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A THREE-DIMENSIONAL POSITION MEASURING SYSTEM

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Abstract. When checking robot performance, a measuring system with the ability to measure both the static and dynamic behaviour of a robot arm is essential. The system can also be used to check on robot performance and on validity of already developed models. This device should be able to measure the position of a fixed point on the robot arm, the so-called Tool Center Point, in three dimensions with an accuracy of 10μm, together with a large scale bandwidth of 30Hz. The device uses three identical laser-optical distance measuring systems, each of which measures the displacement of the Tool Center Point with respect to a reference point belonging to that system.

Each distance measuring system consists of a frequency stabilized laser, a tracking system and a laser interferometer. A useful laser stabilization based on thermal expansion has been developed, as well as an interferometer detection unit and a bidirectional interferometer counter.

Keywords: Actuators; counting circuits; data handling; laser interferometer; position control; stabilization; target tracking.

INTRODUCTION

In today's industries, and on the factory floor, there is a fast growing interest in and use of the programmable multi-functional manipulator or industrial robot. The industrial robot can be used excellently as a fast and precise positioning or handling machine. However, in spite of its many qualities concerning speed and precision, the robot also has its limitations. Due to the robot dynamics, the positioning accuracy is inversely proportional to the speed. One way of reducing the effect of the robot dynamics is to alter the ratio between the mass and stiffness, e.g. by using new materials.

Another possibility is to diminish the negative effects of the dynamics without changing the dynamics themselves. Now the accuracy and repeatability of the manipulator can be improved by adding some intelligence to the programmed robot, i.e. by changing its program in such a way that an unwanted movement is compensated for. For this, it is essential that the dynamics of the robot arm are known a priori.

Recently, much attention has been paid to the analysis of dynamic structures of manipulators (e.g. Asada, 1983; Book, 1982). On the development of dynamic robot models a measuring system with the ability to measure the position of a fixed point of the robot arm as a function of time could be most useful. Such a measuring system could also be used when checking robot performance and validating already developed models. The development of such a system is the subject of this study.

Basically, we are only interested in the position of one point on the robot arm, namely the one at the end of the arm, the Tool Center Point. Various measurements have shown (e.g. Beljaars, 1984) that the most dominant eigen-frequencies are below 30Hz. These frequencies have a maximal amplitude of several mm's. Furthermore, it has been shown that most robot arms have a maximum accuracy of about 0.1mm together with a maximum speed of 3 m/s.

From these data the following specifications can be extracted:
- a position measuring accuracy of at least 10μm with respect to all three dimensions;
- a dynamic range of 0 - 5 m/s;
- a bandwidth of 0 - 100Hz for vibrations of very small amplitude (a fraction of a millimeter) and 30 Hz for amplitudes of up to several millimeters.

At the moment there is no commercial three-dimensional position measuring machine that satisfies these specifications. Therefore we decided to develop a (low-budget) measuring system ourselves.

PRINCIPLE

The objectives and specifications show that indirect measurements, e.g. by determining angular positions of the motor axis, is inadequate. By using laser-optical techniques it is possible to increase the measurement accuracy. Becker (1984) describes a system which uses two laserbeams which are constantly projected at the Tool Center Point (TCP). The position of the TCP is determined by angular measurement of the laserbeams and triangulation. The achieved accuracy is about 0.1mm and is bound to the inaccurate angular measurements.

Pfeifer and Hof (1985a, 1985b) built a laboratory prototype which uses four laser interferometers. This prototype produced some very satisfying results. Due to these results, we decided to use the principle of length measurement by laser interferometers.

The principle is depicted in Fig. 1. Three laser interferometers, situated at the reference points \( z_1 \), \( z_2 \) and \( z_3 \), measure the distance to the TCP (g).
The lengths $L_1$, $L_2$, and $L_3$ can be converted into the coordinates of $y$. The describing equations have two solutions, $y$ and $y_r$, the latter being the image of $y$ and may easily be omitted by proper choice of the three laser interferometers. In fact, a laser-interferometer measures displacement instead of length. It can be shown that if the coordinates of a starting point $p$ are known beforehand, the equations for determining $y$ have exactly the same form as when using length measurement. By using a semi-automatic calibration cycle the efforts needed for setting up the system is kept to a minimum.

