Automated part positioning with the laser tracker

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Abstract
Improvements and new developments for Leica's laser tracker make it suitable for measuring the relative position of two parts or components during the manufacturing process.

This facility is made technically possible by the development of an Absolute Distance Meter (ADM), accurate to some 30 - 50 microns, as well as small, lightweight, wide-angle retro-reflectors known as Tooling Ball Reflectors (TBRs). The ADM enables the tracker to locate individual target reflectors without the need for continuous interferometric tracking. The TBRs are particularly suitable for attachment to both large and small components. By measuring a small number of target reflectors on each component, the relative positions of those components can be regularly updated with full positional and tilt information.

This concept is currently being applied and evaluated within the aerospace industry where the objective is to use the tracker as a measurement controller within a complete manufacturing loop. A beta program is available for this purpose. It is based on Leica's ***Axyz*** software platform and uses the programming functions (Visual Basic scripts) which are part of this package.

1. Introduction

Many tasks in manufacturing and alignment are defined by the problem of measuring the relative position of two components, re-positioning them and re-measuring. This cycle is then repeated until the components are correctly located with respect to one another and/or with respect to some reference coordinate system.

This general task is partly characterised by a change of emphasis from measuring 3D locations to determining all 6 degrees of freedom (6 DOF) of a single component. The 6 DOF represent the location and angular attitude of each component and can be calculated by measuring, in a common (global) coordinate system, 3 or more target reflectors whose coordinates are also known in a local coordinate system on the component. In effect, by standard transformation procedures the targets enable the local origins and axes to be found in the common coordinate system.

Leica's tracking laser interferometer can, in principle, be used to measure the reflector locations. In practice, the original tracker and its reflectors were not well suited to the task. The interferometer must continuously track a single reflector and this would have to be moved in some way between the target locations on each component. Any interruptions of the beam would require re-setting the interferometer's datum distance. These restrictions would not enable the development of the sort of automated cycle described above.

There are many applications for which single reflector tracking is ideal and which provide the motivation for the tracker's development. However even these applications require re-establishing the distance datum after a beam break. This would be made much easier and more convenient by the development of an Absolute Distance Meter (ADM). Such a device is now available and can independently measure the absolute distance to any unknown reflector location, thus providing an excellent mechanism for re-initializing the interferometer (IFM). However, the ADM requires a finite time for measurement and cannot itself be used for tracking.

For the task described above, tracking is not necessary and the ADM could therefore be employed as a stand-alone device. If targets were placed at every location to be measured, and a suitable search routine available to allow for small errors in target location, then the tracker with ADM could work as an automatic polar measuring instrument. To be really effective, the reflectors must be small and lightweight so that they are convenient to attach to the components and do not interfere with their movements. The tracker's original reflectors were too large for this purpose. A search routine and suitable reflectors have also now been developed.

These devices and features are incorporated into the tracker's standard software in the form of a mode of operation called "Auto-Inspect". In this mode the tracker takes a list of points with known nominal locations and attempts to find, and then measure, a reflector at each location. Where there is a problem such as a missing or obscured reflector, the point may be skipped or the operator given the option to intervene.

The general application described here is like an auto-inspection controlled from an external computer. Three or more reflectors attached to known positions on both parts are automatically measured to provide full positional and rotational data as outlined above. The results of this "auto-inspection" can be then be used to compute the relative positions of the parts. This information can in turn be fed back to positioning devices which move the parts into improved locations.

2. New hardware

2.1 The Absolute Distance Meter

The Absolute Distance Meter (ADM) is a separate device "piggybacked" onto the interferometer. (A retro-fit to existing trackers is possible) The beam coupling section is mounted between the IFM and the tracking head. The challenge has been to avoid disturbing the HeNe beam by introducing new optical components in the interferometer’s beam path.

