KERN SMART 310 - Leicag's Approach to High Precision Dynamic 3D Coordinate Determination

by

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0. Abstract

Using a single beam laser interferometer, precise angular encoders and a sophisticated servo-tracking system, a highly dynamic measuring system for 3-D coordinate determination was developed.

This paper describes the system design and the software features available. The accuracy is supported by test results. Potential applications are also presented.

1. Introduction

Laser interferometers have been used in an industrial environment for several years for high precision distance and angular-measurements. Their use was limited by the need for precise guidance of the reflector prism or mirror to avoid beam interruptions. In the past several efforts have been made to improve the performance of interferometers and reduce the effects of this limitation (e.g. self aligning reflectors (Gervaise & Wilson (1987))). Major improvements were the combination of precise angular encoders and the single-beam laser interferometer (3-D polar coordinate measurements) and the use of a multi-interferometer set-up for trilateration measurements.

Studies and efforts have been made by different companies and universities (e.g. Cheasapeake Laser Systems, University of Surrey, FhG Karlsruhe - see references). To our knowledge, only two products based on this technology are available now on the market. This paper reports on one of those two systems - the Kern SMART310 (System for Mobile Angel and Ranging to Target)

The basic-technology of the SMART310 was developed by a small group at the National Bureau of Standards (NBS) in USA and was patented in 1987 under US patent No. 4,714,339 (see references, Lau et.a1.(1986), Zik and Lau (1988)). The further development of this technology was continued by a small company 'Automated Precision Inc. (API)'. In 1988 this company looked for a production and marketing partner, and in early 1989 Kern&Co.Ltd (now Leica Aarau Ltd.) acquired this technology. They improved it and introduced a completely redesigned laser tracking interferometer at the 1990 Quality Show in Chicago. The following paper describes the improved system design, the software and possible applications, as well as results from test measurements.

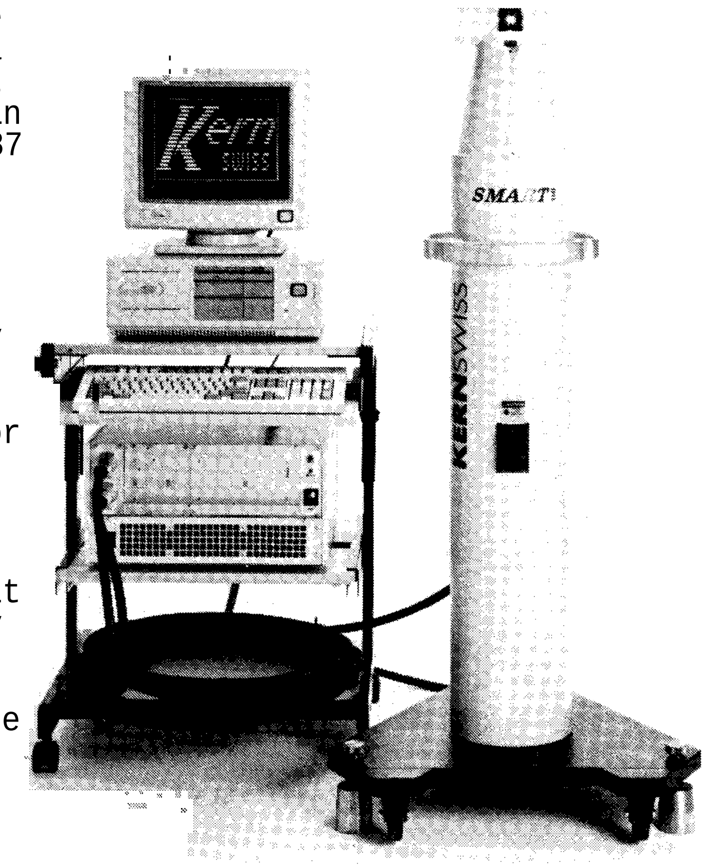

Fig. 1: SMART Prototype System

2. The Components of the Laser Tracking System

The components of SMART are shown in the block diagram Fig. 2.

2.1. The Sensor

The task of the sensor component is to acquire raw angle and distance information. For this the tracking head provides rotation about two orthogonal axes. Each axis has an encoder for angle measurement and a direct drive motor to allow remote controlled movement.

The upper part of the tube contains a Zeeman type laser interferometer to measure distance differences. The laser beam also functions as the collimation axis of the instrument and is sent to a reflector via a mirror attached to the transit axis.

A two-axis photosensor (PSD) beside the interferometer receives a portion of the reflected beam and is responsible for the tracking facility of SMART.

