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OPTICAL SENSORS FOR ROBOT PERFORMANCE TESTING AND CALIBRATION

Nicholas Dagalakis, National Institute of Standards and Technology and **Kam C. Lau**, Automated Precision Inc.

Despite the tremendous growth in the use of robots during the last five years, no standard robot performance and calibration tests exist. Currently, several commitees formed by the International Organization for Standardization (ISO) are working on the development of such standards on the international level. In the US, several technical committees of the Robotic Industries Association (RIA) in Ann Arbor, MI, in collaboration with the American National Standards Institute, are working for the establishment of similar standards.

Fundamental to the establishment of these robot performance and calibration tests is the existence of reliable and accurate metrology sensors to perform the required measurements. Our experience is that noncontact sensors are preferable since contact force (depending on its magnitude) could have a significant effect on the robot's dynamic response. Thus, optical metrology sensors could be ideal for such uses assuming that they satisfy the needs of the robot testing and calibration applications.

All the optical metrology sensors that we are familiar with are position and/or velocity sensors, which either automatically or manually aim at one or multiple targets mounted on the robot arm to be monitored. More advanced ones can even track the arm as it moves in three-dimensional space. Tests which may use this type of metrology sensor are the following:

1. Measurement of the robot accuracy and repeatability errors.

Accuracy error is the difference between the commanded robot arm end-effector pose and the average achieved pose. Nonrepeatability is the statistical deviation of the achieved robot arm end-effector pose under an identical input command. During operation, most manipulators will either move under Pose-To-Pose (PTP) control mode, stopping every time when they reach a goal pose, or under Continuous Path (CP) control mode, flying by the goal poses describing their desired path and stopping only at the last goal pose. The CP control mode requires that the optical metrology sensor can track the end-effector in real time as it moves in three-dimensional space. Most manipulators are designed to be programmed either manually or off-line.

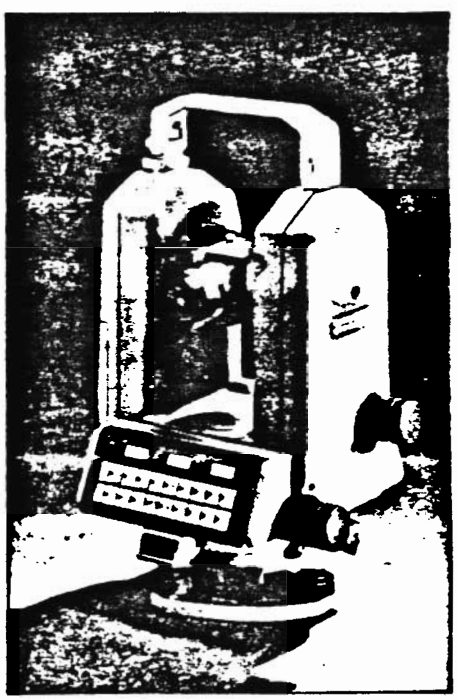

Figure 1. A 0.3 Arc-second commercial theodolite. (Courtesy Wild, Inc., Rockleigh, NJ).

In the case of manual teach programming all the manipulator motions are planned relative to the taught poses. In the case of off-line teach programming all motions are planned with respect to a reference frame. Since the metrology sensor has to determine the error with respect to that frame, the sensor should have the ability to calculate its location in three-dimensional space.

2. Measurement of robot overshoot, settling time, distance, and velocity errors.

These are dynamic performance parameters in classical control systems for evaluating the performance of the robot arm control system. Although they contribute to the accuracy and repeatability errors of a robot system, they are often measured separately. Since most modern robots can move at high speed, measuring these dynamic parameters requires that the metrology sensor be able to track and sample at high speed.