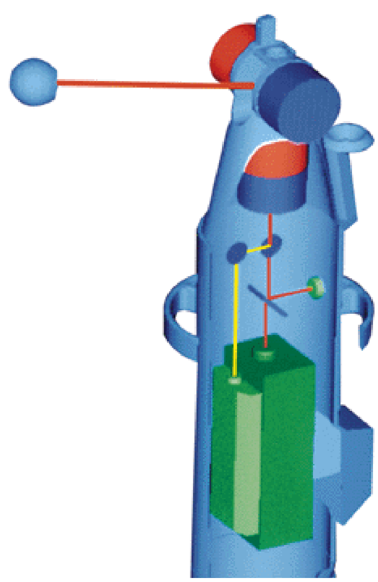


Fig. 1 Integrating the ADM with the IFM inside the Laser Tracker LTD 500

The ADM's measurement technique is based on a systematic modulation of a light beam, such as is found in other Electro-optical Distance Meters (EDMs). There are different generally known modulation methods which superimpose this periodic structure on the measurement beam. The ADM modulates the linear polarization of the laser light. This proven technique, previously used in the Mekometer ME5000, has been adapted to the next technology generation.

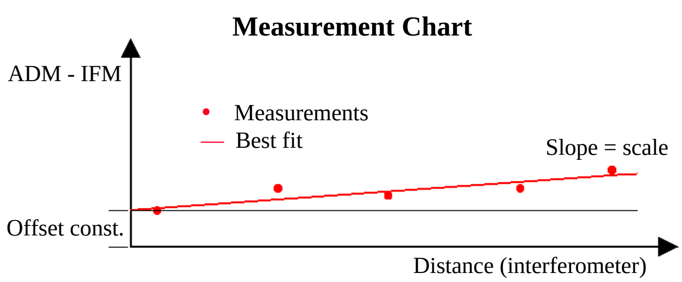
To clearly separate the interferometer beam (632.8 nm) from the ADM light, an infrared laser diode with a wavelength of 780 nm is used as the ADM's carrier beam. The modulation is done by applying an alternating current to an optical crystal. The frequency of this current can be set between 750 MHz and 920 MHz. A minimum bandwidth of 150 MHz is necessary to achieve the shortest measuring distance of 2.6 m for the ADM, which reduces to 2.0 m when integrated into the LTD 500. The maximum range of the ADM is limited to 40 m, corresponding to the measuring range of the LTD500 (35 m). The very high resolution and accuracy of the ADM is based on the Fizeau principle. The key elements are that measurements are always made at the same phase position and the phase detection is based on a differentiation method. The synthesizer must therefore be able to set the modulation frequency in very small and accurate steps to the detected value. These essential requirements are fulfilled in the ADM where the synthesizer permits a resolution < 1 µm over the complete measuring range and an accuracy < ± 35 µm (2σ). All effects specific to the ADM, such as internal thermal influences, are included in the stated reproducibility. However, a stable atmosphere is additionally required in order to reach these accuracy values.

In the LTD 500, the user has normal interferometer as an “onboard calibration reference”. It is very easy to run a short set of measurements where a minimum of 5 ADM distances are best fitted to corresponding IFM values using an offset and scale factor. This type of measurement mode is provided by a separate command and gives the user the possibility of an online reference check. The following table shows a set of typical measurement results:

IFM Distance [mm]	ADM raw Distance [mm]	ADM reduced Distance [mm]	Δ ADM - IFM [mm]
1646.686	2338.355	1646.685	-0.001
3434.607	4126.745	3434.609	0.002
9666.260	10360.019	9666.260	0.000
17234.995	17930.726	17234.995	0.000
23126.018	23823.285	23126.020	0.002

Table 1 Addition Constant and Scale Factor Calibration

Fig. 2 Best-fit diagram, offset and scale calculation



ADM distances are used to re-initialize the interferometer, i.e. set the IFM distance datum, when interferometry has been lost and must be re-established in order to measure reflector coordinates. This may occur after a positioning command to a pre-defined reflector location, or after a beam interruption. The

Laser Tracker must then re-establish the servo loop and if there is no direct feedback signal a search routine is started automatically. As soon as the beam locks onto the reflector, an ADM distance measurement is made. Each ADM distance measurement takes approximately 1.5 seconds and the IFM distance is then re-established. After this first part of the measurement, a normal single point measurement of the Laser Tracker records the 3-D coordinates, according to the defined integration rate.