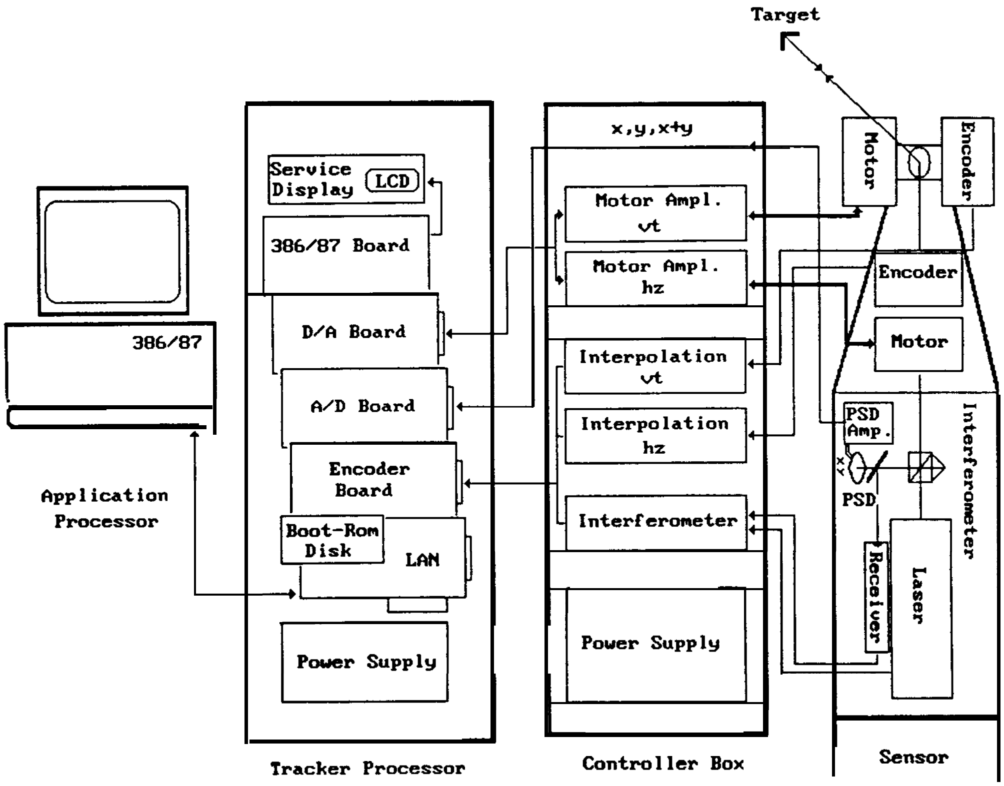

Fig. 2: Block Diagram SMART

The tracker's 'home point' supports a reflector. This provides a known offset distance from the tracking head which can be used to set the interferometer's initial distance.

The liquid bubble attached to the tube is a means of detecting if the instrument has tilted during measurements. Two wheels on the base allow easy transportation of the sensor over short distances.

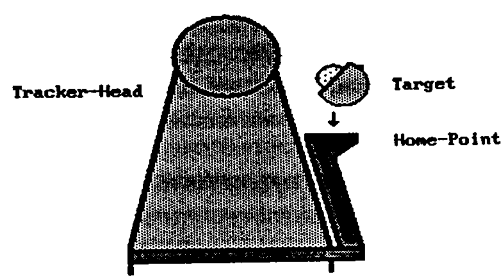

Fig. 3: Home Point

2.2. The Controller

The controller, which is connected to the sensor by two cables of 5m or 10m length, contains the tracker's main electronics. These are :

- power supplies
- 2 motor amplifiers
- 2 encoder- and 1 interferometer electronics board which square the signals and interpolate the encoder steps.

The signal from the photosensor needs no further amplification before transmission to the tracker processor via the controller.

2.3. The Tracker Processor (TP) and Firmware

The hardware of the TP is arranged on a back plane and consists of :

- a 386/87 SX board
- a A/D board, which digitizes photosensor data coming in via the controller. PSD data are used to calculate the servo loop and to correct angle values measured by the encoders.
- a D/A board which transforms digital commands for the motors into analog values. These are sent back to the motor amplifiers in the controller.
- an encoder card which counts the signals delivered by the encoder and interferometer electronics, and generates the actual angles and distance.
- a board for the local area network (LAN) used to exchange data with the application processor (see 2.4).

The hardware-related software (firmware) running on the TP is downloaded from the application processor after each system start. The firmware works in the background and fulfills two tasks :

- Using interrupt control, it calculates the servo loop 1000 times per second in order to direct the tracker's head to the target. Besides the x,y photosensor values needed in the loop, the interferometer and encoder readings are recorded almost simultaneously.

- It executes commands sent from the application processor. E.g. in case of data acquisition the 5 raw values

  # horizontal encoder count
  # vertical encoder count
  # interferometer count
  # x, y photosensor voltage

  are transformed into a single distance [m] and 2 angles [radian]. An offset distance is added to the interferometer count and the photosensor offset is used to reduce the angles to the reflector's center. Further corrections are applied for instrumental errors and atmospheric conditions before transmitting the 3 values to the application processor. The maximum data rate which can be achieved with the 386/87 SX board is half of the servo loop frequency i.e. 500 points per second. If necessary the rate can be doubled with a 386/87 board.

