.: Great Strides in Optical Fabrication

Largely unchanged for centuries, optical fabrication is today an evolving and dynamic field with notable advances in molding, surface process optimization and freeform-capable tools.

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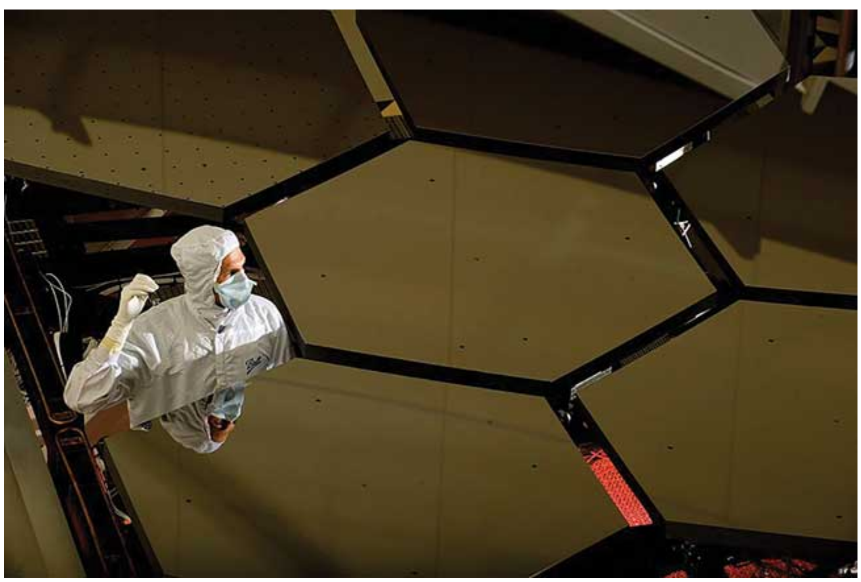
In 2018, a six-and-a-half-meter mirror made up of 18 hexagonal segments will quietly unfurl 1.5 million km from Earth, marking the end of years of intense research and refining of **optics** fabrication techniques. In the silence of space, the James Webb Space Telescope will turn its giant primary mirror toward deep space, kicking off the start of man's chance to look further back in history than ever before.



Mirror segments for the James Webb Space Telescope, which will be launched in 2018 and help scientists look further back in history than ever before. Courtesy of Coherent.

Its development, and other high-tech projects like it, has led to many improvements in optics fabrication techniques in use today. From smartphones, wearable optics and head-up displays, to airborne and space-borne remote sensing and surveillance, some of the latest trends in technology have emerged thanks to impressive progress in the way optics are made.

Being the largest mirror ever to be sent to space, one of the challenges of image quality and resolution was met by the team at the Integrated Optical Systems business unit of Coherent Inc. in Richmond, Calif., currently led by Brandon Turk.

An 8.4-m primary off-axis segment mirror for the Giant Magellan Telescope being fabricated using a stressed lap at the Richard F. Caris Mirror Lab, Steward Observatory, University of Arizona. Courtesy of Steward Observatory, University of Arizona.

The task was to polish each of the 18 hexagonal mirror segments, which are made of ultralightweight beryllium and coated with gold for broadband IR performance. One of the biggest challenges was to ensure the optics are light enough to launch and unfurl, but sturdy enough to withstand the harsh conditions of space.

“Beryllium was chosen because it is extremely light and stiff, with low thermal expansion at the cryogenic temperatures at which the observatory will operate,” Turk said. “However, beryllium is a challenging material to polish, and requires special handling because beryllium dust is a health hazard when inhaled. So we deliver the requisite image quality and resolution by finishing components to very tight figure and wavefront specifications.”

*A 28-m-tall testing tower housing a set of four **metrology** systems that provide independent measurements of the Giant Magellan Telescope segments to guide the* *computer-controlled optical surfacing process at the Richard F. Caris Mirror Lab, Steward Observatory, University of Arizona. Courtesy of Steward Observatory, University of Arizona.*

Some of the fabrication and metrology methods Coherent uses today were in fact developed and matured during that program. But it's not just Coherent that has made improvements in optics fabrication; the industry as a whole has seen remarkable progress in a number of key areas:

• More predictable/deterministic figuring process for higher convergence rates, by simulating, optimizing and controlling the fabrication process.

• Faster removal process, resulting in a shorter fabrication time, using various polishing/figuring materials and slurries.

• Smarter computer-controlled optical surfacing process optimization for more efficient directed figuring, using different deconvolution/search methods.

