A strategy for accurate guidance of a manipulator using laser interferometry-based sensing technique

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Introduction

The increase in the number of complex applications of robots in manufacturing and service industries has emphasised the need for higher levels of positioning accuracy from robot manipulators. It is well-known that the repeatability of today’s industrial robot is at least an order of magnitude better than its absolute accuracy (Vincze et al., 1994). This is due to the fact that the position and orientation (i.e. pose) of a robot manipulator are described using a kinematic model. This kinematic model uses the joint positions determined from the axes encoders to provide the three-dimensional co-ordinates of the manipulator. The accuracy of such a model relies heavily on the accuracy of the parameters used (e.g. link lengths). The accuracy is also affected by the geometric (e.g. bending) and non-geometric (e.g. temperature) errors. Further, joint backlash can also play an important role in such errors. Therefore, accurate robot pose measurement and calibration techniques are required to improve the robot accuracy.

Recently, a single beam laser interferometry-based sensing (LIS) technique, capable of performing dynamic measurements of robot end effector’s pose, has been proposed and established for such purposes (Parker and Gilby, 1982/3; Gander et al., 1993). This technique provides high accuracy, a large working space, a high sampling rate, and automatic target sensing capability in real time (Spiess et al., 1996). In this paper, a technique using the LIS as the pose sensor to accurately guide the manipulator’s end-effector to a specified point or along a specified path is proposed. This approach is expected to provide accurate laser-based remote control of fixed based robots, mobile robots, and long reach manipulators. The physical make-up, measurement and analysis techniques, together with the control algorithm for the above technique will be described. Preliminary results of such an approach will also be presented.

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Laser interferometry-based sensing principle

Laser interferometry-based sensing (LIS) generally involves the dynamic acquisition of the 3D pose of an end-effector in its workspace. The LIS system uses the angular and distance data, obtained from the beam steering mechanism and the interferometer, respectively, to provide the pose of the target retroreflector attached to the end-effector of the manipulator. It maintains tracking of the target by sensing the offset of the incident and reflected beam. It subsequently performs offset corrections by adjusting the angles of the beam steering mechanism. A LIS system was developed for this study. A functional layout of the overall design of the LIS is provided in Figure 1.

In this layout, the laser beam generated by the HeNe laser travels to the interferometer where it is split into a reference beam and a measurement beam. The reference beam is directed to the measurement board in the laser interferometer controller via the fibre optic pickup. This beam will later be compared with the returning measurement beam, whose frequency will be Doppler-shifted, to determine the distance between the target (i.e. a retroreflector mounted on the robot end-effector) and the laser head. The measurement beam travels through a 70-30 per cent beam splitter and is directed to the target by the beam steering mechanism. Once the beam hits the target, the beam is reflected through 180° and it travels back parallel with the incident beam. There will exist an offset between the incident and the reflected measurement beam if the beam does not hit the centre of the retroreflector.

The reflected beam then travels through the mirror assembly and back to the 70-30 per cent beam splitter. Of the beam power, 30 per cent is diverted through a 50-50 per cent beam splitter, where it is split equally and directed to a charged coupled device (CCD) camera and a position sensitive diode (PSD). The CCD camera, which is connected to a high-data-acquisition-rate frame grabber board, captures the diffraction pattern of the retroreflector, so that analysis can be performed to determine the orientation of the retroreflector. The PSD detects the offset of the beam from the centre of the PSD sensor. This offset error is referred to as the tracking error. The remaining 70 per cent of the beam power will be combined with the reference beam via the interferometer and the fibre optic pickup. The Doppler shift of the reflected beam can be detected and used by

Figure 1 Set-up of the laser interferometry-based system
the processing electronics within the laser interferometer controller to determine the distance travelled and the velocity.