The positions of the reference points $x^i$ ($i=1,2,3$) can be calculated in a calibration cycle: one $x^i$ takes the place of $y$ and three known different TCP positions $x^1$, $x^2$, and $x^3$ replace $x^1$, $x^2$, and $x^3$. In order to register the robot movements, all three length, c.q. distance measurements have to be done periodically. With a sample frequency of 100 Hz the most important eigen-frequencies (up to 30 Hz) can be determined.

**THE CONSTRUCTION OF THE SYSTEM FOR ONE REFERENCE POINT**

Although the complete system consists of three identical length measuring systems, we will focus our attention on only one measuring system belonging to one reference point.

Each length measurement system consists of a frequency stabilized laser, a tracking system and an interferometer as depicted in Fig. 2. A stabilized laser frequency is necessary in order to avoid mode jumping and for the improvement of the accuracy of the system. The tracking system will focus the laser beam at the TCP independently of its movements. The interferometer counts the displacement of the TCP with respect to the reference point in terms of half-wavelengths of the laser light.

It will appear that a very important part of the system is embodied in the retroreflector. This is an optical instrument with the following qualities:

- the incoming and reflected beams are always parallel, regardless of the incoming angle;
- the distance between both beams will change if the centre of the retroreflector is moved perpendicular to the direction of the fixed incoming beam.

The interferometer will count the displacement in terms of half-wavelengths of the laser light.

Figure 3 shows two implementations of the retroreflector. The corner cube or tripod is made up of three perpendicularly placed mirrors. The so-called cats-eye consists of two half spheres with the same refraction index but different radius.

**LASER STABILIZATION**

A laser constitutes the centre of the measurement system. In an interferometer an unstabilized laser cannot be used because, in general, the spectrum of the laser shows more than one spectral line; the laser modes. These modes are subjected to frequency drift, which may discharge into mode-jumps, i.e. complete vanishing of a mode and re-appearing at another frequency. Mode-jumps should be avoided at any cost because they influence all modes by changing the direction of their polarization.

To prevent these negative effects, the laser should be stabilized. A stabilized laser is very well-suited to interferential length measurement due to its high light intensity, its small divergence and its great coherence length (the latter being inversely proportional to the small spectrum).
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In our experiments we used a 22 cm long He-Ne plasma tube of 0.5 mW power. The wavelength \( \lambda_0 \) of the He-Ne light is approximately 6328 Å. The amplitude of the spectral lines follow a so-called Doppler-profile (Maitland, 1969) which is a Gaussian distribution around \( f^\prime \%
y \begin{equation}
f_0 - \Delta f = c \cdot n \cdot t \] (c is the speed of light and \( n \) the refraction index). The modes can only exist if they exceed a certain threshold \( t \), see Fig. 4, otherwise a mode-jump will occur. It can be shown that, due to the chosen tube length of 22 cm, the successive modes are separated by 685 MHz, so the Doppler-profile of about 1.2 GHz will screen two of the modes.

One phenomenon which has not yet been fully understood is that the successive modes have a linear perpendicular polarization, so they can be separated by polarizing filters. Our laser stabilization unit must keep the two spectral lines under the Doppler-profile until they have the same amplitude. To accomplish this, it is necessary to measure the difference of both intensities. The spectral frequencies of the laser are related to the tube length. A length deviation \( \Delta L \) results in a frequency deviation \( \Delta f \) as follows: \( \Delta f = -\Delta f / L \). This means, for example, that 0.05 \( \mu \)m tube expansion results in 100 MHz frequency reducing. We have chosen thermal expansion as a very simple yet effective way of adjusting the tube length. It is implemented by a heating spiral made of resistance wire around the plasma tube. The control current of the spiral is provided by the difference of the intensities of both laser modes as stated above (Fig. 5).

To improve the performance of the stabilization a PI (proportional and integrating) controller is added. Long term stability tests have shown a stationary overall drift of 100 MHz which is, in fact, quite tolerable. Beat measurements also showed a repeatability within 100 MHz. The remaining frequency drift may well be caused by drift in the photodiodes or the op-amps in the PI-controller.

