No Stars

Research and data for Status Report 92-01-0035 were collected during October - December 2001 and November 2002.

Enhanced CMMs Could Potentially Revolutionize Manufacturing

A coordinate measuring machine (CMM) measures shapes of known geometry by using a computer-controlled probe tip to map the surface of a part along a predetermined path. Whenever the probe contacts the part surface, the computer control records the instantaneous displacement of the probe with respect to each of the three orthogonal axes (x, y, and z). This produces a measurement of the actual part in terms that can be used to determine the deviation of the part surface from the mathematically correct nominal surface. Manufacturers use CMMs primarily for quality control purposes to ensure that actual part geometry matches the intended specifications.

Because CMMs are made from aluminum, steel, and other metals, they are susceptible to expansion and contraction caused by changes in ambient temperature. These thermal effects cause displacement of CMM positioning and subsequent drift of the probe tip from its programmed path. This affects the precision of the CMM's measurements. When precise dimensional measurements are required, manufacturers usually restrict the use of their CMMs to temperature-regulated quality control labs.

This requirement has several drawbacks for high-precision parts manufacturers, who need to maintain high-volume, high-speed, cost-efficient production of first-quality parts in order to remain competitive. First, climate-controlled rooms are expensive to construct and maintain. Second, the quality control process is time-intensive, because the measured parts need to reach thermal equilibrium. To reduce scrap levels and achieve labor efficiency, manufacturers require in-process feedback for immediate detection and correction of dimensional error to avoid an entire production run of defective parts. Yet with existing technology, manufacturers must periodically delay production (or risk unacceptable scrap levels) to take sample parts to the control room for inspection. In a competitive business environment, a CMM that could withstand the environmental instability of the factory floor could potentially revolutionize manufacturing methods. It could provide an early warning system for error and provide quality audits at every step of the process.

Current Thermal Compensation Techniques Are Unsuccessful

Because thermal effects represent the single largest source of CMM dimensional error and apparent non-repeatability of equipment, a successful thermal compensation technique could provide appreciable improvement in CMM precision, reliability, and repeatability. In 1995, several existing techniques had attempted to limit the problem of thermal effects. These methods included using uniform materials for all CMM components, rigidly clamping CMM scales, installing insulation pads and reflective foil to protect against temperature change, and using a thermal insulating enclosure and various measures to establish a uniform temperature throughout the machine by active heat flow control. Another approach involved gathering empirical data on displacement under varying temperatures and storing this information in a memory table in the original software. Measurement output readings would refer to this memory table to incorporate thermal error compensation according to an input temperature variable. While this compensation method estimated thermal drift reasonably well, it relied on trend prediction rather than real-time knowledge of machine and environmental conditions and, therefore, lacked the precision of an online monitoring system. Thus, available thermal compensation techniques merely supplied stopgap solutions that improved measurement precision to some degree, but failed to aggressively tackle the thermal drift problem.

Enhanced CMM Technology Could Provide Significant Cost Savings

The size of the CMM market, boasting sales of $1.2 billion in 1995, indicated the importance of these machines in improving manufacturing practices in various industries. CMMs have particular value in enhancing the efficiency of manufacturing processes in automotive, aerospace, and other transportation industries. These industries accounted for $516 billion in U.S. revenues and employed 1.5 billion workers according to 1997 Census Bureau statistics. In order to sustain industries of that size, U.S. machine tool makers needed to supply flexible, best-in-class CMM tools to facilitate resourceful and effective manufacturing processes. For example, the loss of a single complex jet engine component with high accumulated value could cost up to $50,000 and delay completion of an engine, leading to additional financial penalties. Giddings & Lewis projected that a factory-floor CMM could save manufacturing industries hundreds of millions of dollars by eliminating the costs associated with climate-controlled labs and by enhancing CMM precision and speed required for defect prevention.

A CMM that could withstand the environmental instability of the factory floor could potentially revolutionize manufacturing methods.

Giddings & Lewis, in cooperation with the University of Michigan, proposed a solution to enhance CMM precision by developing advanced, adaptive compensation technology for CMMs to allow them to adjust automatically to environmental changes without loss of precision, thus removing a major roadblock to the use of CMMs on the factory floor. Giddings & Lewis was a small company without the resources to undertake high-risk R&D. Because they had already invested $100,000 and were not able to obtain funding from investors due to the project's high risk and long-term payoff, they submitted a proposal to ATP and were awarded $755,000 in cost-shared funds. If successful, the project would significantly advance the current CMM technology and contribute to the knowledge base, which would have great potential to positively impact U.S. manufacturing productivity and cost-effectiveness.

Giddings & Lewis Incorporates Laser Technology and Enhanced Software

Giddings & Lewis and the University of Michigan proposed a unique but risky solution that addressed the thermal drift problem. They intended to address the problem from a software perspective instead of a hardware perspective. The research team would attempt to simultaneously characterize four geometric errors (horizontal straightness, vertical straightness, pitch, and yaw) using an original invention provided by the University of Michigan.