3. Measurement of the robot arm workspace, dexterity, flexibility, and manipulability.

Dexterity, flexibility, and manipulability are terms used to describe the capability of a robot arm to move its end-effector within its workspace. Mapping this workspace can be challenging since the workspace can vary widely from robot to robot and the orientation of the end-effector can rotate by as much as 360°. The workspace of a robot arm may be divided into at least the dextrous (or primary) and the secondary workspace. In the dextrous workspace, all the end-effector orientations around the end-effector gripping point are possible poses. Robot arm manipulation flexibility refers to the number of possible arm poses to reach a certain point in the workspace. Robot

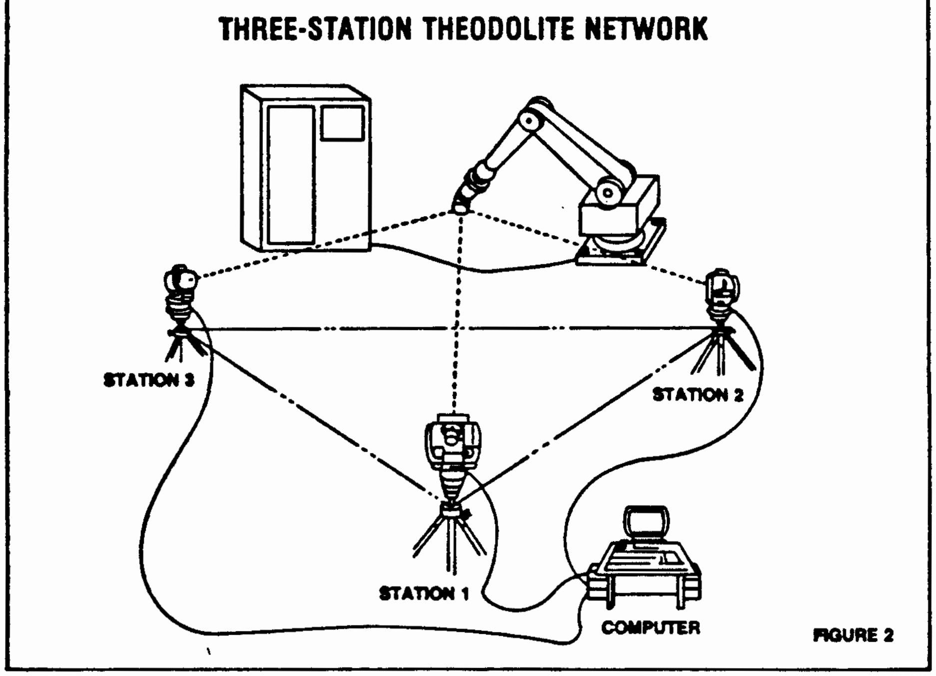

FIGURE 2

arm manipulability may be described as the easiness of changing the position and orientation of the end-effector, at a particular point in the workspace, as a function of the maximum allowable joint velocities. For small displacements of the joints, at the limits of their velocities, the corresponding velocity vectors of the end-effector gripping point define a volume which may be called the manipulability volume. Mapping this volume requires again that the metrology sensor can sample and track at high speed.

Based on these applications the following optical metrology sensor performance characteristics should be considered:

Accuracy: It should be at least 2 times the accuracy of the robot arm. An accuracy of 1 part per 1000 is usually considered low, 1 part per 50,000 is usually considered high, and 1 part per 100,000 is usually considered very high. Robot arm accuracy error varies depending on the type of robot used. It can range from a few inches to a few thousandths of an inch.

Precision (or Repeatability): It should be at least two times the repeatability of the robot arm. Robot arm repeatability ranges from a few hundredths to a few thousandths of an inch.

Resolution: The robot arm resolution would be equal to either the resolution of the digital computer controller, or that of the digital to analog converter, or the position feedback sensor, whichever is worse. Robot arm resolution ranges from a few hundredths to a few thousandths of an inch.

Optical metrology sensors are ideal for testing

Sampling Rate: It should be at least two times higher than the maximum frequency of the robot arm oscillation. Robot arm oscillations frequencies range from 0 to 50 Hz.

