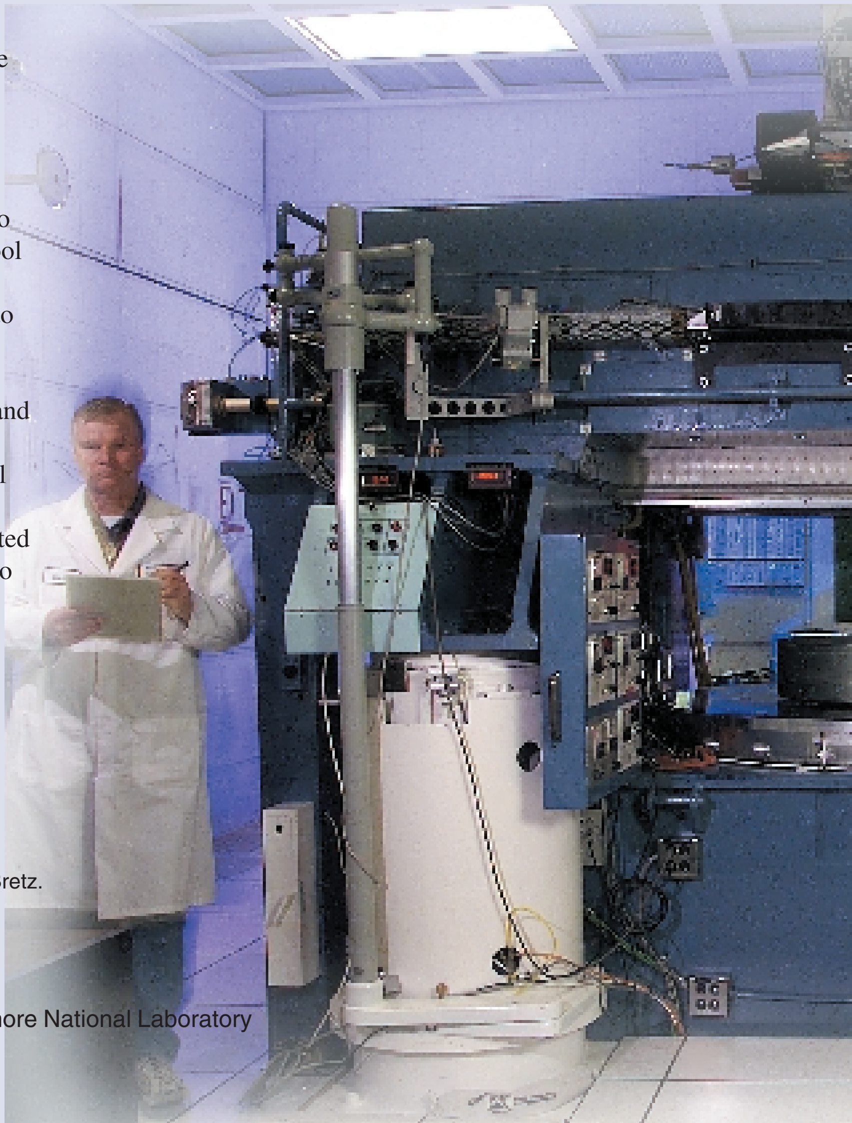
The World's Most Accurate Lathe

THE wood lathe in a home workshop is remarkably similar to Livermore's Large Optics Diamond Turning Machine. Both spin a workpiece while a cutting tool cuts the revolving surface. But their end products bear little resemblance. Built to form large, irregularly shaped mirrors for experimental lasers, the LODTM (pronounced "load 'em") leaves behind a gleaming reflective surface that often needs no further finishing. It is the most accurate large machine tool in the world.

Diamond turning is routinely used today to manufacture contact lenses and parts for videocassette recorders. Defense contractors also use diamond turning to make lenses for heat-seeking missiles and other weapons. All of these products are transmissive optics, meaning that light passes through them. They are also relatively small with a regular, curved shape. Says engineer Jeff Klingmann, leader of the Precision Systems and Manufacturing Group, "That type of diamond turning is a whole different animal from the large, reflective optics we do. Reflective optics—mirrors—are often ground and polished. But that doesn't work for mirrors with aspheric shapes. When the Department of Defense needed large, aspherical metal mirrors back in the early 1980s, Livermore built LODTM. Producing aspherical shapes is no problem. We just program the shape in, and the diamond tool goes to work."

LODTM can handle a workpiece with a diameter of up to 1.65 meters, a height up to 0.5 meters, and a weight of as much as 1,360 kilograms. A diamond the size and quality of a half-carat engagement ring is secured to a steel shank and carried on the end of a vertically moving tool bar. The workpiece rotates about 50 times a minute on the horizontal face plate while the diamond tool cuts gossamer threads of aluminum, copper, silicon, gold, or nickel with unprecedented precision. The LODTM can produce parts with tolerances to 28 nanometers (about a millionth of an inch), accuracy more than 1,000 times greater than that of a conventional machine tool.