The invention had a high-resolution, compact-size, and low-cost multi-degree-of-freedom geometric error measurement system for simultaneously measuring the four geometric errors. The pitch and yaw error measurements were based on a new method of angle measurement, namely angle measurement based on the internal reflection effect. This method utilized the characteristics of internal reflection of a laser beam in the vicinity of the critical angle of an air/glass boundary. They used a differential detection scheme to reduce the inherent non-linearity and measure by the reflectance. The reflectance would be calculated with an online computer-numerical controller (CNC) equipped with sophisticated software, which would account for any positional deviations and would produce adjusted measurements. In addition, the team would use a stable, single-mode optic fiber beam, conditioned through a collimation lens, for increased precision.

Giddings & Lewis and the University of Michigan proposed a unique but risky solution that addressed the thermal drift problem.

Prior to the ATP project, state-of-the-art CMMs featured some type of geometric error compensation procedure for adding microprocessor-enhanced accuracy (MEA) to measurement readouts. However, these systems assumed that geometric error information would remain static in field use. The ATP project aimed to improve the precision of a CMM measurement readout obtained on the factory floor by including temperature-variant error components in the measurement compensation formula. To do this, they would construct a laser sensor for online monitoring of changes in dominant error components and would develop a scheme to update the information base in an MEA compensation system.

The research team outlined a unique technical plan:

1. Design and construct an optic fiber multi-degree-of-freedom laser measurement (MDFLM) system to monitor the change of multiple error components simultaneously for each motion axis. Prior to the project, several technical barriers hampered the use of non-interferometric laser technology for sensory systems, including problems with laser beam drift, air turbulence, and low sensor resolution. However, researchers at the University of Michigan had discovered prior to the project that the use of the internal reflection effect and a single mode optic fiber beam solved these problems. This breakthrough cleared the way for the use of laser technology for a CMM sensory system. Thus, the team aimed to develop a conditioning and delivery system for a highly stable single-mode optic fiber laser beam. This laser beam would have superior pointing stability for use in a movement reference system that could provide high-precision angle and straightness measurements of CMM positioning on the x, y, and z axes. The system contained a multiple channel data acquisition system to receive information from multiple position-sensing detectors (PSDs).

2. Identify sound metrological (measurement) bases for properly mounting the laser optical system on a CMM. The careful selection of stable bases for the MDFLM system was imperative to the system's ability to detect the changes of geometric error components when the CMM experiences thermal distortion. To do this, the team intended to develop an error-sensitivity analysis model. They planned to accomplish this by determining the sensitivity of various structural parts to environmental distortions and then by evaluating the influence of these changes on the identified error sources. This model would inform the selection of a solid base for the MDFLM system.

3. Develop adaptive compensation software, written to process online error information from the multiple channel data acquisition system. The software would calculate the final positional and angular deviation of a probe tip relative to the worktable reference and would adapt the measurement reading accordingly.

4. Develop a fast, stand-alone calibration device as a byproduct of this project. This low-cost device would provide simultaneous measurement of six geometric-error components to calibrate CMMs and other machine tools, replacing existing devices that are too slow for the calibration of multiple geometric-error components.

Broad Economic Benefits To Result from Improved CMMs

If successful, Giddings & Lewis' technical plan promised broad-based economic benefits to CMM builders and to various users, including automotive, aircraft, aerospace, and off-road equipment industries, as well as thousands of their suppliers. The economic benefits would result from increasing the quality and cost-effectiveness of CMM inspection capabilities through increased speed and reduced scrap. Additionally, the project sought to expand the U.S. knowledge base by demonstrating a successful application of non-interferometric laser measurement methods and thereby increasing the acceptance of this novel technology. Through meetings with CMM technology-sharing organizations, such as the University of Michigan's Industry/University Cooperative Research Center on CMMs, Giddings & Lewis defined a project goal: to establish a validated technology base for its adaptive compensation method so that the industry could initiate commercialization and bring CMMs to the factory floor rapidly and efficiently, compensating for errors associated with temperature changes.

Significant Problems with Thermal Drift Affect Prototype Viability

During the project, the research team developed two prototype MDFLM systems using non-polarizing optics and PSDs capable of measuring the four error components simultaneously. The first prototype used helium-neon laser beams and the second used diode lasers. The second prototype was preferred, because it produced less heat. Later, the second system was also able to measure the component of roll, an accomplishment previously unattained by a laser-sensing system. Despite the development of the prototype, its laser collimator (a device used to provide desired beam diameter to meet specific beam delivery requirements) and PSDs experienced problems with thermal drift that dramatically impaired the performance of these electro-optical components and hindered validation of the tool concept.

Because this thermal drift prevented the full development of the system, Giddings & Lewis worked to understand the thermal characteristics of the laser collimator and PSDs to reduce destabilizing drift. They explored enhancements such as the addition of a thermoelectric cooling system to stabilize the relatively low-power PSDs (a design adaptation that created better machine symmetry) and the construction of the system using materials that have low coefficients of thermal expansion, such as Invar (an alloy of iron and nickel).