2.4. The Application Processor (AP) and Software

As the hardware configuration shows, the systems firmware and software run on separate processors. The advantages of this procedure are

- more computer power is available for time consuming calculations and high rate of data acquisition
- the AP is less dependent on system needs
- the interface between firmware and application software is better defined and both are therefore easier to maintain

The AP is a 386/87 IBM compatible computer and serves to operate the tracking system. It is equipped with a LAN card and must have sufficient speed to handle a data stream of up to 500 (or 1000) points per second.

The system software is written in C and runs under MS-DOS. Commands can either be selected from menus using a mouse, or from a command line using the keyboard. If a command requires parameters, a pop up window requests the user for an input.

The display offers graphic representation of the results, e.g. out of tolerance effects.

Major software includes:

- Static point measurement; a mean value of several single measurements can be stored.
- Dynamic measurement; a data stream is stored to disk.
- Choice of units and coordinate systems
- Coordinate transformations e.g best fit to an object coordinate system.
- Set reference points which enables measurements to be easily continued after an interruption of the beam.
- Support of calibration measurements e.g. the initial distance calibration
- Output to printer or log file
- Editor, which permits viewing and modifying of data and parameters
- Use of macros to create command sequences
- Shape fit / analysis / intersection

Special packages will be available for treatment of curves and surfaces, as well as for robot calibration.

2.5. Accessories

2.5.1. Reflectors

Because an interferometer is used, a suitable reflector is necessary as target. Two kinds of targets are recommended :

- An air-path corner cube consisting of three orthogonal mirrors. Compared with a glass prism, distance does not depend on the incident angle of the beam.

- A cat's eye reflector made from two glass hemispheres. The radii of the hemispheres are different and depend on design and type of glass. The bigger hemisphere is silver-coated. As with the corner cube the reflected beam is parallel to the incoming one.

The advantage of the cat's eye is its large useable angle of +- 60° (corner cube: +- 20°). The disadvantages are larger size and weight. Two sizes of cat's eyes are available. The smaller one is recommended for use at short distances up to 10m whereas the bigger one works up to the specified maximum distance of 25m.

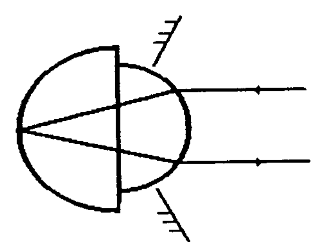

Fig. 4: Cat's Eye

A cat's eye containing 5 optical elements to correct for spherical aberration is under test.

The targets are housed in metal hemispheres. In conjunction with a 3-point magnetic support, reliable centering is guaranteed. The spherical housing is also suitable for measuring surfaces because of the constant offset between surface and center of reflector.

Further types of housings and tools for measuring discrete points are envisaged, but their development depends on market requirements.

2.5.2. Scale Bar, Ball Bar

To determine the initially unknown offset distance, a scale bar with a centering at each end is provided. A ball bearing can be adapted to upgrade the scale bar to a ball bar. This ball bar, which can be rotated, serves as a means for checking the system's performance and accuracy by generating an ideal circle for comparison with the measured data.

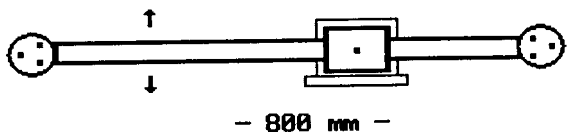

Fig. 5: Ball Bar

2.5.3. Hand Terminal

A hand terminal plugged into the AP permits remote controlled start and stop of data acquisition. One person operating the reflector can therefore execute the measurement.

2.5.4. Cart

A cart is available which accommodates all components of the system except for the sensor itself. Its main features are:

- moves on 4 wheels
- breaks down into two parts for easier transportation by car
- lockable
- components fixed in position so that no special setup is necessary except for cable and power connections.

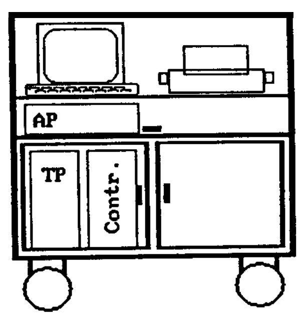

Fig. 6: Cart

2.5.5. Thermometer, Barometer

To correct the measured distances for atmospheric conditions, tools are necessary to determine temperature and pressure of air. For example an accuracy of l°C or 3 Torr corresponds to 1ppm in distance error. Humidity can normally. be neglected. These figures are based on a formula given by Hewlett Packard, which is obviously derived from the 'simplified Owens' formula.

The thermometer, incorporated in a special sensor, permits also measurements of the scale bar's temperature. The coefficient of expansion must be taken into account, since the scale bar is made aluminum.