• Smoother optical surface controlling low- to mid- to high-spatial-frequency surface errors, such as power spectral density (PSD) or structure function specifications, by using multiple metrology systems and overall manufacturing process control to minimize residual surface ripples.

• More stable and maintainable freeform-capable tools by introducing conformable subaperture tools.

• Better molding of IR materials.

• Improvements in critical line beam shaping optics for excimer laser annealing tools for display fabrication.

Freeform optics

Aspheric/freeform optics manufacturing has become a main theme in the optics community over the last 12 months. Defined as surface shapes that lack rotational symmetry, freeform optics allow for higher performance, such as wider field of view or better modulation transfer function and also enable reduced system envelope at the same performance level. It also means that an incredibly wide range of substrate materials can be used, including metals, glasses, composites and even organics.

The creation of nontraditional optical components has paved the way for some of the latest technologies we see today, including wearable or portable optical devices, visual display or human machine interface (HMI) systems.

“Due to their strict form factor, light-weight and optical performance requirements to fit [the] human’s body and ergonomic needs, highly asymmetric/aspheric/freeform/noncircular-aperture optics become essential components to realize those post-smartphone devices,” said Dae Wook Kim, principal investigator of the Large Optics Fabrication and Testing (LOFT) group and assistant professor of optical sciences at College of Optical Sciences at the University of Arizona.

“Efficient, precise and cost-effective manufacturing technology for these future optics is naturally one of the most essential technologies to deliver those various conceptual lab-demo devices to daily human life,” Kim added.

“One can imagine that everyone wants smaller optics for head-worn displays,” said Andrew Fisher, an optical engineer at Barrington, N.J.-based Edmund Optics Inc. “Some challenges that exist when trying to keep components small have to do with the edges of these parts. Most current optics always have a clear aperture specified that is smaller than the outer-most dimensions of the surface.”

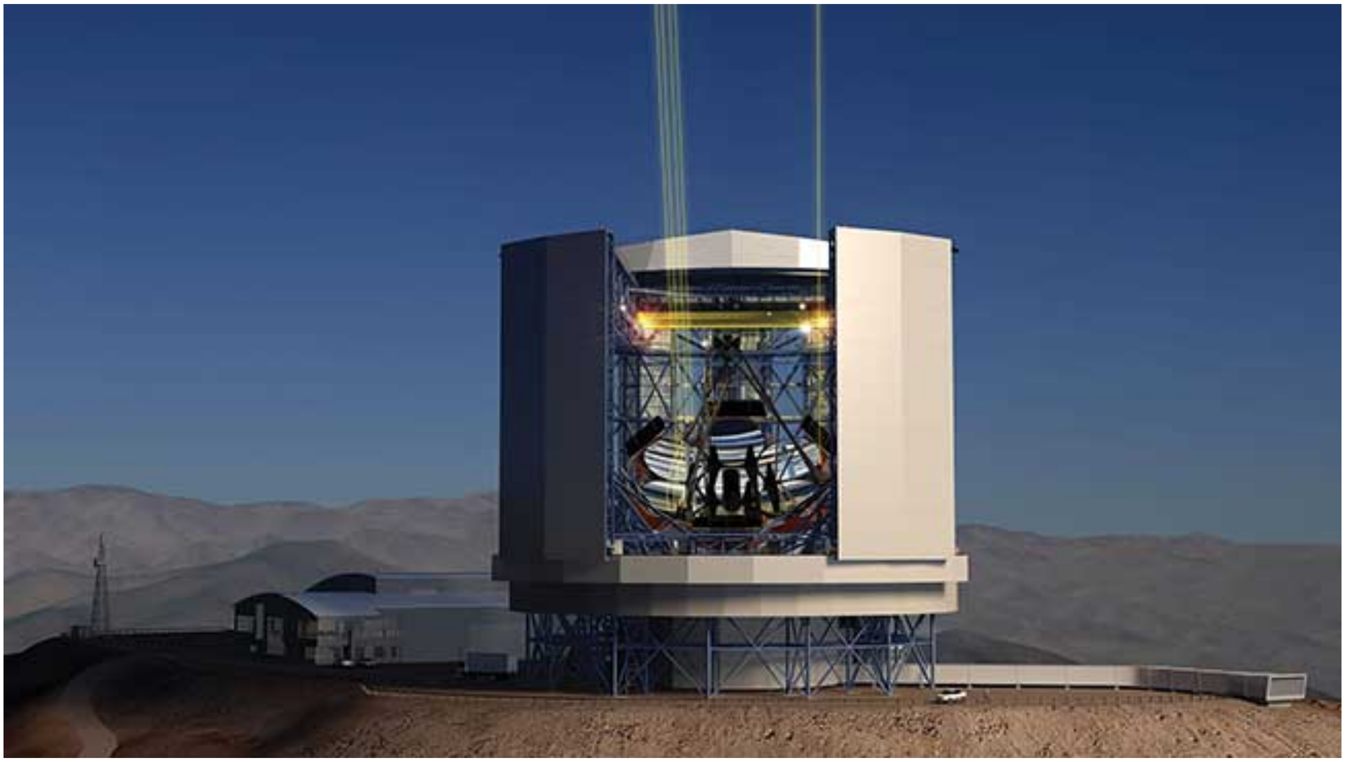
One way to reduce component size is to bring the clear aperture right to the edge of the part, which means that any coatings need to be applied all the way to the edge of a surface and that there can be no chamfers or bevels on the corners. Both of these requirements can prove very challenging, but are demands to which the industry is currently responding.

