Computer Aided Optics Manufacturing

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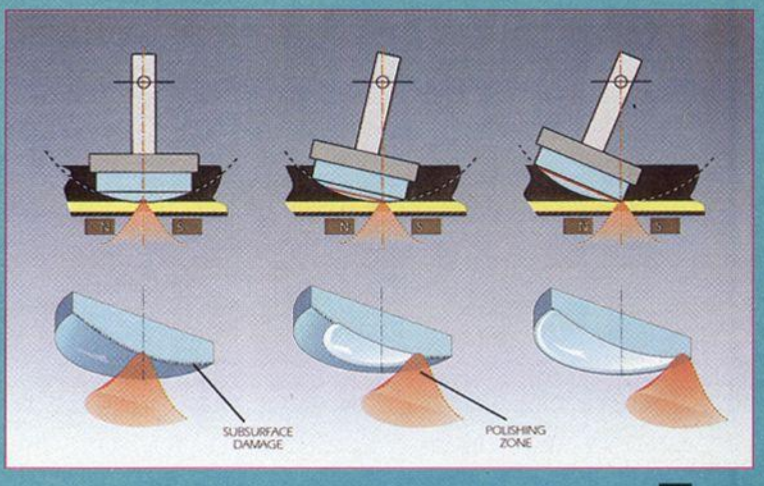
Flexibility and time-based performance are just two of the measures that differentiate manufacturers in the aggressive environment of global competition. In most industries, computer numerically controlled machining centers are considered a basic necessity in the battle to maximize flexibility, increase speed, and achieve the consistent perfection required by today's quality-conscious buyer. But, while computer-assisted machining has been readily available in most industries, it was not an option for optics manufacturers until recently. In 1993, the computer-controlled *Opticam*™ equipment developed at the Center for Optics Manufacturing (COM) became commercially available. Today, *Opticam*™ machining centers are eliminating the specialized tooling, long cycle times, and special craft skills required with conventional manufacturing equipment.

Under the sponsorship of the American Precision Optics Manufacturers Association (APOMA) and the U.S. Army Materiel Command, the Center is developing computer-aided machining centers and deterministic microgrinding techniques to automate optics manufacturing. Using *Opticam*™ technology, precision optics can be produced faster, and with consistent precision. These accomplishments have been recognized by the Department of Defense (DoD) Manufacturing Technology Achievement Award and the industry's Photonics Circle of Excellence Award. COM's most important commendation has been *Opticam*™*'s* immediate industry acceptance and high implementation rate. Three machines are installed at industry sites; four are being built on order; and three more are currently in negotiation.

Opticam™ computer-aided technology maximizes optics manufacturing flexibility and improves productivity. Trials by APOMA industry members, who use their own production parts to directly compare their in-house manufacturing time to *Opticam*™ process time, routinely achieve cycle time reductions of 50% and decrease lead times even



The magnetorheological fluid (yellow) realizes a rapid and reversible increase in viscosity of several orders of magnitude in the presence of a magnetic field (red). Polishing action occurs only in the "high viscosity" zone. The lens rotates on a spindle and is swept across the polishing zone by computer control. Annular zones are polished as they become exposed to the fluid, with removal in each zone increasing linearly with dwell time and optimized for figure correction.

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more dramatically. Specialized tooling is eliminated, process times are substantially reduced, and yields are dramatically improved. It is not unusual to attain 100% yields on trial lots, which are run by Computer Numerical Control machine operators, not skilled opticians.

Forecasting that future products will have more rigorous specifications, need more difficult shapes, require higher quality, and that customers will demand shorter delivery times is easy. Future business success is more difficult to predict, but a critical factor will be the technology chosen to meet the ever-increasing demands of the ever-more discriminating customer. The choice for the optics manufacturer is clear: Continue using high-cost, non-deterministic, labor-intensive conventional processes, or implement cost-effective deterministic processes and computer-aided manufacturing technology.

Computer-Integrated Manufacturing

Center development initiatives are redefining the manufacturing and competitive capabilities of the precision optics base. COM's development approach is much more comprehensive than simply performing isolated research or building new machine tools. COM's consortium effort has established an industry-designed, agile enterprise system. It is a systems approach that incorporates computer-aided concurrent engineering techniques to intelligently integrate the activities essential in optical design, engineering, manufacturing and distribution.