3. The Principle of Measurement

3.1. The Servo Loop

A significant difference between SMART and a theodolite measuring system is that a SMART system can automatically track a prism. This is possible due to the Servo Control Loop which calculates correcting signals for the motors using x, y offset values from the photosensor. To make things more obvious, consider the path taken by the beam.

The beam, transmitted by the laser tube, passes through the interferometer optics, is reflected at the mirror on the transit axis and arrives at the prism. After reflection the beam returns to the interferometer again and merges with the reference beam.

As it can be seen from Fig. 7, the interferometer works in single beam mode. A beam splitter transmits 50% of the light to the interferometer receiver to count changes in distance. The remaining light is directed to the photosensor. On this path the component of the reference beam is blocked by a polarization filter. Assume the reflected beam is focussed on the electrical zero of the photosensor when returned from the center of the target prism. Moving the prism causes the reflected beam to move away from this zero position. The x, y offset is measured and a correction signal for the motors is generated, which turns the tracker head such that the beam strikes the prism in the center again and the offset returns to zero. In this way the beam follows the reflector, within certain limits.

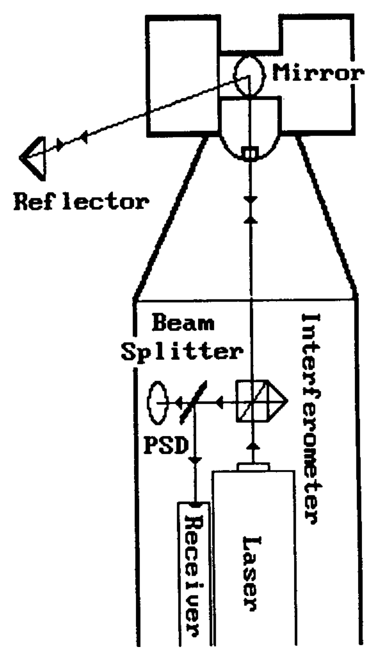

Fig. 7: Beam Path

The correction itself is processed with normal servo control methods. A PID loop is employed which contains a proportional, integral and differential part of the offset for generating a correction to each axis.

Because the photosensor and its coordinate system is fixed, the offset direction depends on where the tracker is pointing. The loop therefore contains a linear transformation which takes this factor into account.

3.2. Coordinate Measurements

The sensor delivers two angles and a distance difference measured to a reflector at the object of interest. Polar coordinates in the tracker coordinate system are therefore available which are transformed into x, y, z coordinates and stored on the AP hard disc. Coordinates related to the object coordinate system can be calculated if known points in this system are observed. Compared with current theodolite measuring systems only one sensor head is necessary for coordinate determination.

In use, the sensor should be located close to the object and on a stable floor. The liquid bubble serves to control this. If the cat's eye cannot be directly pointed at the sensor while the measurement is executed, the measuring cone of 60° must not be exceeded. This range should be sufficient for most tasks. If the prism can be directed at the tracker, a measurement range of +-45° vertically and +-240° horizontally is possible. Obstructions between sensor and object will cause loss of interferometry and must be avoided.

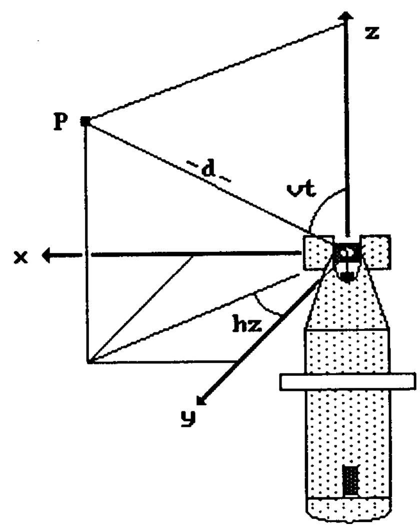

Fig. 8: Polar Method

After switching on the system, a warm up time of about 60 to 90 minutes is recommended for the electronics, especially the laser.

The first step prior to measurements is to set the absolute distance. To do this, simply position the reflector in the trackers home point, whose offset distance is an instrument parameter, and lock the interferometer.

As an independent distance check, the scale bar can be used. To reduce the error effects due mainly to the angles, set up the scale bar close to the tracker. Set a rough distance and lock the interferometer. Then observe the first end-point, move the reflector to the second end-point and observe again. The absolute distance is found by solving the measured triangle with the known elements.

- scale bar length 'b' where coefficient of expansion of aluminum must be taken into account
- distance difference 'dr' between points supplied by the interferometer
- angle 'beta' at the sensor derived from two measured horizontal and two vertical angles

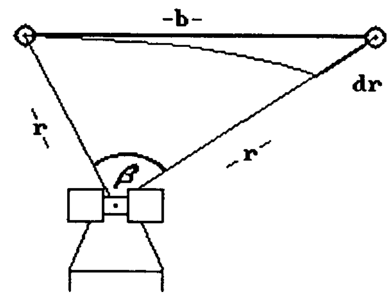

Fig. 9: Initial Distance Calibration

Now the reflector is brought to the object and the beam tracks it. Position the prism by hand at the points of interest or attach it to a moving object such as a robot.