The Large Optics Diamond Turning Machine with machinist Steve Bretz.

Birth of an Ultraprecision Machine

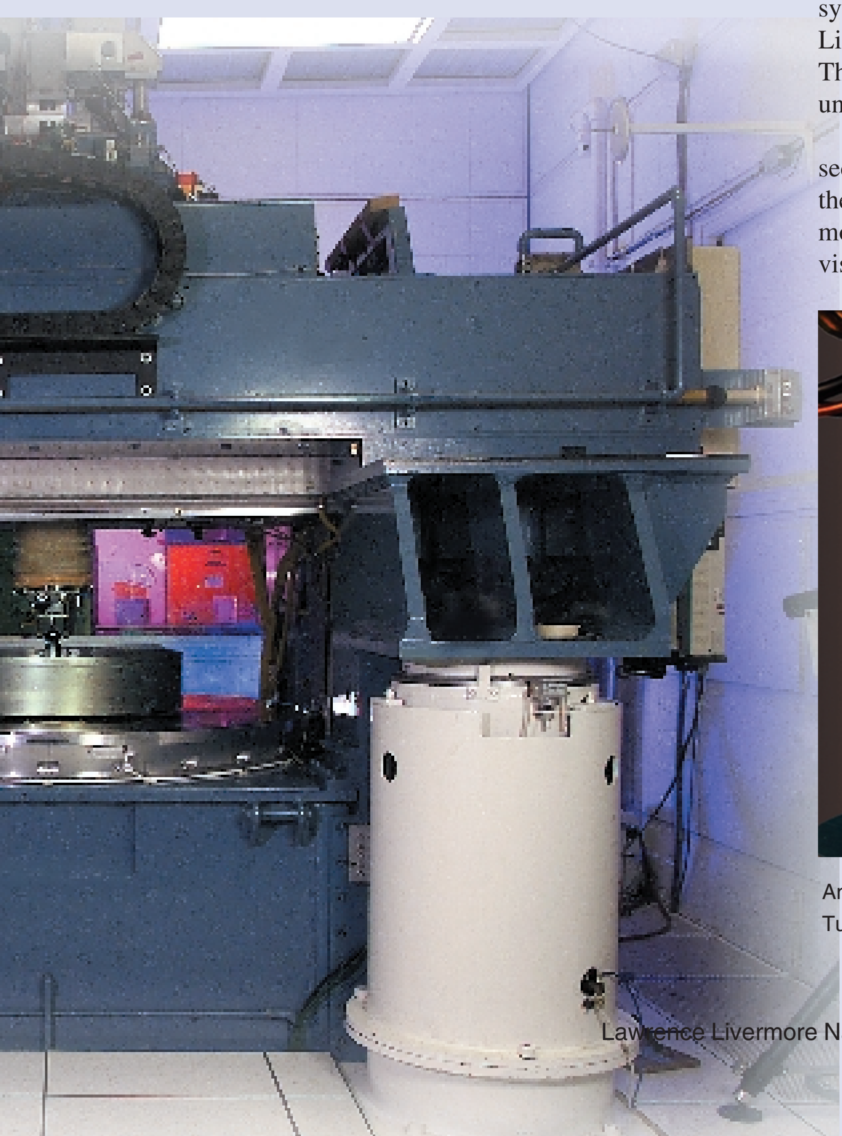
In the 1970s, researchers were considering the development of powerful experimental lasers as an element of missile defense. These ideas became part of the Strategic Defense Initiative, or Star Wars, a program born in the 1980s during the Reagan administration. The laser system's optics had to be extremely large, exotically shaped, and fabricated with a precision corresponding to a small fraction of the wavelength of light. In meeting those requirements, LODTM achieved levels of accuracy that defied measurement by existing methods. Even today, the machine's accuracy is such that it cannot be corroborated by the National Institute of Standards and Technology.

Livermore's Precision Engineering Program designed the machine as the culmination of research in machine tool accuracy. They had determined in the late 1970s that by pushing the limits of precision, they could develop a diamond-turning machine for machining large, oddly shaped optics to exacting tolerances. LODTM incorporated the results of an exhaustive analysis and elimination of factors that cause machine errors, from the heat of a human body to the vibration from a heavy truck passing by.

For example, LODTM has several ways to handle the temperature fluctuations that are typically the largest single cause of diamond-turning machining error. Air temperature in the LODTM enclosure is maintained at precisely 20°C. After the tool is set up, machining does not begin for at least 12 hours to allow the effect of the machinist's body heat to dissipate. All personnel remain outside the LODTM enclosure while a part is being cut. What little heat the diamond cutting tool generates is carried away by cutting oil, also maintained at 20°C.