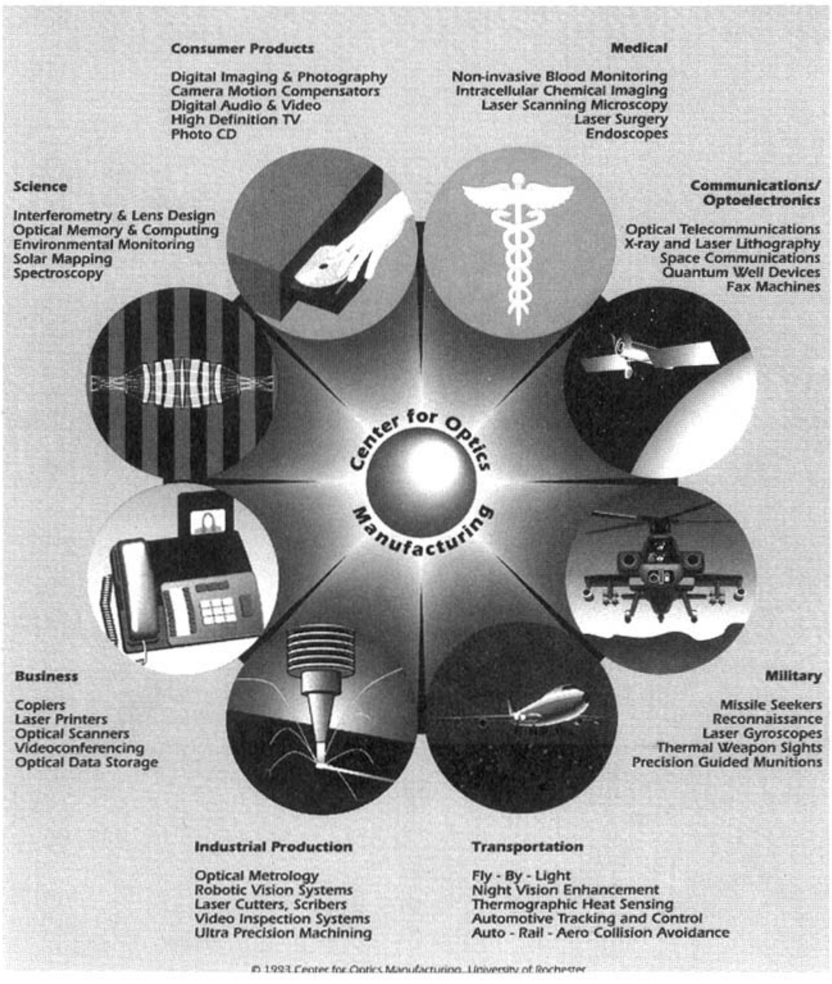
Opticim™ integrates both the operational and production needs of the manufacturing enterprise. The system will replace today's isolated design decisions and enable industry use of concurrent engineering. It also accommodates above-the-shop-floor operations, which provide the input and feedback needed to manage the enterprise. *Opticim*™ is DoD CALS (Continuous Acquisition and Life-cycle Support)-compatible and increases the effectiveness and capability of flexible automation equipment.

Consortium-developed computer-aided procedures, knowledge-based instruction sets, and software modules have been combined into a system that integrates the activities performed during the design and manufacture of an optical device. A COM-industry created standardized Optical Design Data File provides the lens design parameters needed by the system to automate the generation of manufacturing and management data.

It supplies all the information needed to process the part, including part set-up, tools, and the numerical control machining instructions. Parts can be designed, engineered, and manufactured in real-time, or process information can be stored in a database to be later retrieved and downloaded to the machine controller.

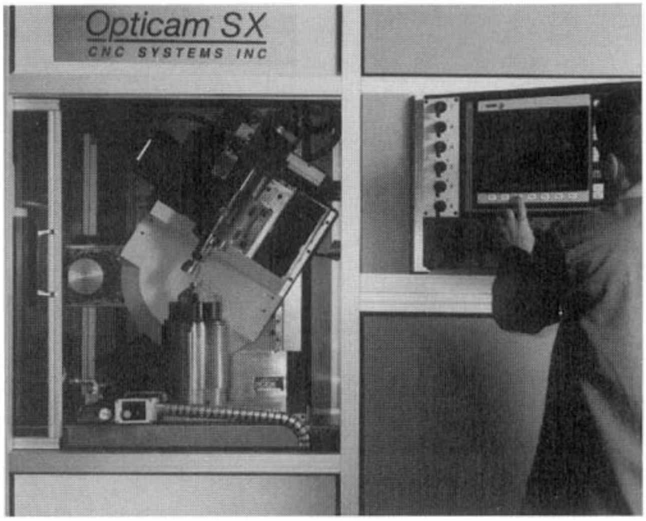
Integrating computer-aided design (CAD) and computer-aided manufacturing (CAM) technology automates the fabrication process. Machine accuracy, on-board metrology, and closed loop controls replace labor-intensive processes that previously required skilled hand-operations. Computer-controlled machining centers have the capability to produce lenses with levels of surface roughness and subsurface damage so low they do not require final polishing in many non-imaging and infrared optical applications. Lens grinding accuracy and the reduction of grinding damage are improved by a factor of 10 over conventional processes.