In the case of static measurements the reflector is fixed at the target position and the mean value of single observations, within a selectable time frame, is stored. This reduces for example the effect of atmospheric fluctuations.

When a dynamic measurement is recorded the data rate must be selected and start / stop commands must be given.

If the beam is blocked, interferometry is lost. It is therefore an advantage, especially for distant objects, to set a reference point (with a known distance) near the object. Measurements can be continued by restarting again from this point.

3.3. Calibration

The scale bar method, as an independent way of calibrating the distance to the tracker home point, has been mentioned above.

Because the sensor permits measurement in two faces, the user can check for those geometric errors of the instrument which are sensitive to this procedure. Although similar to a theodolite test, it is not quite the same. For example, the normal to the mirror, rather than the telescope's line of sight, is important to collimation error (mirror tilt) and transit axis tilt.

When aiming to a target on the instrument's horizon, the mirror- and transit axis tilt are correlated. However they have different effects and the errors can be computed if targets at different heights are observed in both faces. Once found or updated, the corrections are applied to the measured data.

If appropriate, a second observation in face 2 can be executed to improve the result.

Another way to test the sensors performance is offered by the ball bar method. By rotating the bar with the reflector attached to one end, data is recorded dynamically. A circle is fitted to the data and the size of the residuals gives a measure of the tracker's accuracy.

Further investigations aim to determine instrumental errors automatically from ball bar data, including those which are insensitive to two face measurement. The problem here is the correlation between the various instrumental errors.

Currently instrumental error sources can be applied on a trial and error basis to the ball bar data, in order to reduce the residuals. If measured data are corrected for the errors found in this way, the result is normally improved by a factor of about two.

3.4. Future Developments

3.4.1. Active Reflector

SMART is able to measure the 3 dimensional coordinates of the target, but some industrial applications also require knowledge of the three rotations, pitch, roll and yaw, of the target.

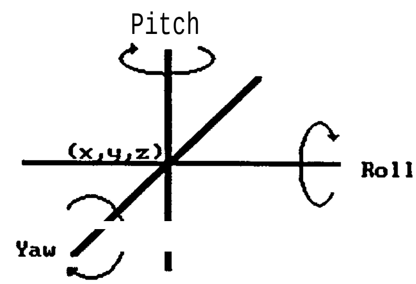

Fig. 10: 6 Degrees of Freedom

An active plane reflector, which will be fixed at the target, must be designed to achieve this. This looks similar to the tracking head of the sensor. The targets axes are controlled by photosensor such that the incident beam is reflected on itself. This enables the measurement of yaw and pitch. An additional tilt sensor could deliver the roll angle.

3.4.2. Multi Tracker Systems

Based on the components of the sensor, it is possible to create new configurations.

One idea is to use only the precise interferometer distances for coordinate determination. This trilateration method requires 3 sensors to be connected to the AP.

Another alternative depends on the fact that the angle tracking speed is 2-3 times better than that of the interferometer. Thus a system containing 2 trackers which deliver only angles is feasible. In this case, simpler targets made from adhesive reflective sheet may be sufficient.

As with theodolite systems, multi-tracker configurations must be oriented, for example by using a bundle adjustment procedure. Geometry must also be optimized.

A technical problem still to be solved is the synchronization between the different trackers to ensure a simultaneous data recording.

A disadvantage of a multi-tracker set-up is the increased chance of beam interruption. Practical use will determine if multi tracker systems are competitive with standard systems which are easier to use.

4. Measurement Results

The following results have been obtained with a SMART prototype and pre-production series system. The first section shows the repeatability of the system at different distances. Five observations have been taken, each a mean value of 10 single measurements. The reflector was moved by hand before every observation and put back into a v-notch.

Distance: 3.5 m

Ser.	x [mm]	y [mm]	z [mm]
1	1892.224	2935.255	-246.037
2	1892.201	2935.241	-246.008
3	1892.191	2935.239	-246.017
4	1892.196	2935.244	-246.012
5	1892.201	2935.243	-246.015
dmax	0.033	0.016	0.029

Distance: 12.5 m

Ser.	x [mm]	y [mm]	z [mm]
1	6870.456	10480.918	-239.345
2	6870.463	10480.915	-239.317
3	6870.452	10480.915	-239.333
4	6870.439	10480.925	-239.314
5	6870.458	10480.928	-239.309
dmax	0.024	0.013	0.036

Distance: 20 m

Ser.	x [mm]	y [mm]	z [mm]
1	11086.636	16872.402	-246.678
2	11086.643	16872.394	-246.667
3	11086.581	16872.437	-246.647
4	11086.598	16872.447	-246.669
5	11086.616	16872.420	-246.660
dmax	0.062	0.053	0.031

The maximum differences between coordinates of the same point (dmax) are of the order of several hundredths of a millimeter. The largest coordinate value, which mostly represents the distance measurement, is normally more accurate. The error caused by the encoder repeatability increases with distance and is about 0.05mm per 10m.

