by Bob Bridges and Kevin Hagan

Laser Tracker Maps Three-Dimensional Features

Early in the 17th century, René Descartes invented the coordinate system, which enables measurements of three-dimensional features of large objects. Today, the ability to make such measurements accurately and rapidly is critical to maintaining and improving quality, cost, and productivity in many industries.

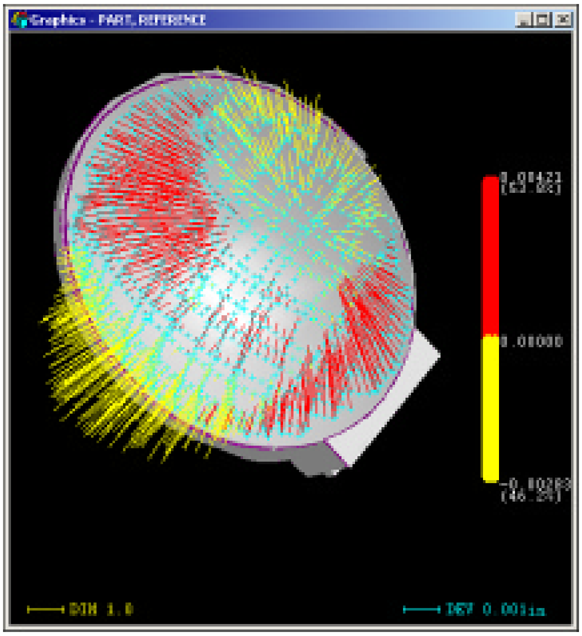

Figure 1. Full-screen bit map of a parabolic subreflector dish for an antenna, obtained with a laser tracker, can be manipulated in any direction. Multicolor spikes indicate deviation of actual surface measurements from nominal data.

Many instruments can measure coordinates, and each has its particular strengths and ideal applications. Traditional coordinate measuring machines (CMMs) make repeated measurements rapidly and accurately. Although they are immobile and limited in measurement distance, their speed and accuracy make them useful for inspecting production components. Theodolites measure angles with high accuracy over large distances. They are most often used in pairs to determine radial distance with moderate accuracy. Total stations are similar to theodolites but incorporate an electronic distance-measurement system. Jointed-arm CMMs consist of a probe tip attached to the end of a sequence of mechanical links whose angles are measured by angular encoders. They are manually guided over the measurement target and provide moderate to high accuracy. Photogrammetry and videogrammetry systems use cameras to record the locations of reflective targets on film or charge-coupled-device arrays. Typically, cameras take photographs from two or more locations to obtain three-dimensional measurements of moderate to high accuracy.

Laser trackers are portable CMMs that measure coordinates by tracking a laser beam to a retroreflective target. Introduced in the late 1980s, they can make measurements of objects ranging in size from inches to about 30 ft (Figure 1). Trackers provide accuracy, speed, and versatility, can collect coordinate data at up to 1,000 samples/s, and usually require one operator. The laser tracker made by SMX Corp. (Kennett Square, PA) measures features up to 35 m away, with an accuracy of 25 µm at 5 m (Figure 2).

Laser trackers have penetrated deeply into the automotive and aerospace industries, and their use continues to grow elsewhere. Applications for trackers include inspection of tools and parts to compare actual dimensions with design values; stock verification to ensure desirable tolerances; measurements of tools, fixtures, and assemblies during fabrication; alignment of equipment such as precision rollers; dynamic measurement of components such as robot arms in motion; and reverse engineering of computer-aided design models from prototypes.

A basic laser-tracker system consists of a tracker, control unit, personal or laptop computer, and software. Simply put, the tracker determines coordinates by measuring two angles and a distance. It sends a laser beam to a retroreflective target glued to, or held by hand against, the object or surface being measured (see Figure 3). The beam reflects off the target and retraces its path, reentering the tracker at the same location it left. Of the several types of retroreflective targets, the most common is a spherically mounted retroreflector (SMR). An SMR consists of a cube-corner retroreflector centered within a three-quarter metal sphere, with the vertex of the cube corner at the sphere's center.

As light reenters the laser tracker, part goes to an interferometer that measures the distance from the tracker to the SMR. Angular encoders measure the angular orientation of the azimuth axis and the elevation axis. Together, the angles of the encoders and the distance of the interferometer from the target precisely locate the center of the SMR. The tracker's software applies an offset equal to the SMR radius to obtain the exact coordinates of the surface being scanned.