One of the biggest challenges is overcoming the hurdle of mass production of such nontraditional highly aspheric/freeform optics. With traditional optics, you can manufacture 10 spherical surfaces and mount 10 substrates at once, using a single large tool to polish them; but this is impossible for a freeform optic.

“The optics often suffer from mid- to high-spatial-frequency surface errors. It becomes a critical issue for advanced imaging systems targeting diffraction-limited spatial resolution such as astronomical telescopes or surveillance satellites and/or an extremely high-contrast imaging application such as exoplanet search cameras,” said LOFT’s Kim.

Some of the next-generation flagship optical instruments and systems such as the European Extremely Large Telescope, post-LIGO systems, space telescopes and surveillance satellites also require superior quality optics components.

“They are often large and/or highly aspheric, freeform optics, such as the Giant Magellan Telescope’s 8.4-m-diameter primary mirror segment with around 13 mm of aspheric departure and a super smooth surface finish,” Kim said. “Although these are not public market projects with an immediate economic impact, their scientific and technological impacts will be significant.”



Artist’s representation of the Giant Magellan Telescope with seven giant mirrors by GMTO Corp.

Many of today’s impressive ground-based astronomy programs, including the Thirty Meter Telescope and the European Extremely Large Telescope, boast massive segmented primary mirrors, and even with relatively large (>1 m) segment diameters, will require many hundreds of aspheric mirror segments to be fabricated.

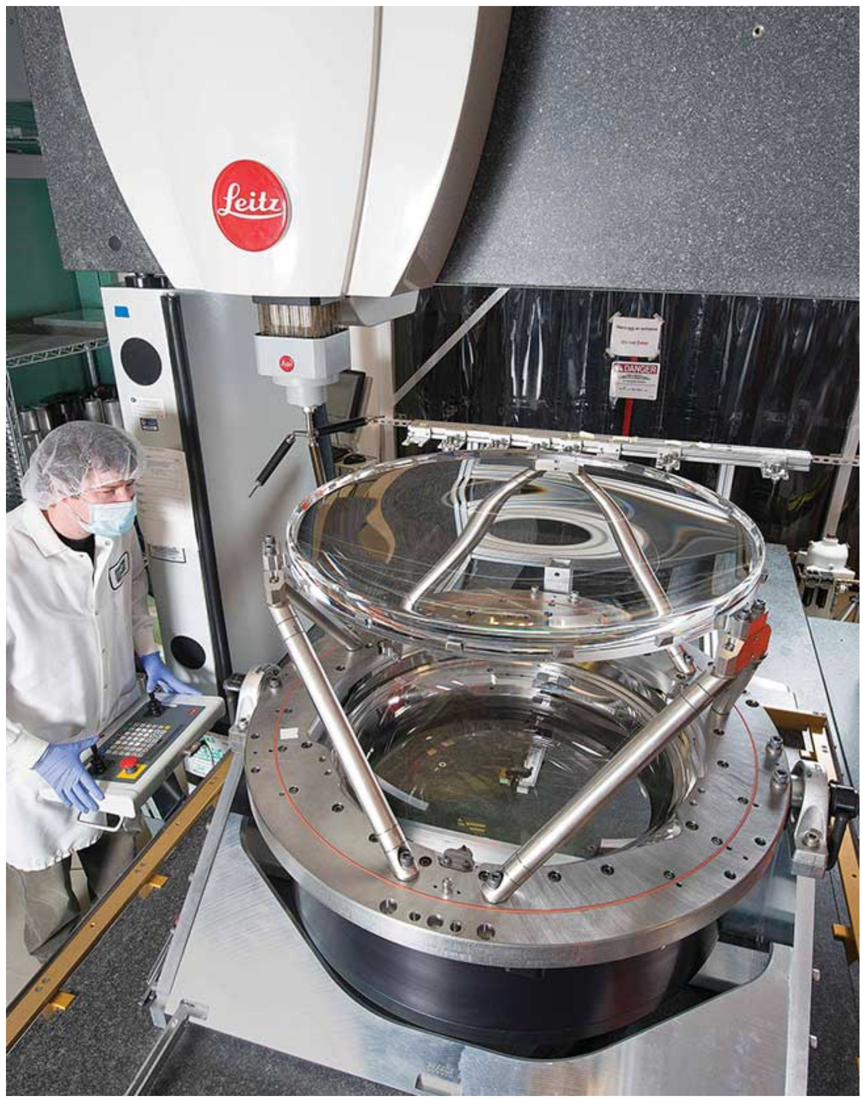
An 8.4-meter mirror for the Large Synoptic Survey Telescope being fabricated using a stressed lap and a non-Newtonian lap at the Richard F. Caris Mirror Lab, Steward Observatory, University of Arizona. Courtesy of Ray Bertram, Steward Observatory, University of Arizona.