Tracking Speed: It should be at least as fast as the maximum speed of the robot arm part which is being tracked. End-effector speeds can reach up to several feet per second.

Measurable volume: It should cover the robot arm workspace of interest, which could vary from a few cubic feet to a few thousand cubic-feet.

Portability and Ease of Use: Most robots are anchored onto the floor so the metrology sensor has to be easily transportable. A fully automated system with high-speed data acquisition and data analysis would be ideal for robot measurement.

Metrology Sensor Calibration Requirements: They should be simple especially when the system has to be calibrated every time the power is turned on. Calibration fixtures should not interfere with the operation of the robot arm.

The optical robot metrology sensors available today are the following:

1. Theodolite Network

Accuracy: 5 parts per 100,000
Sampling rate: static, 60 second per data point (est.)
Ease of use: skill and labor intensive, portable, moderately easy to set up, initial distance calibration required
Measurable volume: unlimited; geometry unrestricted
Measuring objectives: absolute or relative, point-to-point (only), accuracy or repeatability
Cost: $60,000–$90,000 per system

A theodolite [1, 2] is an optical instrument widely used in field surveying and has recently been adopted for use in robot metrology [3, 4]. The instrument consists of a telescope which rotates about the vertical and horizontal planes. The angles of rotation are measured with two high-precision encoders with accuracy typically in the orders of arc-seconds. Modern theodolites provide digital interface to a computer for angle readouts. *Figure 1* shows a commercial theodolite with 0.3 arc-second resolution and 1.0 arc-second accuracy angle readouts.

In a theodolite network, two (minimum) or more theodolites are used (*Figure 2*). The relative positions between each theodolite are obtained by calibrating against a known length (i.e., a standard meter bar) to establish the measuring coordinate. A tiny illuminated target (usually in the form of a light emitting diode (LED) or a 1-2 mm diameter polystyrene sphere illuminated by a low-power laser through a fiber optics) is mounted on the robot end-effector. During the measuring process, the theodolites are manually directed and precisely aimed at the target. The angle readouts combined with the base distances of each theodolite are used to compute the X, Y, and Z positions of the target. This method of using the base distances and the angle information to deduce the target position is commonly referred to as the triangulation technique.

This technique is primarily designed for point-to-point measurement of the end-effector position. It is also possible to obtain the end-effector orientation if multiple LEDs are used to form a target. The use of the triangulation technique by a theodolite network often requires redundant measurements of a single point in order to obtain a better measuring accuracy. This process is rather laborious if the entire robot work zone is to be measured. Well-trained operators are required to minimize measuring errors caused by unskilled operators. A typical measuring accuracy of up to 5 parts per 100,000 is common for this kind of technique.

2. Laser Tracking System

Accuracy: 2-10 parts per 100,000

Sampling rate: continuous, 50 data points per second (est.)

Ease of use: fully automated, portable, easy to set up, initial distance calibration required

Measurable volume: unlimited, geometry unrestricted

Measuring objectives: absolute or relative, point-to-point or continuous-path, accuracy or repeatability

Cost: $100,000–$200,000 per system.

The idea of combining laser interferometer and optics and electromechanical devices to measure the positioning performance of robots has gradually evolved in the last few years [5]. Several ideas have been developed; they include single-beam target tracking [6] and multiple-beam target tracking [7, 8, 14]. the former system uses both length and angle measurement information for computing the X, Y, and Z coordinates of the target; the other uses purely length measurement information to obtain the target position.