As a second example a comparison between SMART and a coordinate measuring machine (CMM) is shown. The reflector was attached to the CMM probe mount. The probe mount was moved to 28 discrete positions. These positions were measured statically by SMART which was positioned about 2 m away from the CMM.

The coordinates recorded were compared with the CMM coordinates using a 7 parameter transformation. The residuals can be seen on the following diagram :

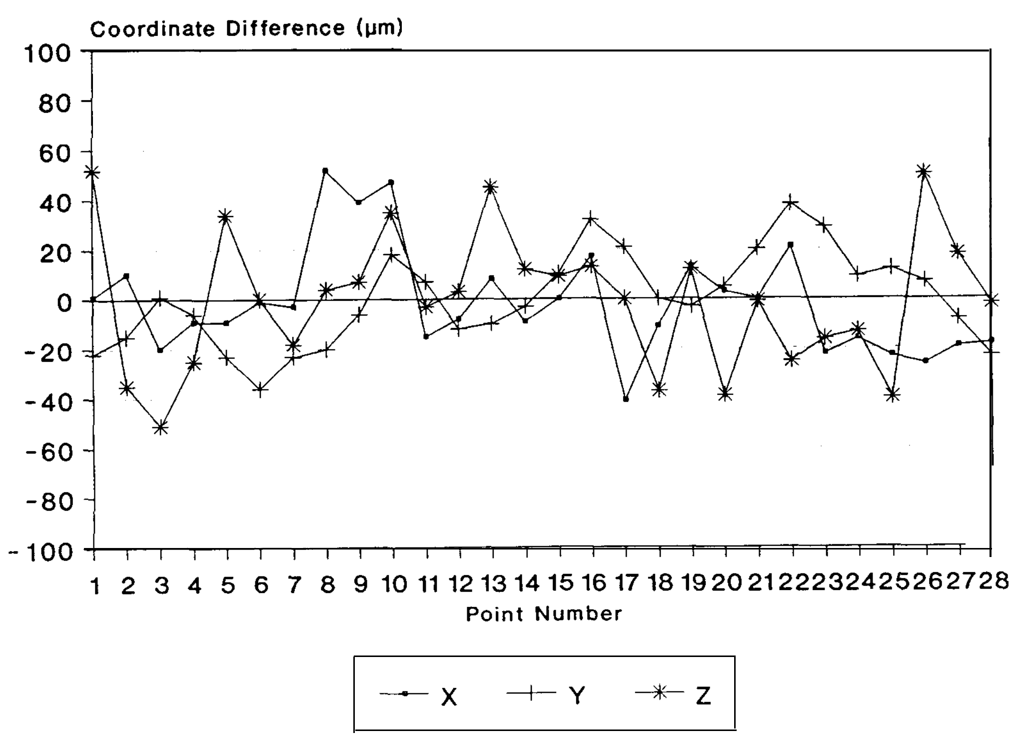

Fig. 11: SMART310 / CMM - Absolute Coordinate Comparison

The transformation parameters were:

Translation X0/Y0/Z0 : -241.493 / -2482.796 / 13.960 [mm]
Space angle of rotation : 2.29668 [Deg]
Scale : 0.9999227

RMS : 0.024 [mm]

The unfavorable environmental conditions result in a large scale factor of -77ppm. The reasons for this difference between CMM and SMART are :

- no stabilization of the temperature in the machine's hall
- small movements (tilt) of the CMM when the probe mount changed its position. This has no effect on objects measured on the CMM itself but affects the coordinates obtained with SMART.
- The scale bar could only be set up at 3.5 m distance, further away than optimal. The error propagation of the angle measurement therefore has a greater influence.

The next diagram shows the residuals of a comparison of two SMART coordinate sets. Both measurements have been carried out after each other to the same positions (within some microns) of the CMM.

