Indoor GPS Metrology System with 3D Probe for Precision Applications

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Abstract

There is an increasing demand from industry for intelligent reverse engineering solutions. The requirement is to be able to perform reverse engineering, to create CAD models, or to compare prototypes with CAD models. A reverse engineering solution that can be used for 6 degrees of freedom pose measurement in a large area is desired. With this application in mind, we have developed a ‘3D Probe’ solution. The 3D Probe is a portable measurement tool equipped with three receivers in optimum locations and a ball probe tip. The operator holds the 3D Probe in his hand and moves the probe tip over an object surface. Then, the X, Y and Z coordinates of the probe tip are measured in real time with high accuracy. Different probe tips of all sizes and shapes can be used on the probe to have access to all areas of the objects. The buttons on the probe allow the operator to start and stop the scanning process. The indicators on the probe give information concerning visibility and scanning mode.

The 3D Probe is specifically designed for intelligent scanning using recently available indoor Global Positioning System (GPS) technology. A battery-operated transmitter uses laser and infrared light to create one-way position information, the relative azimuth and elevation from the transmitter to the receiver. The receiver contains photodiodes and senses the transmitted laser and infrared light signals. With the addition of a second transmitter of known location and orientation, users can calculate the position of the receiver in the base coordinate system. Adding more transmitters increases the accuracy of the system. The signal is transferred through a wireless network connection providing mobility to the operator.

This paper describes the indoor GPS metrology system and the 3D Probe designed for reverse engineering and calibration. The concept of the 3D Probe is presented with the description of its design, components, and calibration process. The general concept and kinematics of the metrology system are described. The metrology system is applied to various engineering problems such as reverse engineering of standardized interface connection, actuator metrology, and robot metrology. Experimental results of standardized interface tests are presented along with procedures for actuator and robot metrology.

Keywords: Metrology; Indoor GPS; Modular robotics

1. Introduction

Open Architecture Systems (OAS) are automated systems built by actuator joint and link modules connected with standardized interfaces. They can be assembled on demand into different geometries ranging from 6 degrees of freedom (DOF) manipulator to 40 DOF manufacturing workcells (Fig. 1) [1]. Such systems allow flexible manufacturing, rapid repair, and upgrade, but these benefits have yet to be realized. A significant barrier is the presence of error between the actual and desired frames. While the accuracy error of a typical robot may be 20 times larger than its repeatability due to assembly, compliance, and tolerance errors [2]. Currently, teaching a robot, an essential process for high precision operations and Off-line Programming (OLP), is a time-consuming operation required for repair, upgrade, reconfiguration, and task change. This fact trumps other modular technology benefits.

The successful application of OAS on high precision operations depends on three research areas [1]. First, high performance standardized interface connections, which guarantee the needed level of connection exchangeability, repeatability, and rigidity, are required. This will make it possible to exchange or reconfigure OAS without decreasing the overall accuracy. Secondly, both geometric and compliance metrology procedures must be developed to model, measure, identify, and compensate for the errors of modular structures. The final step is to develop an advanced metrology system which is accurate, flexible, and easy to use for OAS metrology. The completion of these areas of research will make it possible to correctly predict and maintain the accuracy of the OAS. In the following sections, an advanced metrology system and its applications to actuator, and robot metrologies will be described.

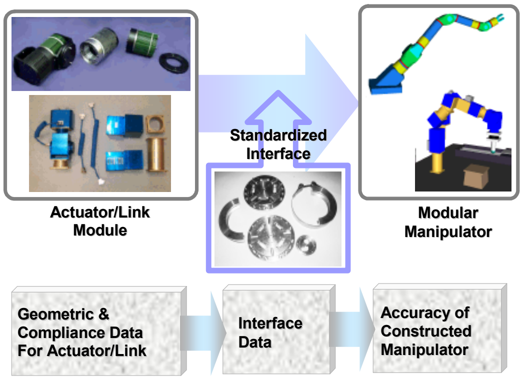

Fig. 1. Open Architecture Systems

2. Indoor GPS Metrology System

Metrology research for robotics involves the development of new technologies and techniques to measure robot poses accurately. Many measurement systems have been developed with large variations in complexity, cost, and required operator skill. State-of-the-art accuracy is on the order of 4/10,000 – 2/1,000 of an inch (0.01 – 0.05 mm) over the robot workspace [1, 2]. Commonly used sensors are: theodolites, laser trackers, cable potentiometers, Coordinate Measurement Machines, acoustic sensors, ball bars, articulated arms, and vision systems.

