

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.

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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.

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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.

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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	<u>469</u>	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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