An optional CCD camera can help the user in finding the reflector position. Each search camera has pulsed illumination directed at the workspace. Every reflector flashes back at the same frequency and the user can position the measuring beam onto any visible reflector using the arrow keys on the controlling PC's keyboard. This feature is very helpful for defining a "drive library", for "auto inspection" or to reposition an interrupted beam.

2.2 The tooling ball reflector

The Laser Tracker can use different types of reflectors such as a cat's-eye, corner cubes with different sizes and small glass prisms. Technically there was never a problem for the IFM and its tracking loop, nor for the ADM, to track and measure such glass prisms, but they have only recently become available. Currently Leica's "Tooling Ball Reflector (TBR) is supplied with a ½ " (12.7 mm) diameter housing.

Fig. 3 Tooling Ball Reflector, handle attachment and mounting adapters

This type of reflector is very easy to use, especially for tracking. The reason is the beam refraction at the glass surface. The beam is bent towards the apex of the prism, making the servo loop less sensitive to reflector orientation. However there is a disadvantage associated with this. Due to the angle of incidence, a measurement error is introduced. As fig. 4 shows, the error mainly influences the tracker's angle measurement. Here the size of the glass cube and the location of the rotation point are the important parameters. During the manufacturing process each glass cube is measured and individually positioned within the housing to minimize this error. Larger glass reflectors do not offer sufficient accuracy and are therefore not produced.

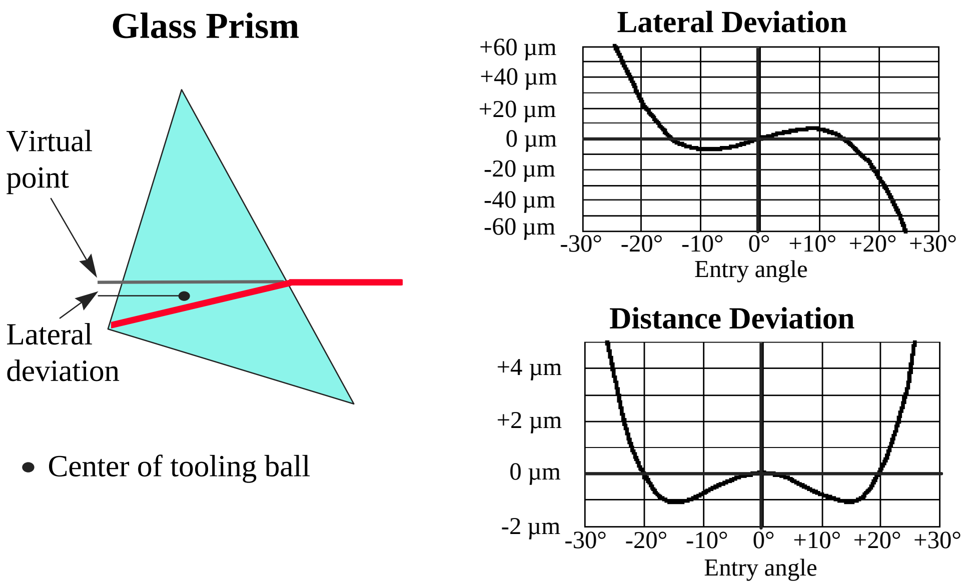


Fig. 4 Light path in the glass prism and error diagrams

3. Application software

The application software for automated part positioning is similar to the "auto-inspect" function supplied with the standard software. Briefly, the tracker works through a list of nominal positions and attempts to find a nearby reflector at each position.

3.1 Concept of current software

The software interface shows a list of points to be measured, displayed in a grid like a spreadsheet. Each point displays nominal coordinates and last measured coordinates, if already measured.

From within the software commands are available to modify the list of points, set suitable operating parameters and initiate measurements. This enables the software to be used manually and independently, with results returned to the operator.

There is also a set of equivalent commands which can be sent by an external computer over an RS232 serial interface. This also permits control over the list of measured points, enables measurements to be initiated and results to be returned.