Distance measurement can be either incremental or absolute. Incremental distance is measured with the interferometer and a frequency-stabilized, eye-safe helium–neon laser. The laser light splits into two beams, and one beam travels directly into the interferometer. The other beam travels out of the tracker, reflects off the SMR, and on

Figure 2. This laser tracker mounts on a stand on the shop floor. A spherically mounted retroreflector sits in its home position in the nest on the front of the tracker.

return, also passes into the interferometer. Inside the interferom the two beams of light interfere, resulting in a cyclic change each time the SMR moves a distance equal to one-quarter of the wavelength of the light (~ 0.17 µm). Electronic circuitry counts the number of cyclic changes to determine the distance traveled.

In a typical incremental measurement, the operator first places the SMR in the home position (a nest built into the tracker housing), and resets the interferometer to the home-distance setting, a known three-dimensional location. As the operator moves the SMR to the measurement site, the laser tracks along, remaining fixed to the center of the SMR. This procedure works well as long as nothing breaks the beam. If that happens, the number of cyclic counts is no longer valid and the distance cannot be determined. The tracker then signals that an error has occurred, and the operator must return the SMR to the home position or to another known reference point.

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Schematic representation of spherically mounted retroreflector

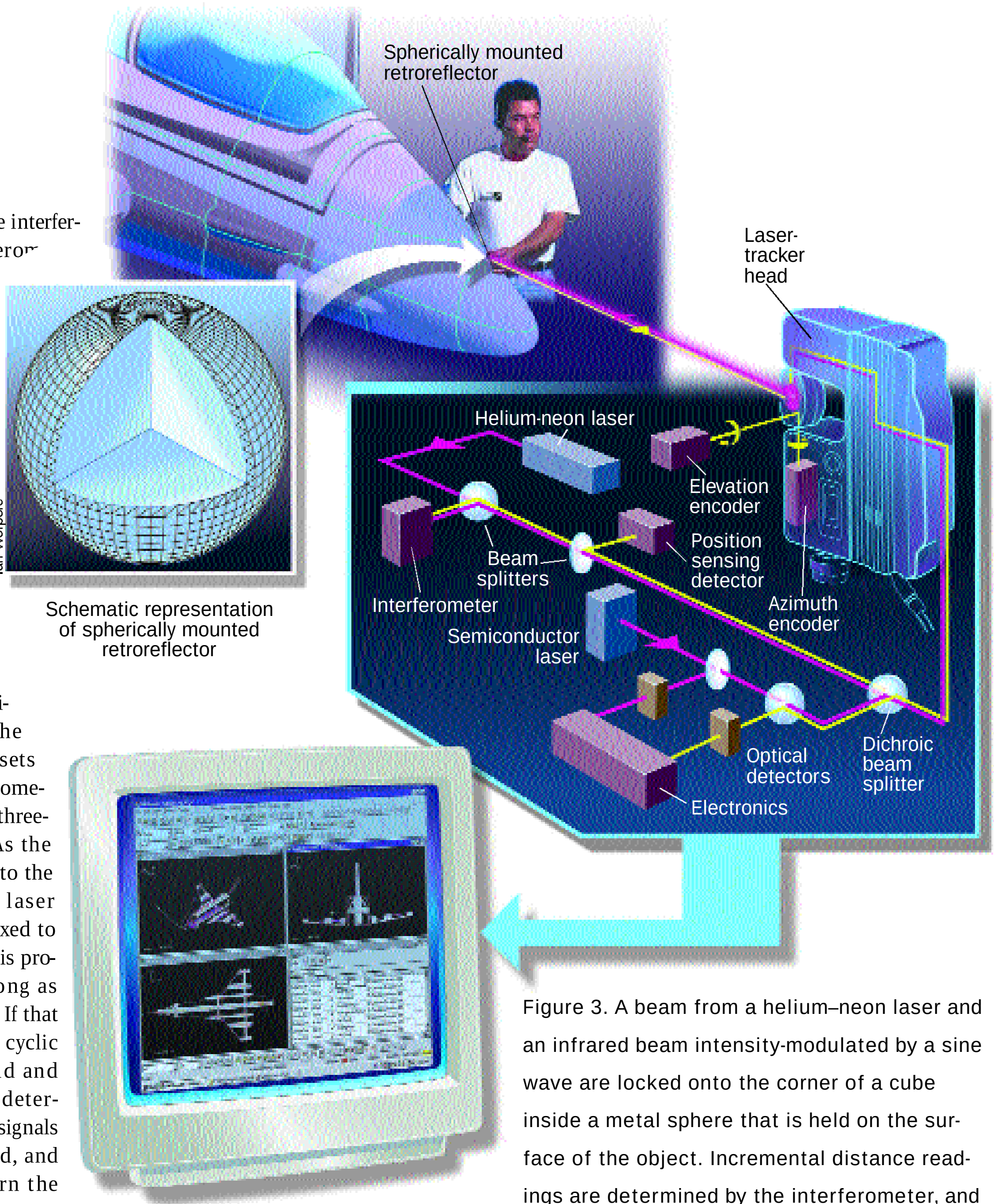

Figure 3. A beam from a helium–neon laser and an infrared beam intensity-modulated by a sine wave are locked onto the corner of a cube inside a metal sphere that is held on the surface of the object. Incremental distance readings are determined by the interferometer, and absolute distance readings are determined by the time of flight of the sine waves. Elevation and azimuth are determined by encoders gimbal-mounted on the laser-tracker head.

A different device, the absolute distance meter (ADM), eliminates the need to return the SMR to a reference location after beam interruption. Because of its convenience, an ADM is added to most trackers sold today. The ADM in the SMX tracker begins with infrared light from a semiconductor laser that is modulated by a sine wave and combined with the red light from the helium–neon laser before leaving the tracker.

After reflecting off the SMR, the beam reenters the tracker, where the infrared light is separated from the helium–neon light and converted into an electrical signal. Electronic circuitry analyzes the signal to determine the time of flight of the sine wave. It multiplies this value by the speed of light in air to determine the distance from the tracker to the SMR.

A tracker with ADM capability can perform many tasks. For example, it can monitor the relative position of large components such as an aircraft wing and fuselage as they are joined, which is accomplished by measuring the positions of multiple small targets mounted on the sections. An ADM tracker can also monitor the slow drift of components out of alignment. Because of this capability, the ADM has proven to be particularly advantageous for machine-tool inspection and certification.