Single-Beam Tracking System: Illustrated in *Figure 3* is the schematic of a single-base laser tracking interferometer system developed at the National Bureau of Standards (Gaithersburg, MD) in 1987. A tracking unit, which consists of a laser interferometer and a dual-axes-servoed mirror mounted on a tripod, is located in front of a robot. A second dual-axes-servoed-mirror, which is installed on the robot wrist, becomes the target of tracking and measurement. The idea is to continuously direct the laser beam to the target by controlling the angles of the tracking mirror. In the meantime, the target mirror is also controlled to stay perpendicular to the beam and returns the beam precisely to the laser system. Two bilateral effect photodiodes are installed at the back of the target mirror to supply misalignment information of the tracking process to a control computer. The computer then computes and issues the appropriate servo-commands to the four servo-axes to null the misalignment. The change in "length" measurement obtained from the laser system, when combined with the angle measurements of the tracking mirror, yields the position of the target (or the robot end-effector, which maintains a constant positional offset from the target) in spherical coordinates. The angular orientations of the robot wrist with respect to the tracking system can also be obtained by measuring the target mirror angles.

FIVE-AXES SINGLE-STATION LASER TRACKING SYSTEM

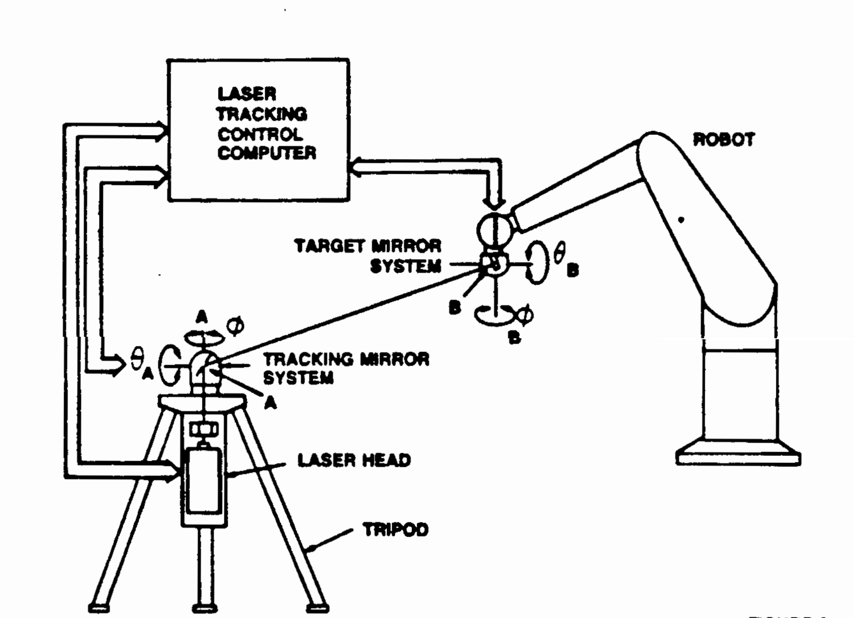

FIGURE 3

The laser tracking system described above yields 5-axes measurements of the robot wrist; namely X, Y, Z positions and pitch and roll rotations with respect to the measuring origin. Another version of the single-beam tracking system, which uses a retroreflector (or "corner cube") as a target, is shown in Figure 4. Because of the use of a "passive" target, this system can only measure the 3-D positions of the robot, but at a much lower cost. The position measuring accuracy of either version is generally in the order of 1-2 parts per 100,000 with angle accuracy of 1-2 seconds of arc for the 5-axes system.

Multiple-beam Laser Tracking System: In a "multiple-beam" system [8], three or more independently servoed laser beams are employed to track a common target (retroreflector) mounted on the robot wrist (*Figure 5*). The tracking control technique is similar to the single-beam system using a retroreflector. The change in "length" measurements from each tracking unit are combined with their precalibrated base distances for