The list of points to be measured can therefore be generated manually, input from a text file or transferred over the serial interface.

When points are measured, their measured values are recorded in the grid.

When searching for a point, the tracker can either use the nominal coordinates or the last measured values. Either set of values should be within 10 - 20 mm of the actual location to enable the search routine to function correctly.

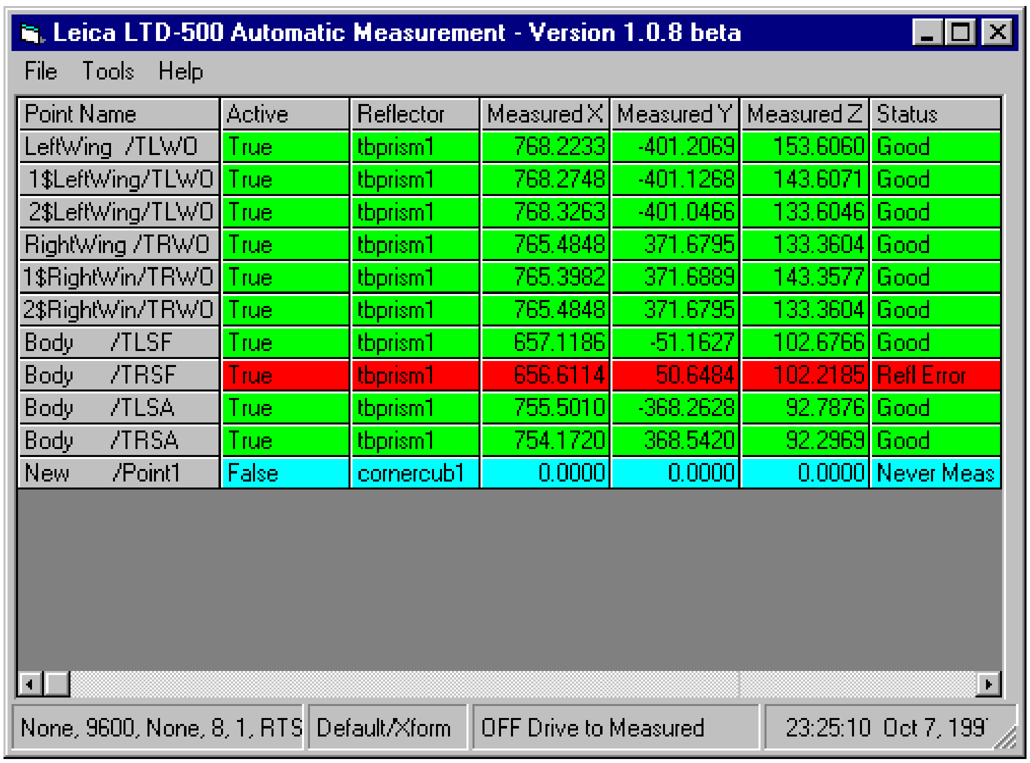
For large part movements it is likely that the external system can make good estimates of current position. These revised estimates can be input into the grid, via the serial interface, as modified nominal positions which can then be reliably measured.

The software also has the ability to measure hidden points. Hidden point rods are adapters which insert into a point to be measured but which is not directly visible. Two reflectors on the rod are offset from this point. These are visible and can therefore be measured. Simple vector geometry enables the hidden point to be located from the coordinates of the measured offset points.

This concept is implemented through the ***Axyz*** software which has Visual Basic extensions to directly drive and query the tracker. A Visual Basic (VB) script has been developed to provide the diverse measurement functions, and return results, in response to external commands via the RS232 serial port.

The VB script uses EXCEL for importing and exporting nominal and measured locations and for on-screen presentation of results.