The LIS control system minimises the tracking error obtained from the PSD acquisition system by signalling the motor controller which in turn rotates the axes of the beam steering mechanism, thus following the arbitrary movements of the target. Measurement of the position of the target in space is obtained from the interferometer measurement, tracking errors, angular displacements of the axes of the beam steering mechanism, and the kinematics of LIS. The tracking algorithm utilises a predictive control algorithm that allows estimation of future position of the target from the previous position, velocity and acceleration values (Shirinzadeh and Teoh, 1998).

**Laser interferometry-based guidance technique**

Laser interferometry-based guidance (LIG) is the technique of positioning the end-effector of a robot manipulator accurately to a desired point in Cartesian space along a predefined trajectory by steering the laser beam. In this technique, the LIS system is used as a pose sensor to measure the dynamic pose of the end-effector. It also acts as a processing unit for path generation and guidance error compensation in the control algorithm. When the beam steering mechanism has directed the laser beam to a new desired pose, the offset will be detected by the LIS system. It subsequently performs offset corrections by adjusting the joint angles of the robot manipulator.

**Control algorithm**

A flow chart of the control algorithm is provided in Figure 2. The control software is designed to have two modes of operations: (1) a jog mode; and (2) an auto mode.

In the jog mode, the operator will manually control the rotation of the axes of the beam steering mechanism using the keyboard or an input device (e.g. joystick). The laser beam direction will be displaced by a predefined distance and thus generate the guidance error. The robot controller will be automatically commanded to move in the required direction to reduce this error (this will be described in detail later).

In the auto mode, the system will first prompt the operator to enter the desired pose for the manipulator. The control software will determine the total offset of the desired pose with respect to the current pose. An appropriate path with multiple target points, which is to be followed by the laser beam, is generated. This will be discussed further in the path generation section. The control software will command the motors to direct the beam to the required pose, increment by increment, following the target points along the path. There will be a guidance error when the laser beam has moved at each increment. This methodology can be seen in Figure 3.

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**Figure 2** Flowchart of the control software

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Guidance error determination and compensation

Two different sub-systems are used to determine the guidance error of the manipulator. This section describes these sub-systems and the method of compensation.

Position-sensitive diode (PSD) acquisition sub-system

To detect the guidance error in the plane perpendicular to the laser beam, the PSD acquisition sub-system in the LIS system (Shirinzadeh, 1998) is the focus of attention. There are two main types of PSDs, the quadrant detector and the lateral effect detector. The detector used in this study is the Melles Griot 13PSL001 Lateral Effect Detector System (Melles Griot, 1999). It has four electrodes connected equidistant around its perimeter, as shown in Figure 4. The electrodes are connected such that opposite pairs yield photo currents that are processed to give the displacement of the beam in the $x$ and $y$ directions. It can accurately measure beam position with a position resolution of...
frequencies, F1 and F2, which are polarised at right angles to one another. The laser beam consists of two separated frequency components separated by 20MHz. Each component has an opposite circular polarisation that allows each to be separated by optical polarisers. It relies on Doppler shifts caused by the movement of the target retroreflector to generate interference fringes. The structure of the sub-system is provided in Figure 5.

The laser interferometer sub-system

To determine the guidance error of the end-effector in the plane parallel to the direction of the laser beam, the laser interferometer (Shirinzadeh, 1998) is the focus of attention. The laser interferometer currently being used is the Zygo ZMI1000 high-velocity interferometer system. This laser interferometer is based on a He-Ne heterodyne (dual frequency) laser with a beam diameter of 6mm. It employs the Zeeman split to generate two frequency components separated by 20MHz. Each component has an opposite circular polarisation that allows each to be separated by optical polarisers. It relies on Doppler shifts caused by the movement of the target retroreflector to generate interference fringes. The structure of the sub-system is provided in Figure 5. The laser beam consists of two separated frequencies, F1 and F2, which are polarised at right angles to one another. As the beam passes through the interferometer, F2 is directed to the reference retroreflector while F1 passes through the polarising beam splitter to the target retroreflector. As the target retroreflector moves, the frequency F1 will be shifted based on the Doppler principle. F1 will increase or decrease by ΔF1 as the target retroreflector moves towards or away from the interferometer respectively. F1 and F2 are recombined in the laser interferometer to give the measurement signal of:

\[
F_2 - (F_1 \pm \Delta F_1)
\]

A reference signal of F2 – F1 is created by the laser head and combined with the measurement signal, leaving only ΔF1, the rate of change of position of the target retroreflector. This can then be integrated to yield the relative motion of the target retroreflector. The HeNe heterodyne laser interferometer has a resolution of 0.16μm.