A robotic tool changer provides the flexibility to perform a variety of surfacing, edging, and centering operations. This additional flexibility is especially critical when the optical axis and outside part geometry are closely toleranced. Furthermore, automated metrology and closed-loop feedback control allow in-process correction and statistical process control is used to automatically flag process drift and reject conditions. The machine resident quality management system can also provide hardcopy inspection data without additional off-line labor. *Opticam*™ machines eliminate the need for specialized skills and dedicated tooling, permitting inexpensive and rapid prototyping.



Precision optics are pervasive in high technology instrumentation and systems.

The *Opticam SX*™ is a flexible 6-axis CNC precision machining center. The machine can produce convex to concave hemispheres in diameters from 10-100 mm with generic tooling. Several machines are being used in industry today.



Deterministic Microgrinding

The expanded capabilities of *Opticam*™ equipment result in a repeatable and predictable regime for machining brittle materials. The computer-controlled deterministic micro-grinding process demonstrates a very high level of form accuracy ($\lambda/2$ peak-to-valley) and surface finish (<100Å rms). Application of deterministic microgrinding technology to spherical lens production significantly improves industry competitiveness in the short term. The process takes about 10 minutes per surface and is unprecedented in its success.

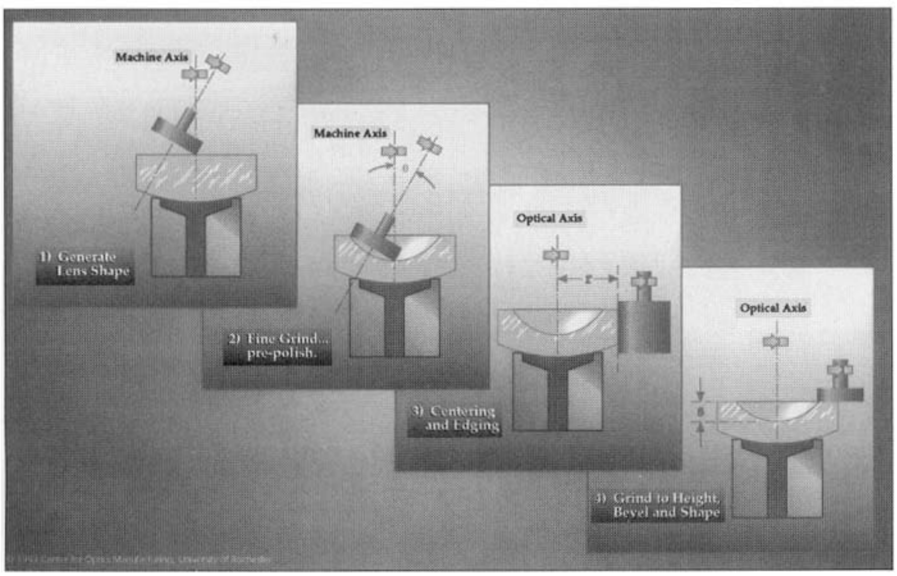
Continuing COM developments will sustain those gains in the long term as the deterministic microgrinding process is optimized for a wide range of application to other optical and brittle materials. COM intends to build on these breakthroughs and extend deterministic microgrinding to the development of a family of computer numerically controlled machining centers. This will include micro-optics, cylinders, toroids, and aspheres. Each machining center will evolve through concept development, design, system assembly, prototype machine acceptance testing, and feasibility demonstration. These machines will automate the production of the full spectrum of refractive and reflective optics.