3.2 Sample screen display



Point Name	Active	Reflector	Measured X	Measured Y	Measured Z	Status
LeftWing /TLW0	True	tbprism1	768.2233	-401.2069	153.6060	Good
1$LeftWing/TLW0	True	tbprism1	768.2748	-401.1268	143.6071	Good
2$LeftWing/TLW0	True	tbprism1	768.3263	-401.0466	133.6046	Good
RightWing /TRW0	True	tbprism1	765.4848	371.6795	133.3604	Good
1$RightWin/TRW0	True	tbprism1	765.3982	371.6889	143.3577	Good
2$RightWin/TRW0	True	tbprism1	765.4848	371.6795	133.3604	Good
Body /TLSF	True	tbprism1	657.1186	-51.1627	102.6766	Good
Body /TRSF	True	tbprism1	656.6114	50.6484	102.2185	Refl Error
Body /TLSA	True	tbprism1	755.5010	-368.2628	92.7876	Good
Body /TRSA	True	tbprism1	754.1720	368.5420	92.2969	Good
New /Point1	False	cornercub1	0.0000	0.0000	0.0000	Never Meas

Fig. 5 Simplified sample screen display

The simplified screen display shows a list of points. Green rows indicate successful measurements, red rows indicate some problem, further explained in the "Status" column. Blue rows indicate locations which have not yet been measured.

This is not a full description or display of the actual software, which provides further facilities and information.

3.3 Coordinate system

Axyz software allows the user to make measurements in any defined coordinate system. If measurements are made with a single laser tracker, as here, the default system would be defined by the tracker's centre of rotation and its own axes. However other more convenient coordinate systems can be defined by appropriate measurements of points in the object space. The equipment may then present results in any of these coordinate systems by making it the "active" system.

In summary:

- Nominal and measured data are displayed and transmitted in the tracker's active coordinate system.
- It may be necessary to establish this system before measurement if the nominal data is provided in a design coordinate system.
- It may be useful to establish reflectors in stable locations off both parts, so that each part may be referred to a common fixed reference system.

Finally it may <u>not</u> be necessary to define another coordinate system if only relative part positioning is required. In this case any convenient system, such as the tracker's default system, will be sufficient.

4. Applications

4.1 British Aerospace, Chester, UK

British Aerospace, at Chester in the UK, is evaluating ways of ensuring that two robots cooperate accurately in drilling operations. In the sample application the skin of an aircraft wing is attached to the foot of a wing rib by first drilling through the outside of the skin and into the foot.

Two robots are used in this application. An internal robot has a laser locating unit attached to its end-effector. This device is used to identify the rib foot and accurately position itself with respect to it. (The operation of the device is not described in this paper.) An external robot with a drill attached to its end-effector must then be positioned with respect to the internal robot such that it can drill the hole normal to the wing surface, emerging at a suitable point on the foot. A riveting or bolting operation would complete the attachment. It is the task of the tracker to supply the basic measurements which locate the external drilling robot with respect to the internal robot.

To test the full feedback loop of laser tracker, cell controller and robots, and evaluate accuracies and examine problems, a simplified version of this operation has been set up. This involves a single rib and small section of wing in a relatively uncluttered environment. Future testing will deal with a realistic configuration in which access is more restricted.

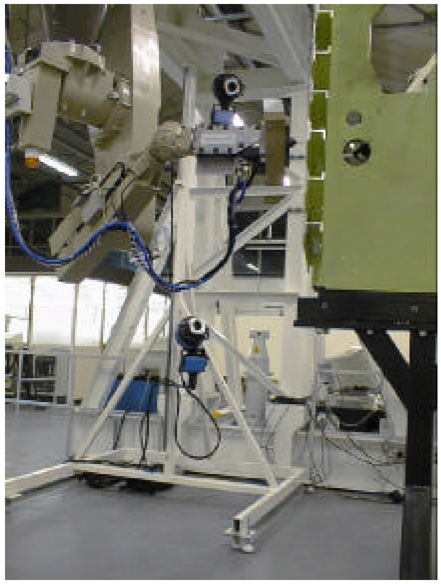


Fig. 6 From rear to front: Laser Tracker, photogrammetric cameras, drilling robot

The overview in fig. 6 shows the tracker on site in the background, with the drilling robot in the left foreground and the test piece in the right foreground. Two photogrammetric cameras (VSTARS system) can also be seen.