Using the above sub-system, the offset of the next target point from the current one is calculated. The offset is sent to the control unit of the manipulator to calculate the required joint angle rotation using inverse kinematics to position the retroreflector at the desired point. Dynamic measurements are acquired at the same time to update the Doppler shift readings. When the robot has moved, the new offset is detected and the process is repeated until the desired point is reached.

Path generation

In order to guide the retroreflector to the desired pose in the auto mode described above, the path of the guiding laser has to be first determined. Linear or non-linear path can be used. For the purpose of this study a linear path is used. Further, it is also assumed that there are no obstacles within the working space of the robot.

When a desired pose is selected through the computer software, a linear path between the desired pose, Pd (x_d, y_d, z_d, θ_d, φ_d), and the current pose, Pc (x_c, y_c, z_c, θ_c, φ_c), is generated. A discrete number of target points, that are to be followed by the laser beam, are generated and plotted along the path. The distance between any two adjacent target points is defined to be less than the PSD’s range. This is to ensure that the laser beam will not be out of the PSD’s range to maintain dynamic measurement of the retroreflector.

The pose of each target point in polar configuration for the beam steering mechanism can be determined using inverse kinematics. A plot of the angles for both axes of the beam steering mechanism, θ_i and φ_i (where i is the target point number), for every target point can then be constructed against time. Figure 6 shows a sample plot for one of the axes.
Another important issue that must be considered is the sudden changes in direction and angular velocity. These will in time damage the motors and affect the accuracy. Therefore, a parabolic blend between changes in velocity can be implemented. The time step, $\Delta t$, between two joint angles (the desired and the current joint angles) can be determined from the desired average velocity of the manipulator and the distance between the

Figure 5 Structure of laser interferometer

Figure 6 Plot of joint angle versus time
adjacent target points. The blend time, $t_b$, can be calculated with the known values of $\theta_i$ and $\phi_i$, and the desired values of acceleration at the target point angles, $\hat{\theta}_i$ and $\hat{\phi}_i$. The equations are as follows (Craig, 1991):

$$\hat{\theta}_i, i+1 = \theta_{i+1} - \theta_i$$

(2)

$$t_b = \frac{\hat{\theta}_i, i+1 - \hat{\theta}_{i-1}, i}{\hat{\theta}_i}$$

(3)

The first and the last segments are handled differently since the blend time must be included in the time step. The first and the last blend times $tb_m$, where $m = 1$ or $m = n = \text{last target point}$, can be calculated by equating the velocities in the linear phase segment. The initial and final angular velocities can be easily calculated using the blend times. The following relationships are utilised (Craig, 1991):

$$\dot{\theta}_m = \frac{(\theta_m - \theta_{m-1})/\Delta t - \frac{1}{2} t_{bm}}{t_{bm}}$$

(4)

$$t_m = \Delta t - \sqrt{\Delta t^2 - \frac{2(\theta_m - \theta_{m-1})}{\dot{\theta}_m}}$$

(5)

$$\dot{\theta}_{m-1, m} = \frac{\theta_m - \theta_{m-1}}{\Delta t - \frac{1}{2} t_{bm}}$$

(6)

**Preliminary experiment**

Preliminary experiments have been performed to determine the capability of the apparatus for LIG. The experimental set-up consists of the mentioned LIS system and a Scorbot ER VI robot manipulator. The properties of interest are the response time of the LIS system and the response time of the communication between the LIS system and the robot manipulator. This leads to the following equation that represents the total response time for the LIG technique:

$$T_{\text{response}} = T_{\text{robot}} + T_{\text{LIS}}$$

(7)

where $T_{\text{robot}}$ is the response time of the robot to move and acknowledge the command given by the LIS system, and $T_{\text{LIS}}$ is the response time of the LIS system to perform dynamic measurements as well as controlling the axes of the beam steering mechanism.