**THE TRACKING SYSTEM**

For on-line distance measurements of a moving Tool Center Point the laser beam should be focused on the TCP constantly. The most effective way of achieving this is by fixing the laser tube and deflecting the laserbeam by means of a rotating mirror. Since the TCP can move in three dimensions, the mirror must have (at least) two degrees of freedom. The principle of the tracking system is illustrated in Fig. 6. In summary, we distinguish a retroreflector attached to the TCP, a rotating mirror with its actuators, a displacement sensor, and a controller. The tracking system operates as follows. The distance between the incoming and reflected beams at the TCP will change if the TCP is moved perpendicular to the direction of these beams. This movement of the reflected beam will be spotted by the sensor and, in turn, the sensor will provide control signals which activate the actuators into rotating the mirror until the reflected beam has reached its original position with respect to the incoming beam. The controller can be used to optimize the process.

Very high demands are made on the surface of the mirror with respect to power loss, divergence, etc., and on its suspension. In order to minimize any hysteresis and (non-linear) friction, we have opted for cardan suspension with a flexural pivot of laminated springs. Four linear electromagnetic dynamic transducers, two per degree of freedom, are used as actuators for rotating the mirror. The mirror and actuators are mounted in a heavy rigid block of aluminium. When writing this article no data about the transient response of this deflecting unit was available.
Basically, two types of displacement sensor can be used, namely, a CCD-camera and a lateral photodiode. The latter is superior due to its higher speed, better resolution and because it automatically indicates the centre of the beam spot on the sensor.

THE INTERFEROMETER

The interferometer is the part of the system that actually measures the displacement of the TCP with regard to the reference point. In Fig. 7 retroreflector A is attached to the (moving) TCP, and B is a fixed reference retroreflector. The interferometer is able to detect every half wavelength (of the He-Ne light) displacement of retroreflector A. For this, a harmonic interference signal with a frequency \( f_{TCP} \) proportional to the velocity of the TCP,

\[
f_{TCP} = \frac{2V_{TCP}}{\lambda_0}
\]

has to be detected. We are only interested in the absolute value of \( V_{TCP} \) but also in its sign. A second interference signal, which is always present, may supply information about the sign. In using a specially coated separation prism, a phase difference of plus or minus \( \frac{1}{2} \) rad. depending on the sign of \( V_{TCP} \) will appear between the two interference signals. This effect is illustrated in Fig. 8 (with \( \theta = 1/4 \pi \) rad.).

So the sign of \( V_{TCP} \) can be extracted from the sign of the phase difference between both interference signals.

To avoid mutual interference of the two laser modes, one mode has to be removed by means of a polarizing filter. A high-speed photodiode is indispensable for the detection of the interference signals. The maximum frequency to be detected is 16 MHz corresponding with the maximum permitted TCP velocity of 5 m/s.

The obtained photo current is very difficult to tackle due to its enormous dynamic range of 0-10 MHz, its small amplitude due to optical losses, and a relatively high and unstable DC component. In fact, the interference signal is an amplitude modulated signal with a very small modulation index.

We have developed an interference detecting unit that converts the photo current into a useful block signal of the same frequency and a constant amplitude. This detecting unit comprises, amongst other things, a low-cut filter with a cut-off frequency of approximately 0.3 MHz and a comparator. The comparator is made up of several cascaded ECL line receivers. ECL, emitter coupled logic, is a logic family that can be used up to very high frequency (100 MHz) switching network applications. We used the line receivers as boosters and a Schmitt trigger. A laboratory prototype of the detecting unit has given some very encouraging results.

For the detection of the pulses of the final interference signal, each representing a TCP displacement, a counter is necessary. An up-down counter is necessary in order to represent the direction of TCP movements, the counting direction is matched to the sign of the phase difference of the two interference signals. Further more, for dynamic operation, the counter contents must be sampled with a sample time of 0.01 sec., as discussed before. A seven-decade 17 MHz sampled bi-directional counter with microprocessor control has been developed.

The microprocessor takes care of the sampling, storage of data, and the error handling. It may be emphasised that for the complete system, one microprocessor can control all three interferometers.