However, Giddings & Lewis was unable to accomplish these modifications within the ATP project's time and funding limits. The University of Michigan continued with this research and developed empirical models to compensate for thermal drift as a function of temperature within the laboratory environment. Analyzing the experimental data indicates three directions for future improvements in the main sources of unresolved errors: 1) the inclination of the output collimator of the laser beam, 2) the deformation of the optical apparatus, and 3) the heat radiation of the reference stage.

ATP Project Advances Laser Metrology Technology

Despite roadblocks that prevented the full development of a laser-optical-sensing system for adaptive thermal compensation, the project made significant strides in the area of laser metrology. During the project, researchers confirmed the technical value of non-interferometric lasers by the use of single-mode optic fiber laser beams, achieving an unprecedented beam stability of less than one-tenth of a micrometer. The project made another unique advance by validating the ability of laser-sensing systems to measure the error component of roll.

Though the system that Giddings & Lewis envisioned in its proposal for this ATP project was not fully realized, the company later found ways to incorporate technology developed during the project into its Atlas product to improve the quality and cost-effectiveness of its inspection capabilities. Developments under this project also provided a knowledge base that researchers at the University of Michigan utilized in a collaborative effort with the National Science Foundation to develop a miniature-scale machine tool.

Giddings & Lewis was unable to accomplish these modifications within the ATP project's time and funding limits.

Additionally, researchers transferred findings from this project to the industry through paper presentations at major conferences, including a presentation by Dr. Jun Ni of the University of Michigan at the 1995 Society of Manufacturing Engineers Laser Metrology Workshop and publication of a reference book edited by John A. Bosch, Coordinate Measuring Machines and Systems (Marcel Dekker, 1995). Bosch was a consultant to Sheffield Automation Giddings & Lewis at the time and is the former president of Sheffield Measurement.

Conclusion

Although the Giddings & Lewis research team gained extensive knowledge of and improvement in precision for using lasers to define a metrological system for coordinate measuring machines (CMMs), persistent problems with thermal drift rendered the multi-degree-of-freedom laser measurement (MDFLM) prototype system incapable of adaptive thermal compensation. Thus, the project highlighted areas that required further improvement and pointed to the need for continued research and development of factory-floor CMMs. The University of Michigan was able to develop empirical models to compensate for thermal drift as a function of temperature in the lab environment. Current state-of-the art CMM technology does provide factory-floor CMMs and includes the MDFLM laser technology developed in this ATP-funded project, but it still has not achieved the level of precision and the real-time thermal expansion measurement technique originally proposed.

PROJECT HIGHLIGHTS
Sheffield Automation (formerly Giddings & Lewis)

Project Title: Enhanced CMMs To Improve Manufacturing Processes (Development of an Adaptive Compensation Technique for Enhancing Coordinate Measuring Machines (CMM) Accuracy)

Project: To incorporate an innovative laser optical system for monitoring minute dimensional changes in an adaptive control system for CMMs in order to efficiently use them on the factory floor.

Duration: 5/1/1993-4/30/1995
ATP Number: 92-01-0035

Funding (in thousands):

ATP Final Cost	$ 755	62%
Participant Final Cost	469	38%
Total	$1,224	

Accomplishments: Although Giddings & Lewis did not fully develop a laser-optical-sensing system and adaptive-compensation component, they did achieve the following advances during this project:

- Validation of non-interferometric lasers with single-mode optic fiber laser beams for metrology applications, as confirmed by the achievement of beam stability within a margin of less than one-tenth of a micrometer
- Development of a multi-degree-of-freedom laser measurement system capable of measuring the error components of horizontal straightness, vertical straightness, yaw, pitch, and roll

Commercialization Status: Giddings & Lewis was not able to develop a commercial-ready prototype from their work during this project. However, the company applied technology developed during the ATP project to the later development of its Atlas, Discovery, Endeavor, and ProGage series CMMs.

Outlook: The outlook for this project is uncertain; however, research in CMM technology continues within the manufacturing industry. Today, U.S. machine tool manufacturers provide CMMs for use on the factory floor, albeit without the high level of precision sought in this project. For example, Giddings & Lewis' Endeavor Series CMMs, which incorporate the partial successes of the ATP project, feature real-time temperature compensation in the range of +/-5° C, linear accuracy of up to 2 micrometers, and repeatability of 2 micrometers. This does not meet the proposal goals that intended to achieve "accuracy of straightness measurement" better than 0.5 micrometers and accuracy of angular deviation better than 0.05 arcsec. (Precision of angular deviation is not cited in current company literature.) However, factory-floor CMMs are currently available to assist the $500 billion U.S. discrete-parts industry in the cost-effective manufacturing of high-quality parts.

Composite Performance Score: No Stars

Number of Employees: 300 employees at project start, 150 as of November 2002

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