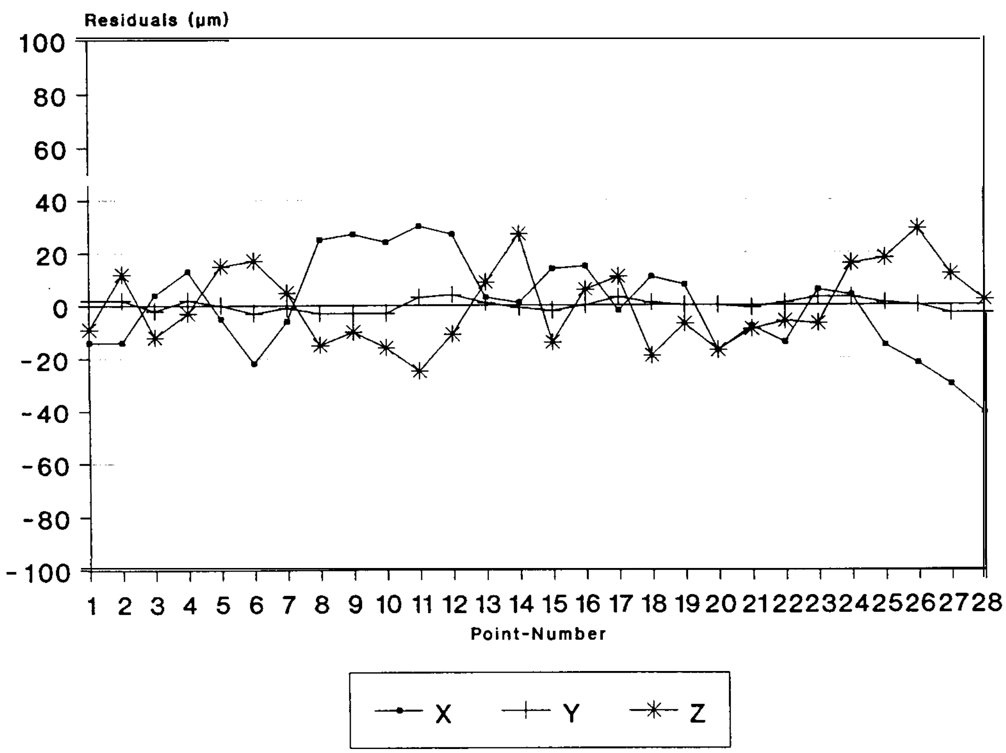

Fig. 12: SMART310 / CMM - Double Coordinate Measurements

The transformation parameters were:

Translation X0/Y0/Z0 : 0.006 / -0.001 / 0.016 [mm]
Space angle of rotation : 0.00087 [Deg]
Scale : 1.0000039

RMS : 0.014 [mm]

The residuals in the y-direction are conspicuously smaller than in the others. Because the tracking beam lay approximately along the y-direction of the tracker coordinate system, the y-coordinates mostly represent the distances measured by the interferometer.

Finally the results of static measurements to a fixed reflector are shown. One observation was executed every minute over a total time period of 2 hours.

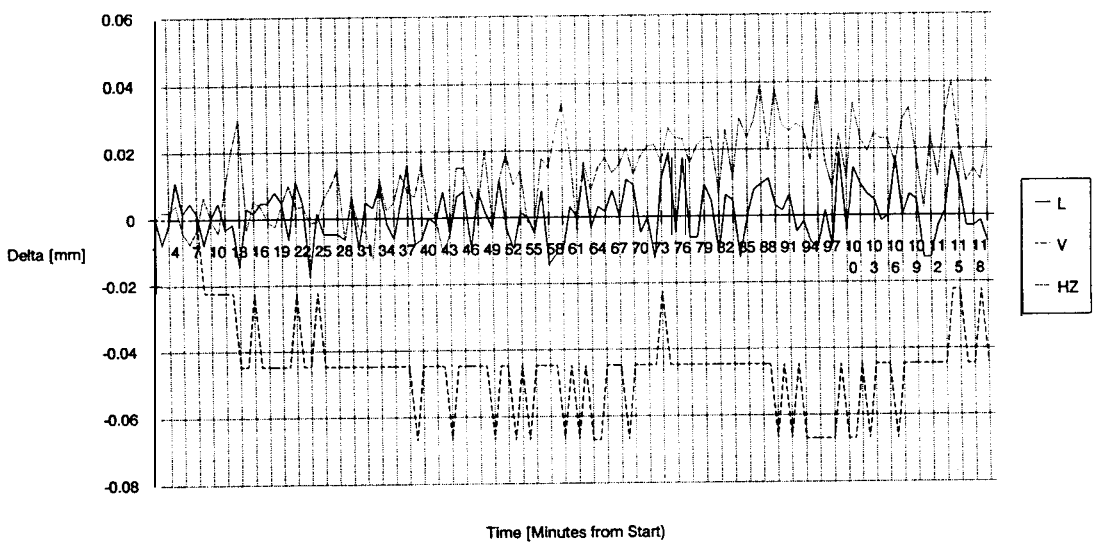

Fig.13: Continues Fix-Point Measurements (7.5 m Distance)

5. Applications

It is very difficult to give a comprehensive summary of all applications which are possible with a laser tracking interferometer. The paper will therefore give an impression of the system performance and flexibility, describing three application groups in more detail.

5.1. Robot Metrology

SMART310 can be used for dynamic or static robot control and calibration. After the laser beam is locked onto the reflector mounted on the robot, on-line 3D position control of the end effector is possible. The field of measurement is limited to +- 20° when using a corner-cube reflector or +- 60° when using the cats-eye reflector.

To obtain much more flexibility and to increase the field of operation, API has developed an optional dual-axis motorized target (see 3.4.1), which exists as a prototype but which is not available on the market for the time being.