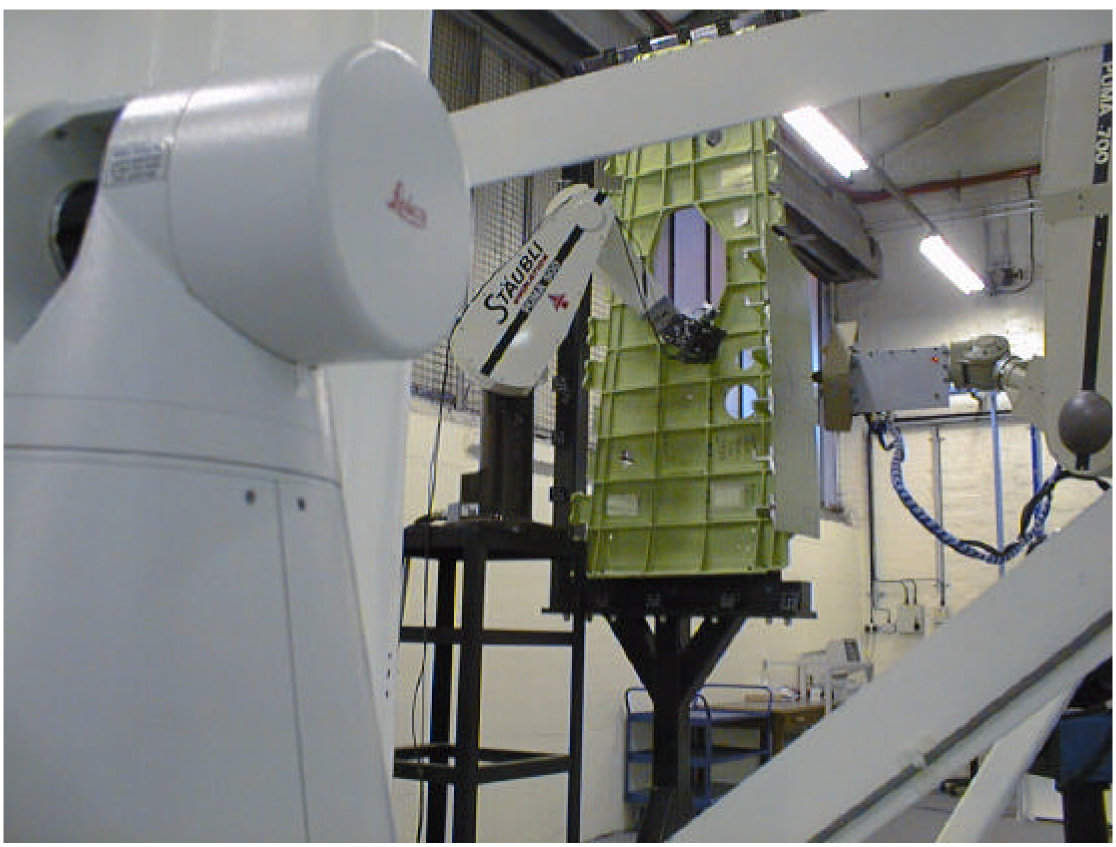


Fig. 7 View from tracker towards internal and external robots on either side of test piece

The view from the tracker in fig. 7 additionally shows a smaller, internal robot supporting its laser locating unit. Four tooling ball reflectors are attached to the rear face of this unit. The drill held by the external robot also has four tooling ball reflectors attached to one face of its housing. Prior independent calibration measurements were made to provide tooling ball coordinates in local coordinate systems relevant to each end effector.

Since only the relative position of one end-effector with respect to the other is required, measurements are only required in the default coordinate system defined by the tracker. No other coordinate system was created. The actual calculation of the relative 6 degrees of freedom is done on the external computer system. The laser tracker delivers the coordinates of the 4 reflectors on each robot's end effector. Since these have known coordinates in the local system of each end-effector, the origin points and local axes can be established with respect to the default coordinate system. The relative location of one origin and set of axes relative to the other is then a simple calculation and this is used to re-position the external robot for the next cycle of measurements.

Tests are not yet complete but positional accuracy appears to be good enough to justify further work with this configuration.

5. References

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