A traditional computer-numeric-control-based approach would lead to long manufacturing cycle times, increasing costs and driving capital requirements to the point of being impractical, so Coherent used a technology known as stressed mirror polishing

in which specially designed fixtures apply precise forces to be applied to the mirrors during their fabrication.

A field corrector for a ground-based telescope application. Coutesy of Coherent.

"In essence, we induce stress fields in the mirror that create the inverse of the aspheric shape we want to obtain," Coherent's Turk said. "We can then use classical spherical polishing techniques to finish the optical surface and will ultimately achieve the desired aspheric shape after releasing the stress applied to the mirror during polishing."



The technique requires less capital investment to achieve the desired throughput rates to manufacture hundreds of very large, precise and smooth aspheres on time scales appropriate for the manufacture of these large telescopes.

Defense is the other part of aerospace with a growing demand for freeform optics. These range from imaging optics for drones, to head-up displays (HUD) for aircraft cockpits; a typical HUD incorporates several aspheric surfaces as well as a beam combiner.

Tighter specifications

A general trend for advanced security and surveillance is incorporating visible channels into traditionally IR-only optical imaging systems. This demands tighter optical surface specifications, both for figure error and surface roughness, than can be achieved with the traditional optical fabrication method, single-point diamond turning.

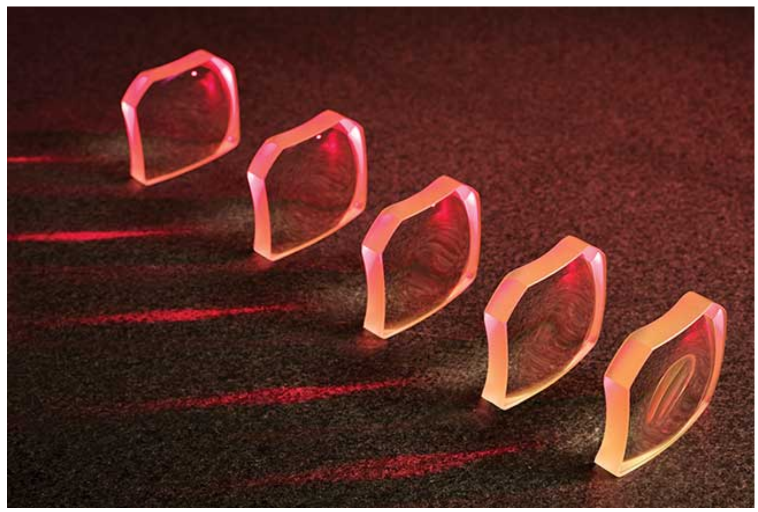
Deterministic polishing of a large aperture lens using magnetorheological finishing. Courtesy of QED Technologies Inc.

QED Technologies' magnetorheological finishing (MRF) platform has improved its system to take advantage of more of the wheel's surface area, which essentially broadens the envelope of surface geometries that can be processed.

"As the performance requirements of optical systems increase, more complex geometries with tighter surface specifications are demanded. Deterministic polishing processes, such as MRF, are therefore ideal for optical fabricators to meet these requirements in a predictable, cost-effective manner," said Andrew Kulawiec, president of Rochester, N.Y.-based QED Technologies.

As the saying in the industry goes, you can’t make what you can’t measure, which means that full-aperture interferometric metrology tools have essentially developed alongside optical fabrication technology.