Magnetorheological Finishing

In parallel, a revolutionary new concept in precision polishing called magnetorheological finishing (MRF) is being developed and integrated with *Opticam*™ machining centers. MRF, in concert with deterministic microgrinding, has the potential to finish optical surfaces in minutes and to eliminate the conventional iterative pitch polishing process that uses skilled-labor and rigid laps.

MRF technology provides a deterministic surface finishing solution with computer control and an independence from specialized tooling. The process is best understood by thinking of the MR (magnetorheological) fluid as a compliant replacement for the conventional rigid lap in the loose abrasive grinding or polishing process. The magnetorheological fluid's shape and stiffness can be manipulated and controlled in real time, allowing its application to any optical element geometry. It has notable application advantages when compared to the non-deterministic pitch or synthetic polishing process.

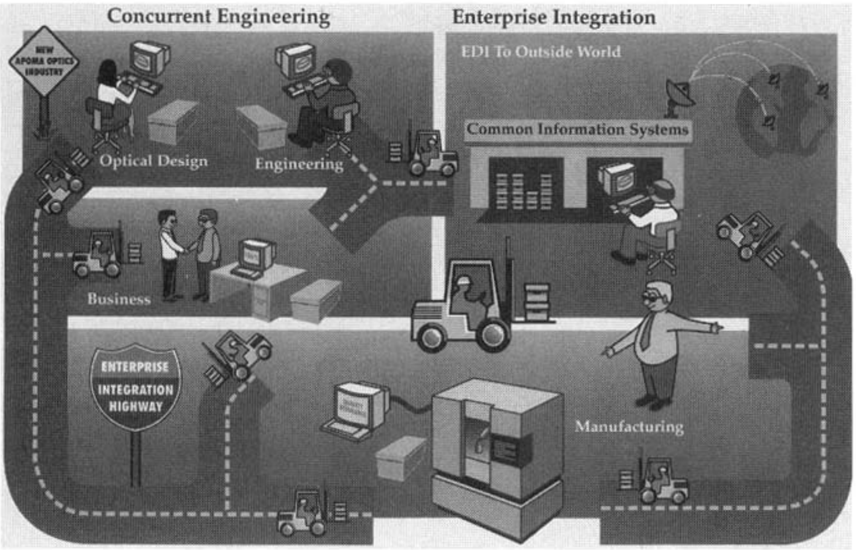
COM plans to develop magnetorheological finishing techniques for all optical surfaces, regardless of symmetry, geometry, or slope variation. After process variables are determined, a computer algorithm will control the specific radial position and material removal function to accurately dictate the final surface shape. MRF will provide the capability to finalize the microground surface to pristine finish, figure, and form. The combination of *Opticam*™ deterministic microgrinding and magnetorheological finishing will redefine the manufacturing capabilities and competitive dimension of the precision optics industry.



Manufacturing Sciences

Underpinning these machining and finishing efforts is a comprehensive manufacturing science and process technology development program designed to develop the tooling, techniques, material science, and metrolo-

***Opticam*™ performs all machining aspects of spherical lens manufacture, including generating, deterministic microgrinding, centering, edging, beveling, sagging, contouring, and shaping.**



COM's *Opticim*™ program addresses all aspects of the business, including EDI, optical design, CAD, CAM, CNC machining, QA, and SPC.

gy required to advance the precision optics industry. These tasks are being addressed by a manufacturing science consortium that includes the collaborative efforts of the University of Rochester and regional development centers at the University of Arizona's Optical Sciences Center, the University of Central Florida's Center for Research in Electro-Optics and Lasers (CREOL), several APOMA industrial members, and includes CRADAs (Cooperative Research and Development Agreements) with Lawrence Livermore, Los Alamos National Laboratories, and the National Institute of Standards and Technology.