The tracker must also steer the beam, which in the SMX tracker is accomplished by sending the beam through glass prisms attached to mechanical axes. By rotating the axes, the tracker can aim the laser beam in any desired direction. In most applications, this ability is necessary but not sufficient. The tracker must also keep the beam centered on a rapidly moving SMR. To accomplish this, part of the reflected laser beam splits off to a position-sensitive detector. If the laser beam strikes the SMR off center, the tracking beam also strikes the detector off center. The tracker monitors the discrepancy and adjusts the rotation of the mechanical axes to keep the beam centered on the SMR.

Measuring

Laser trackers collect three-dimensional coordinate data, which software can convert to geometrical entities such as points, planes, spheres, and cylinders. Usually, the data are displayed within a local-coordinate system tied to features of the object. These features may be part of the object itself, or features may be added physically to the object to represent points or lines. Points are often located by means of tooling holes, into which steel spheres are inserted on steel shanks. The tracker then scans the surface of each sphere to determine its center.

Sometimes it is necessary to move the tracker to several locations to measure all the features of interest. A way to do this is to first determine three or more SMR home positions from which measurements will be made. The tracker measures the coordinates of the SMR at each position before and after the tracker is moved. This process enables the tracker software to automatically convert the data collected after the move into the local coordinate system.

Several accessories add to tracker capabilities:

- RetroProbes are fittings that enable efficient measurements of hidden or recessed areas such as holes, pockets, corners, and etched lines.
- Remote-control devices, including handheld infrared remotes and voice-recognition headsets, allow the operator to access various software functions without walking back and forth to the computer all the time.
- Temperature-sensor accessories compensate for environmental fluctuations. They include sensors that monitor and compensate for thermal expansion and sensors that measure air temperature along the laser beam's path to optimize accuracy.
- A leveling accelerometer integrated into the tracker measures its orientation with respect to gravity.

Manufacturing

Laser trackers have found wide application in industry. For example, DaimlerChrysler has used SMX trackers at its Windsor, Ontario, plant to reduce machine-tool inspection time by as much as 66%. Tracker operators either work from a coordinate system generated from previous measurements or build a new coordinate system themselves. After transforming model coordinates into "car body coordinates"—that is, relating the tool coordinates to the auto parts the tool handles—the operator can quickly move from detail to detail on the tool, certifying each as he goes.