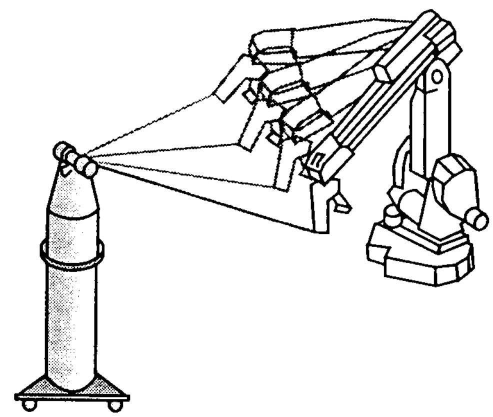

Fig.14: Robot Metrology

With this technology it is possible to control the positioning accuracy, the tracking accuracy, speed and acceleration. A special application software package for robot metrology is under evaluation and development.

5.2. Machine Metrology & Control

Another large field of application is machine and machine tool metrology. Since it is difficult to summarize all applications in this field, only a few typical examples will be given:

- CNC-Milling machines.
  Laser Tracking Interferometers can be used to calibrate CNC-milling machines. This application is very similar to robot calibration

- Milling of virtual objects.
  In the engineering industry huge parts often have to be manufactured on milling machines. Sometimes several test runs of a CNC-program are necessary so that the manufactured part meets the specifications. Depending on size and the material used for the part, it is sometimes very expensive to create a proper prototype. The laser tracking interferometer can be used to simulate the CNC-test run and to mill a virtual part. The coordinates determined during this 'virtual milling procedure' can be compared with the CAD-design data and program errors can be located without wasting a lot of time and expensive material.

- Very large CMM.
  In the engineering industry large CMM are used for the control of parts such as aircraft wing spars. These CMM might have typical dimensions of more than 60ftx20ftx20ft. In this application, the laser tracking interferometer can be used as a 'CMM-encoder'. The reflector is mounted near the probe. The tracker itself is used as coordinate measuring system to determine the exact 3D position of the probe. This enables the CMM to be operated of those machine independently of mechanical deformation and thermal influences.

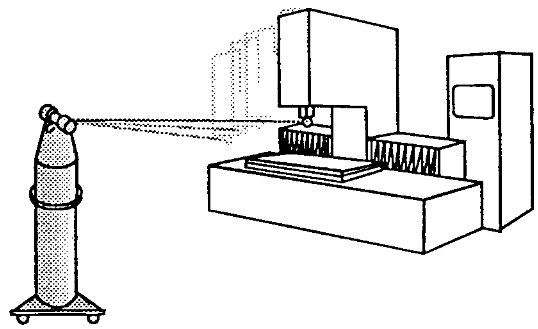

Fig. 15

5.3. Building & Inspection of Fixtures & Tools

This is another large field of applications. Here the trackerfunctions 'surface-scanning' and 'single-point measurement' are mainly used for

- Digitizing (Scanning) of master-tools
- Control of fixtures and gauges
- CAD-system control
- Digitizing of design models
  ...

Most of these applications can also be carried out by other coordinate measuring systems such as 'Theodolite Measuring Systems', CMM or photogrammetry. However, a major advantage is the high speed sampling rate of the laser tracking interferometer, which enables the user to solve his measuring problem much faster and more economically. The only limitation is that objects which might be deformed by probing or touching (e.g. clay models, satellite antennas) cannot be measured using this system.

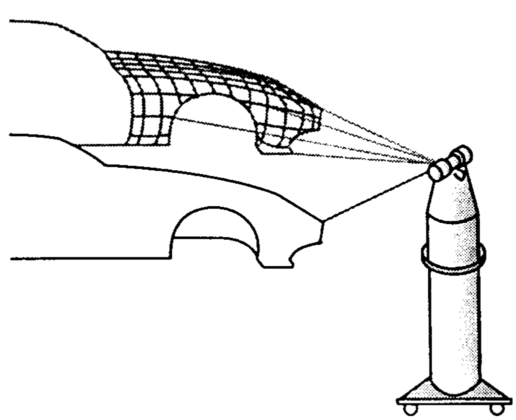

Fig. 16

6. Conclusion

Laser tracking interferometry is an excellent technique to deal with dynamic measurement problems, and applications which require high frequency coordinate determination. SMART310 is Leica's offer to solve these measurement problems in cooperation with the customer.

In addition, this technology and new measuring system is an ideal complement to the family of non-contact triangulation systems (e.g. manual and automated theodolite measuring system). It enlarges the field of applications by including the determination of highly dynamic processes, high density surface scanning and many more. Laser tracker systems will also be able to do many of the measuring tasks performed today by large CMM or by photogrammetric systems.

To develop the full potential of this system, a detailed analysis of the measurement problem and a close cooperation between the manufacturer and the customer is desirable, which will allow an optimal technical and economical solution to the problem.

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