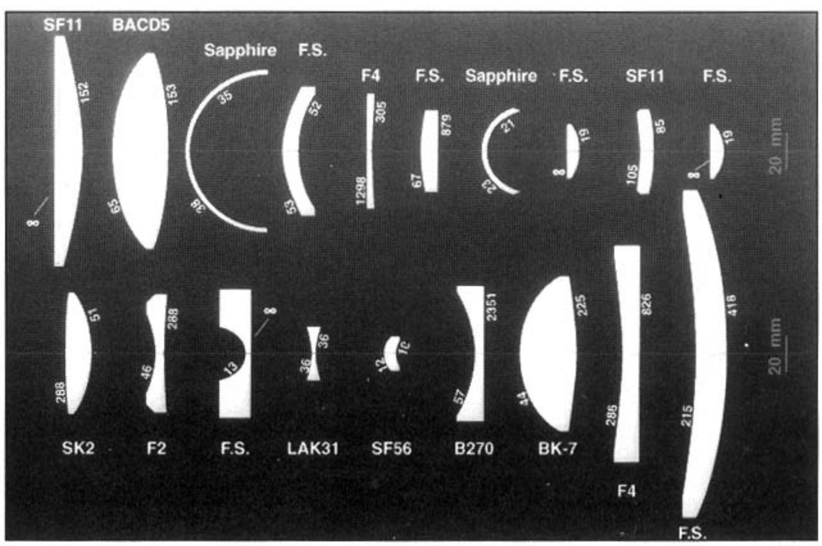
The primary objective of the manufacturing science program is to improve and extend industry manufacturing capabilities and optimize productivity. The near-term goal is to establish manufacturing science basics that optimize current technology, while several program initiatives offer new approaches and solutions. The newest of these is the ARPA (Advanced Research Projects Agency)-managed Active Vibration Cancellation program that will improve surface microroughness by applying this technology to sense and compensate for undesired vibration-induced errors at the cutting tool-part interface.

Another proposed program will develop an optical/electrical/mechanical fabrication and assembly system that can efficiently mass produce products that incorporate elements from each of several independent engineering disciplines. Integration of the current stand-alone optical, mechanical, and electronic system and manufacturing infrastructures will provide the springboard for the creation of a new optomechatronics industry. Special challenges will include fabricating small, fragile components that require complex automated assembly to achieve the desired optical performance. This new assembly concept will include advanced manufacturing system design tools and state-of-the-art flexible assembly techniques that require new concepts of automation and control.

COM manufacturing science focus areas relate to the exploration of the complex interactions between material characteristics, properties, environmental conditions, and machining parameters for a wide range of brittle materials. The long-term goal is to continuously develop new optics manufacturing technology and maximize industry potential—an ongoing improvement program for the optics industry.

ENABLING TECHNOLOGY IMPLEMENTATION

COM's focused cooperative alliance is forging the optics manufacturer's course for modernization and continuous improvement. COM enabling technologies and modernization support will facilitate efforts to establish a competitive advantage in the global market and extend commercial opportunities. Computer-aided manufacturing technology offers significant economic advantage over current methods and will ensure the availability of competitive production processes that support the introduction of new commercial and military optical products. COM will continue to develop breakthrough advances to extend the state-of-the-art and



These lenses are examples of production parts that were machined on the Opticam SX™. Over 20 APOMA industrial members have participated in this benchmarking exercise.

bring new capabilities to the factory floor.

Industry implementation is the only hallmark of development success. To promote implementation, COM's Optimod program provides industry participants with the opportunity to determine first hand how business challenges can be cost-effectively managed through the adoption of COM technologies. Industrial participants try out newly developed manufacturing technology at the Center's User Laboratory using their own parts and technical staff (who receive hands-on training during the visit). This unprecedented approach reduces industry's implementation risk and allows industry participants to actually project savings before capital commitment.

Industry Modernization

COM projects are governed by two mandatory rules: The need for and development of a technology project must be supported by industry, and the continuous and rapid transfer of technology to industry must be assured. The Center's most effective asset in meeting these objectives is its consortium alliance of experts from industrial, academic, and government organizations. These experts are proven leaders in optics manufacturing and bring extensive insight and experience to the modernization process. They include scientists, engineers, and practitioners—all APOMA industry and academic members that accelerate the process of technology development, transfer, and implementation.

COM's model approach has been extremely successful in establishing a strategic partnership between industry, universities, and government to accelerate industry modernization. Drawn from this expert group is COM's Manufacturing Advisory Board (MAB), a cross-section of industry managers that are the ultimate technology end-users. The MAB defines industry needs and ensures that developments are cost-effective and manufacturer-usable. The U.S. Army provides substantial support through the Army Research, Development and Engineering Center (ARDEC) for both development and modernization projects.

COM has provided a framework for defining manufacturer usable research, development, and education that will maximize manufacturing efficiencies, expand product possibilities, and redefine business opportunities. COM's revolutionary systems approach is determining the optics industry's course for continuous improvement and is providing the infrastructure that will speed implementation. These advantages and opportunities will propel the optics industrial base into the 21st century.

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