THREE-AXES SINGLE-STATION LASER TRACKING SYSTEM

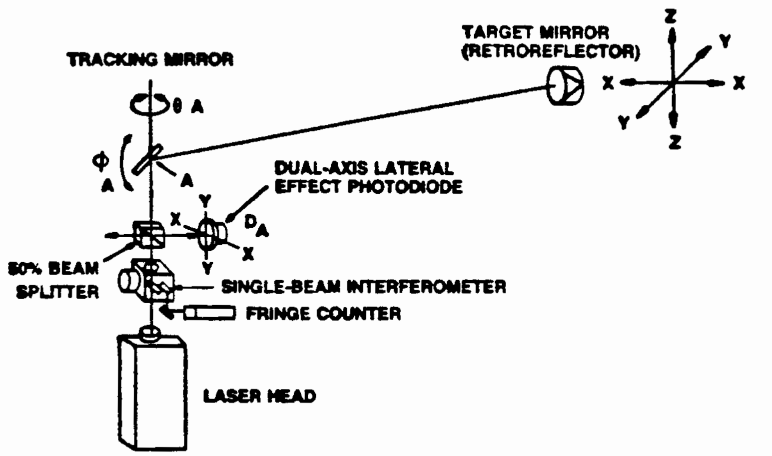

FIGURE 4

THREE-AXES MULTISTATION LASER TRACKING SYSTEM

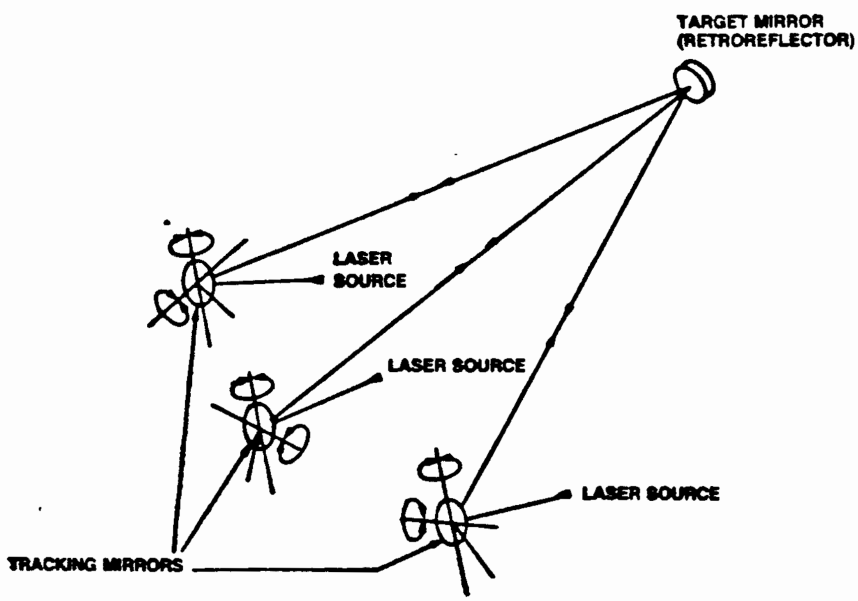

FIGURE 5

computing the X, Y, and Z positions of the target. In order to obtain a 6-degrees-of-freedom measurement (i.e., X, Y, Z, pitch, yaw, and roll), it requires six independently servoed laser beams and three retroreflectors forming an equally-spaced compound target to be mounted on the robot wrist. Because of the complexity of this arrangement, a 6-axes multiple-beam system offers little or no advantages over the single-beam system. In addition, because of the dimensional and spatial instabilities (i.e., change of reflective index of air as a result of changes in temperature, pressure, humidity, and air turbulence) often associated with multiple spatial measurements, the measuring accuracy of a multiple-beam tracking system is in the order of 2-3 parts per 100,000 for robot measurement.

3. Opto-Camera System

Accuracy: 5 parts per 10,000

Sampling rate: continuous, 100 points per second (estimated)

Ease of use: fully automatic, portable, easy to set up, initial distance calibration required

Measurable volume: limited; geometry unrestricted

Measuring objectives: absolute or relative, point-to-point or continuous-path, accuracy or repeatability

Cost: $50,000–$70,000.