Freeform optics metrology requires both high-dynamic range and fine precision, which are often competing with each other. Various non-null, high-dynamic range metrology systems have been developed such as subaperture stitching interferometers, contact type profilometers, noncontact optical sensor scanning systems, deflectometry systems and adaptive null systems.



A set of relay elements for the head-up display in a fighter jet. Courtesy of Coherent.

“Higher-resolution interferometric metrology, which is critical for deterministic polishing processes as well as for characterizing mid-spatial-frequency errors, continues to find its way into more and more optical fabrication shops,” Kulawiec said.

Coherent’s approach to deal with the large area optics is to make subaperture measurements and then use highly customized software for stitching.

“This is not trivial,” explained Coherent’s Turk. “You have to avoid stitching errors and other possible systematic errors. Each test setup is unique and engineered specifically to ensure we can meet the specifications.”

Precision figure correction with magnetorheological finishing, displaying deterministic polishing for superior surface control while providing increased yield. Courtesy of Edmund Optics Inc.

An emerging trend to watch is a multiwavelength interferometer built into freely moving measurement heads that allow a user to measure parts with large aspheric departure or very steep curvature with interferometric accuracies.

“Also, the recently released tilted wave interferometer is reducing full aspheric surface measurement times from minutes to seconds,” Fisher said. “With newer metrology systems being able to move freely around these parts and measure the surface, some of the difficulties come in standardizing and referencing these surfaces. For instance, there is work underway to determine best methods for adding fiducials to freeform optics in order to align parts between their metrology and fabrication steps.”

Optics Fabrication Timeline: Major Milestones

Photonics Spectra takes a look at some of the highlights in the history of optics fabrication.

1220s: Development of glass.

1222: Broad sheet glass was first produced in Sussex, England.

1500s: Development of mirrors. The method of making mirrors out of plate glass was invented by glassmakers on the island of Murano in Italy, who covered the back of the glass with mercury, obtaining near-perfect and undistorted reflection.

1810: The first known spherometer was invented by French optician Robert-Aglaé Cauchoix. They were primarily used by opticians and astronomers to help grind lenses and curved mirrors. Today's digital spherometers are a common way to measure the radius of a surface and are used iteratively when setting up a process to guarantee the shape of the part is correct.

1888: Machine-rolled glass was first developed, enabling patterns to be introduced.

1896: Although first patented in 1883 by watchmaker John Logan of Waltham, Mass., it wasn't until 13 years later that Frank Randall, another watchmaker, purchased the patent and formed a partnership with Francis Stickney to begin manufacturing dial indicators for general industry.

1904: Also supplying dial indicators was the German professor Ernst Abbe after establishing the measuring instrument department at the Zeiss Works. Dial indicators have become an important tool determining the runout of an outer diameter as well as assisting with centering parts on a fixture.

1957: A computer numerical control system was developed by a collaboration between the Massachusetts Institute of Technology and the Air Force Materiel Command at the Wright-Patterson Air Force Base and the Aerospace Industries Association. The invention paved the way for automated tools such as grinding, prepolishing and centering of optics, enabling cost-effective production for manufacturers.

1960s: Addition of coatings to surfaces and the development of the first optical test equipment — swept-tuned instruments.

1965: The discovery of fast Fourier transform led to the first analyzers being developed in 1967.

1970s: Interferometers or test plates are an essential tool for determining the surface accuracy of an optic. Full-aperture interferometric metrology tools have become necessary for today's modern optical fabrication. The development of digital phase-shifting interferometry in around 1970 at Bell Labs was a crucial innovation for optical fabrication. Without this technology, the high-precision optical surfaces used in semiconductor lithography tools would not be possible.

1998: The first commercially available deterministic polishing machine, the Q22 magnetorheological finishing machine, was introduced by QED Technologies of Rochester, N.Y. This machine and technology enabled the widespread use of aspheres with highly complex geometries and tighter surface specifications for high-performance optical systems.

2000s: Stressed mirror polishing is being used to apply precise forces to mirrors during their fabrication, contributing to some of today's latest ground-based astronomy programs, including the proposed Thirty Meter Telescope and the European Extremely Large Telescope.

2012: Completion of the first of seven aspheric mirror segments for the 24.5-m Giant Magellan Telescope primary mirror. With a diameter of 8.4 m, its creation marks the largest ever off-axis aspheric mirror ever manufactured.

2014: Tilted wave interferometry was first presented by scientists at the Institute of Applied Optics, University of Stuttgart, and metrology specialists Mahr GmbH, both of Germany, as a completely new, patented and flexible way of measuring aspheres and freeforms.

GLOSSARY

metrology

The science of measurement, particularly of lengths and angles.