Engineer Jim Hamilton, who translates client needs into specific instructions for LODTM's machinists, says, "We were concerned that construction for the National Ignition Facility over the last several years might cause us problems. Our building is only about 100 meters away from the NIF construction site. But the earth moving and other heavy work didn't affect the machine."

The heart of the machine's accuracy is a metrology (measurement) frame isolated from the environment by temperature-controlled water flowing through expanded stainless-steel panels. The frame is made of super invar, a steel–nickel–cobalt alloy with one of the lowest coefficients of thermal expansion of any metal. The frame "floats" on LODTM, moving independently from the main machine to give an unstressed, undeformed reference. The part being machined is thus made relative to this frame, not the main machine components. Seven interferometers on the metrology frame continuously measure the location of the tool relative to the part. The machine controller uses this information in real time to dictate all machining. This continuous measurement from an unchanging platform eliminates errors from machine geometry and temperature changes so they do not appear in the part.

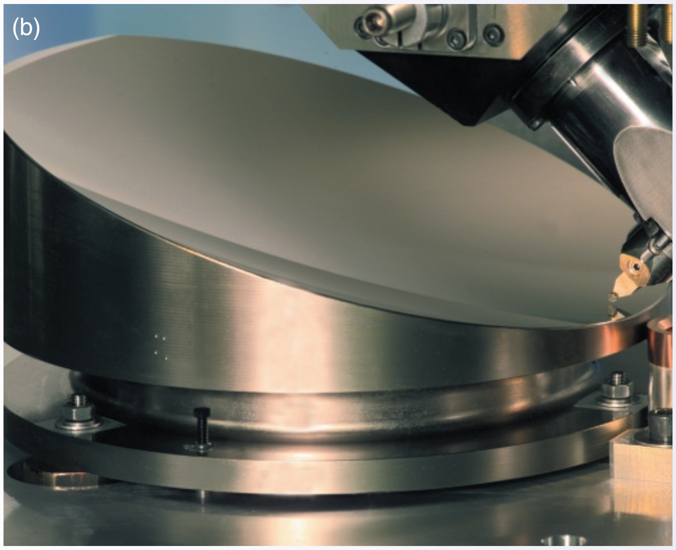


LODTM in Action

LODTM continues to produce one-of-a-kind, prototype optical devices for possible future space-based defense systems. The ultimate client is the U.S. Air Force, with Livermore's technical requirements coming from TRW Inc. These conical mirrors are made of silicon for a simple, light, uncooled laser system.

Previously, Livermore used LODTM to produce three secondary mirrors for the Keck telescopes on Mauna Kea on the Big Island of Hawaii. The Keck telescopes, the largest and most powerful in the world, gather infrared light rather than visible light. For infrared astronomy, diamond turning was the

An example of the aspherical mirrors that the Large Optics Diamond Turning Machine first produced.



(a) National Aeronautical and Space Administration engineer Holly Cagle examines SPARCLE's primary mirrors on the Large Optics Diamond Turning Machine (LODTM) spindle. (b) A close up of a mirror and the diamond tool on LODTM.

only viable process because the mirrors had to be accurate right to the edge of the reflective surface. Processes such as grinding and polishing round off or taper the edge of the critical surface.

Livermore used two precision machining tools, the Diamond Turning Machine #3 and LODTM, to produce the primary mirrors for SPARCLE, an experiment on National Aeronautical and Space Administration's (NASA) Space Shuttle. SPARCLE will demonstrate the ability to measure wind speeds using a space-based lidar system. Diamond Turning Machine #3 first semifinished an aluminum blank that was then coated with electroless nickel. LODTM did final "figuring" in the nickel layer. After leaving Livermore, the mirrors were polished and gold coated for final use.

LODTM Today

The next big project for LODTM may be for NASA scientists who are planning a new space-based telescope. LODTM has the capability to machine some or the mirrors for this next-generation version of the Hubble telescope.

A staff of seven operates and maintains LODTM, about half the number required when the machine first came on line. Over the years, many original, custom-made parts have been replaced by commercial ones. The result is a more efficient and reliable machine that is easier to operate and maintain.

But LODTM is nevertheless a unique machine, and it must machine parts to extremely tight tolerances. Says Steve Bretz, head machinist on LODTM, "We spend about 80 percent of our time keeping the machine running properly. Before I came to Livermore, I was a machinist in a regular machine shop. Working on LODTM is entirely different. Here we have to work very closely with engineers and experts in computers, electronics, and control systems to eliminate deviations and maintain the required tolerances."

They must be doing something right. Eighteen years after LODTM's first operations, measuring devices are still not sophisticated enough to confirm the machine's accuracy.

—Katie Walter

Key Words: Keck telescopes, Large Optics Diamond Turning Machine (LODTM), National Aeronautical and Space Administration (NASA), precision engineering, Strategic Defense Initiative.

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