The opto-camera system was first used to track three-dimensional human body movements of athletes and orthopedic patients for kinesiology studies [9]. It was later modified for tracking the position of robot end-effectors [10-13]. The system consists of two solid state cameras, a target of one or more light emitting diodes (LED) mounted on the robot end-effector, and a controller (*Figure 6*). Each camera contains a tetralateral photodiode and a focusing lens. The outputs of the photodiode are currents proportional to the x, y positions of an imaged light spot (emitted from an LED) from the centroid of the photodiode. By combining the position measurements and the precalibrated base distance of the two cameras, the X, Y, and Z position of the LED (and thus the robot end-effector) can be computed by the controller. Using time division multiplexing, a number of LEDs (minimum of three) can be sequentially lighted, and their relative positions determined. This allows the angular orientations of the end-effector to be computed in real-time while the robot is being tracked [12, 13]. To avoid interference from ambient light, an optical filter can be used to enhance the signal-to-noise ratio of the system.

This system can be used for both relative and absolute measurements. For system calibrations, the "length" measurement is introduced by placing a precalibrated reference frame (e.g. a cubic frame) in front of the camera system. A minimum of four LEDs precisely located at the vertices of the cube are needed to establish the distance and orientation of the camera system with respect to the reference frame. Provided that the camera positions are not changed and the environmental conditions (e.g. background lighting, temperature, etc.) remain constant, the accuracy of the system remains unaltered throughout the measuring process.

OPTOELECTRONIC CAMERA SYSTEM

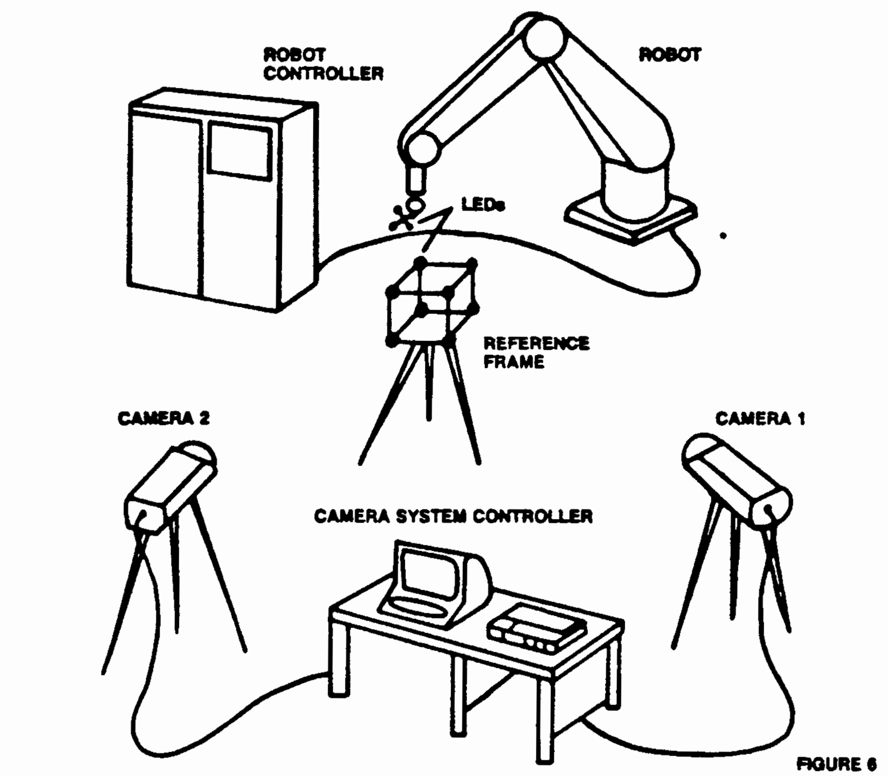

FIGURE 6

Nicholas Dagalakis is a mechanical engineer at the National Institute of Standards and Technology, Robot Systems Div. (Gaithersburg, MD). Kam C. Lau is president of Automated Precision, Inc. (Gaithersburg, MD). ■

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