Recently, Robotics Research Group at the University of Texas at Austin (UTRRG) has been researching advanced metrology systems which can continuously measure both static and dynamic 6 DOF poses and motions accurately. They should be able to measure up to 50 feet even when their lines of sight are interrupted occasionally. This is an important requirement for manufacturing workcell calibration since multiple robots coordinate together in a small area. Multiple laser heads need to be positioned in distributed locations. Metrology systems satisfying these requirements are laser trackers and indoor GPS [3]. As target points increase, however, indoor GPS has a cost advantage over laser trackers due to its measuring capability of an unlimited number of targets [4]. Fig. 2 shows the UTRRG laboratory environment for an indoor GPS, a 6 DOF robot, and a 1 DOF elbow actuator. Four transmitters installed on top of steel posts using tribrachs are rigidly connected to 6 foot deep steel columns. A C-shaped transmitter arrangement is used for reverse engineering.

The concept of a 3D Probe is shown in Figures 3 and 4. A prototype which can be used not only as a hand-held probing tool but also as a tracking device once attached to an object such as a robot or a mobile platform has been built. It has a hardwired connection to a carrying case containing detector batteries, wireless electronics and power supply. Wireless communication has been chosen to transmit data to the control center. A calibration block has also been built for 3D Probe calibration.

Fig. 2. Laboratory environment [3]

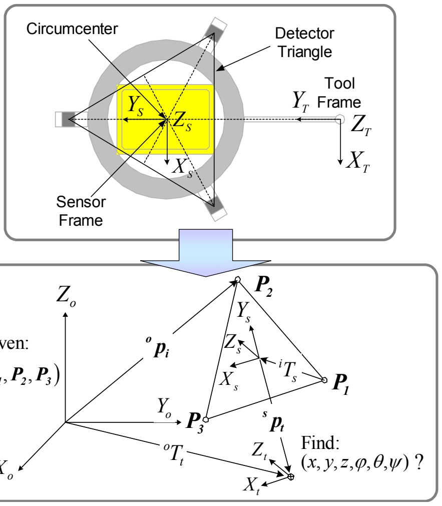

Fig. 3. 3D Probe frames and related vector analysis

3. Implementation

The development of kinematic solution involves three frames. The first is associated with the circumcenter of a triangle formed by three detector positions, the second is attached to the stylus ball probe tip, and the last is the global coordinate system to which all other frames are referenced. Fig. 3 illustrates the 3D Probe with its sensor and tool frames, a vector triangle, and a triangle circumcenter. The pose of the tool frame relative to the global frame can be represented by a homogeneous transformation matrix ${}^oT_t$ as follows

$$ {}^oT_t = {}^oT_s\, {}^s\boldsymbol{p}_t \qquad (1)$$

where ${}^oT_s$ is the transformation matrix from the global frame to the sensor frame and ${}^s\boldsymbol{p}_t$ is the position vector from the sensor frame to the styli ball center. This position vector is unknown, but it can be determined by the calibration process of the 3D Probe once it is assembled or every time a different stylus ball probe is installed. The Eq. (1) can be rewritten as

$$ {}^oT_t = {}^o\boldsymbol{p}_i\, {}^i\boldsymbol{T}_s\, {}^s\boldsymbol{p}_t \qquad (2)$$

where i $(i = 1, 2, 3)$ represents sensor numbers.