Another common automotive application is the creation and inspection of dies. Designers first create a model of the automobile in clay. The tracker digitizes the model's surface, and a computer converts the cloud of points into a smooth surface. The data are used to mill the die. During this process, the tracker measures both the die and the stamped part, and the die can be modified as needed to produce the desired part. The tracker software is used to graphically compare actual and design surfaces.

Aerospace applications include aligning features such as holes, pins, and edges during the fabrication of tools, jigs, and assemblies. New Piper Aircraft, Inc. (Vero Beach, FL), uses a laser tracker to produce its recently introduced Meridian Malibu, a corporate turboprop aircraft, and to periodically inspect tool dimensions, contours, and features. The company plans to incorporate trackers directly into future production lines because the system has helped New Piper to innovate manufacturing approaches—an example of how the laser tracker can help redefine the manufacturing process.

Reverse engineering of parts from physical models is another common aerospace application. Orbital Sciences Corp. (Dulles, VA) has built suborbital space vehicles using a laser tracker to measure the deformation that occurs during static load testing. Tracker data can be recorded in a predetermined sequence throughout the automated procedures.

Laser trackers have proven particularly adept at precision machining of large parts. Remmele Engineering, Inc. (Big Lake, MN), uses trackers to perform initial stock verification, align parts in machines, and complete final quality inspections. In many cases, time is critical, as in a recent job involving huge parabolic dishes for a deep-space antenna system. Total inspection and verification time was slashed to 3 h from an estimated period of two days that would have been required if Remmele had used the alternative technology of photogrammetry (Figure 4).

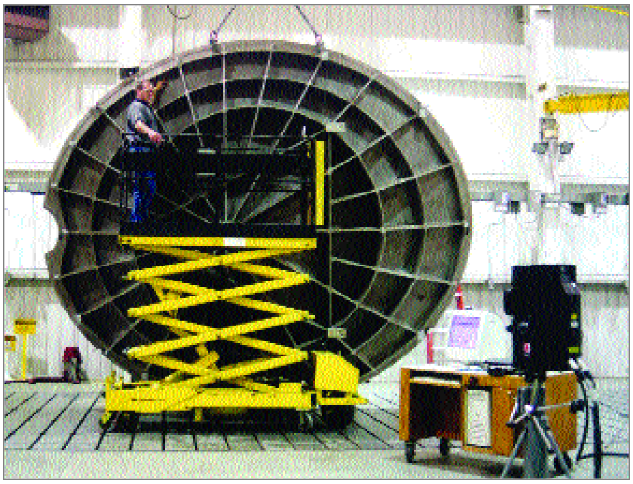

Figure 4. At Remmele Engineering, Inc., in Minnesota, a parabolic dish that will become part of a deep-space antenna system is scanned to verify dimensions before it is precision-machined.

Tolerances are tight at United Defense LP (York, PA), which uses a tracker to inspect horizontal boring-mill machining performed during the fabrication of large military tank cabs. More than 100 separate features are inspected and compared to a coordinate system with tolerances as low as ±0.001 in. The tracker measures these close tolerances and downloads information to a data-reduction software package, which makes results immediately available.

The ability to use the laser tracker in tight conditions was a key advantage in the construction of the laser target chamber in the National Ignition Facility at Lawrence Livermore National Laboratory. Among other things, the tracker was used to position 192 laser ports in the 33-ft-diameter sphere, which will be used for fusion energy research. The measurements were performed by setting up the tracker in one location inside the sphere.

Beyond traditional manufacturing, laser trackers are useful in difficult, large-scale measurement applications, such as positioning magnets at particle-accelerator facilities, properly locating Delta rockets on the launchpad, and setting the direction of the radio antenna at the Smithsonian Observatory atop Mauna Kea in Hawaii.

The greatest impact of laser trackers, however, has come in manufacturing settings where companies have incorporated them into nearly every stage of the process. Their speed, accuracy, portability, and versatility distinguish them from other CMMs and make them a valuable tool in any large-scale manufacturing operation.

For further reading

Selected Papers on Laser Distance Measurements; Bosch, T. M., Lescure, M., Eds.; SPIE Press: Bellingham, WA, 1995; 736 pp.

Coordinate Measurement Systems Committee Web site at http://www.cmsc.org.

The SMX Corp. Web site includes articles on specific laser-tracker applications at http://www.smxcorp.com.

B I O G R A P H Y

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