In the current set-up, the response time of the LIS system is found to be in the order of 0.4 seconds (Shirinzadeh et al., 1998). The accuracy of pose sensing is ± 5 μm. It must be emphasised that the laser interferometer sub-system provides for distance measure-

ment with an accuracy of 0.16 μm and the PSD acquisition sub-system provides for offset error measurement in the order of 1 μm. The beam steering mechanism makes use of three 45° beam steers to direct the beam towards the target retroreflector. Both axes of the steering mechanism currently have a maximum rotational velocity around 1 rev./second. The vertical axis has a resolution of around 0.02°, using a motor step rate of 400 steps/rev. and a precision rotary table with a 45:1 gear ratio – i.e. one revolution of the vertical axis requires 18,000 steps. Further, the resolution can be improved by using the micro-stepping capability of the drive system (up to 50,000 steps/rev.). However, this reduces the maximum speed. There is a negligible amount of backlash in the precision rotary table utilised for the vertical axis. The horizontal axis has a direct drive and currently has a resolution of 0.007° using a step rate of 51,200 steps/rev. The stepper motors on each axis have rotary shaft encoders mounted on the rear shaft. A 500-line DRC encoder is mounted on the rear shaft of the motor responsible for rotating the beam about the vertical axis. This encoder has a maximum resolution of 0.18°. Further, the gearing used increases the resolution of this sensing device to 0.004°. The other encoder used is the 1,000-line E57 encoder that is mounted on the rear shaft of the motor responsible for rotating the beam about the horizontal axis. It has a maximum resolution of 0.09°.

The communication between the LIS and the robot controller requires 1.3 seconds to send the signal and acknowledge a new command. Including the LIS system response time, this leads to a total of 1.7 seconds. This is considered to be too slow for LIG technique. The impediments to a faster response include the following:

1. Slow PSD acquisition sub-system (18Hz).
2. Slow motor controller.
3. Long delays in communication between robot and LIS system.

Steps are being taken to remedy the shortcomings of the system. These will be described in the next section.

**Conclusion and future work**

In this paper, the principle and strategy of the laser interferometry-based guidance
technique have been proposed. The overall structure and the required sub-systems for such an approach were presented. The path generation for literally painting the way using a laser was described. The laser interferometer-based guidance apparatus developed has currently a poor response time of 1.7 seconds but with an excellent accuracy of \( \pm 5\mu m \).

The initial results are promising. However, some major modifications to the system must be carried out to improve the response time and thus the guidance speed. A faster PSD acquisition sub-system capable of 2,000Hz is currently being developed. Further, a high speed motor controller is also being incorporated into the system. Therefore, the LIS system is expected to achieve a response time in the order of 0.004 seconds. Further, an open-architecture controller is being developed for the robot. This open-architecture controller will be directly integrated within the LIS system, thus removing the communication delay associated with external linking of these systems. A predictive algorithm for the robot manipulator to determine its future position from the past positions, estimated velocity and estimated acceleration values is also being investigated. Further, the laser beam used has a low power (i.e. 1mW). This limits the range of the technique to a maximum of 10m. The beam power detected by the PSD acquisition sub-system when the target is further than 10m will be the same as the average ambient light power. This will result in the disruption of PSD measurements in the LIS system. A laser interferometer with higher laser power is also being considered.

The above technique is developed based on a linear path generation. Non-linear path generation method will be investigated to account for obstacles in the workspace.

References