MEASUREMENT ERRORS

At various stages of the system, measurement errors are introduced. As stated in the introduction, the total amount of errors may not exceed a position measurement inaccuracy of 10\( \mu \)m. When defining a measurement work space of one cubic meter, the maximum permitted relative inaccuracy is \( 10^{-5} \). In this case the relative inaccuracy is defined as the absolute error in the position of the TCP related to the work space size.

In the following we will discuss some measurement errors.

The only measurement error introduced by the laser is related to its frequency drift. The overall drift of the stabilized laser is plus or minus 50 MHz, the laser frequency being \( 5.10^{11} \) Hz, implying a relative error of \( 10^{-6} \).

The interferometer causes several errors to occur. The refraction index of the air, for instance, directly related to the laser wave length, is not a constant but it depends on, e.g. air pressure, vapour pressure, temperature and CO\(_2\) percentage of the air. Under normal circumstances this gives rise to a relative error of less than \( 10^{-6} \).

The low-cut filter of the interference detecting unit introduces an error. Very low \( V_{TCP} \) causes a very low interference frequency which can
be filtered out. Every second that a low frequency signal cannot pass the filter an error will occur. When using a filter with a cut-off frequency of 0.3 Hz this error is less than 0.3 x 10^-5 = 0.1 µm per second. The period of time that this type of error occurs is probably a very small fraction of the total amount of measuring time.

Another error may be caused by the data handling. When converting the data into useful TCP coordinates, numerical errors are made. However, these errors can be made sufficiently small by increasing the accuracy of the processor.

Roughly speaking, the tracking system causes three types of errors. First we have the errors caused by imperfections of the physical retroreflector, i.e. the mass corner cube or cats-eye. For the mass corner cube an optical path length difference appears when the angle of the incoming beam changes. This change in optical path length evidently results in a measurement error. For the cats-eye, the incoming and reflecting beams are only parallel when there is a specific distance between them. If the incoming beam moves, the reflected beam will no longer be parallel and this causes a measurement error.

Reference uncertainty. As discussed before, the measurement principle is based on three reference points. If the interferometer belonging to a certain reference point cannot measure a displacement when the TCP is moved on a sphere with that reference point as centre, the reference point is unambiguous. Inversely, a reference point is unambiguous if all points with equal optical path length are situated on a sphere when rotating the mirror. If they are not on a sphere a measurement error will occur when the mirror rotates.

The positions of the reference points are determined by the 'accidental' positions of the calibration positions during the calibration cycle. The extent of this error is highly dependent on the type of suspension of the rotating mirror but is zero if the turning point of the mirror coincides with the beam point of the mirror, which we will call an ideal rotating mirror.

Aiming error. This error arises when the (ideal) retroreflector is not correctly beamed due to tracking imperfections (e.g. slowness). If the incoming beam is not correctly focused on the TCP retroreflector, the distance between the incoming and reflected beams will change, as will the optical path length. The displacement sensor is able to detect this error. When using an ideal rotating error, we found that the aiming error can be calculated with the help of the error detected by the displacement sensor. In this special case, the aiming error can be completely compensated for.

CONCLUSIONS

A three-dimensional position measuring system has been presented. The measuring system can be implemented by three accurate length or displacement measurements done by laser interferometers.

As the total measurement system basically consists of three identical subsystems we focussed our attention primarily on one subsystem, made up of a laser plus stabilization, a tracking system, and a laser interferometer.

We developed a laser stabilization based upon thermal expansion which performs satisfactorily. In order to determine the direction of the displacement or velocity to be detected, an interferometer principle with two interference signals has proved most useful. For this purpose, a properly working high speed (17 MHz) interference detector has been designed and built, as well as a sampled interferometer counter.

At the moment the tracking system, in particular the rotating mirror, is the bottle neck of the system, due to the fact that it makes high demands on its mechanical construction and because improper design may cause considerable measurement errors. The measurement errors which are not introduced by the tracking system are sufficiently small with respect to the postulated specifications. Future research will concentrate primarily on investigation of the transient response of our rotating mirror and on developing a matched controller in order to optimize the tracking performance.

REFERENCES