Fig. 4. 3D Probe, carrying case, and calibration block

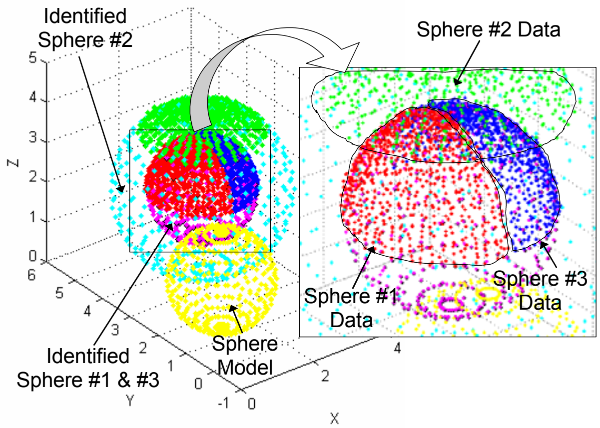

Fig. 5. Simulated sphere data and identification

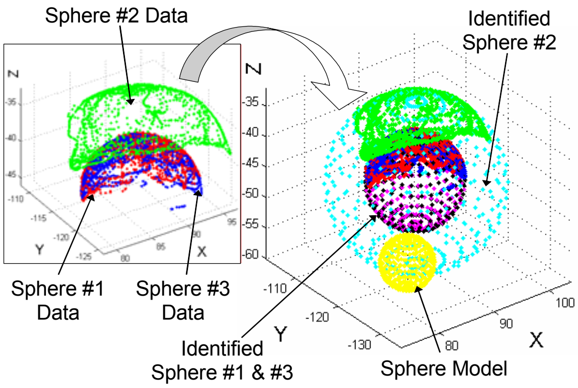

Fig. 6. Measured sphere data and identification

Now an important step is to obtain the vector ${}^{s}\boldsymbol{p}_{t}$ from the sensor frame to the tool frame to eliminate inevitable machining tolerance and assembly errors. The vector has been determined using efficient nonlinear optimization and least squares fitting algorithms [5]. As shown in Figures 5 and 6, the 3D Probe is first placed at the calibration block center. As the probe is rotated about the stylus, three partial spherical data sets are obtained from the sensor measurements. Then, unconstrained nonlinear minimization and least square fitting algorithms are applied to the recorded data which calculate the radii of three spheres and their center locations. The calculated radii are 7.1911, 13.2879, and 7.2723 inches. The x, y, and z coordinates of its center are 88.6076, -118.1211, and -45.8123 inches respectively. Finally, the vector from the center frame to the styli ball center ${}^{s}\boldsymbol{p}_{t}$ is determined. Fig. 6 shows experimentally measured data from the three detectors and the complete spheres created by this technique.

In addition, a distance accuracy test has been performed to investigate the accuracy degradation across the measurement volume. The room floor is divided into several subsections and a scale bar with a known length is used for accuracy tests. Results are shown in Fig. 7. The accuracy error is shown with respect to both vertical and horizontal distance from the transmitters. The 3D Probe prototype tested satisfies the accuracy and operation requirements for robot metrology and workcell calibrations.

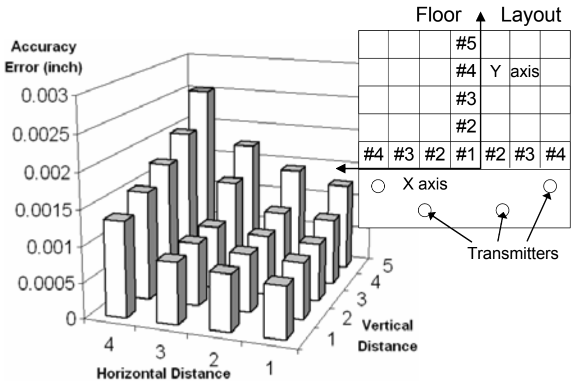

Fig. 7. Accuracy test results

4. Application on OAS Metrology

The developed metrology system has been used for OAS metrology. This includes interface connection performance testing, actuator, and robot metrologies. The 3D Probe has been used for intelligent scanning of these components. Fig. 8 shows how an operator can hold the probe and start scanning. The styli ball center pose is wirelessly transferred to the control center automatically during the scanning. The recorded point cloud data, then, can be used to determine standard geometries such as lines, planes, circles, spheres, and cylinders with the nonlinear optimization and least squares fitting algorithms.

Fig. 9 shows how an interface pair might be tested based on its geometry and what we can learn from this. Both the input and output frames are identified by scanning the surfaces of the female and male interfaces. First, the female top surface is scanned followed by its circular outer surface. After the plane determination, scanned circle point cloud is projected on to the plane resulting in a circle fitting process. The z axis is the normal vector of the plane on the circle center. Either the x or y axis direction is then fixed by a reference

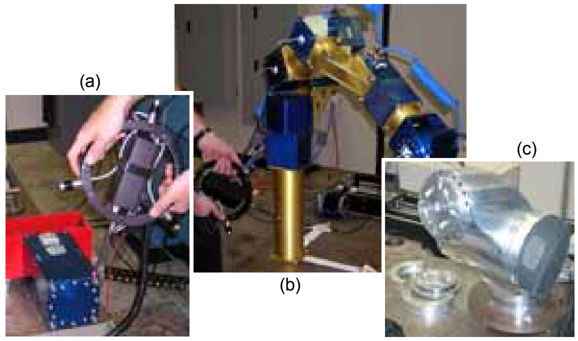

Fig. 8. Application of 3D Probe on actuator (a), robot (b), and interface (c) metrology

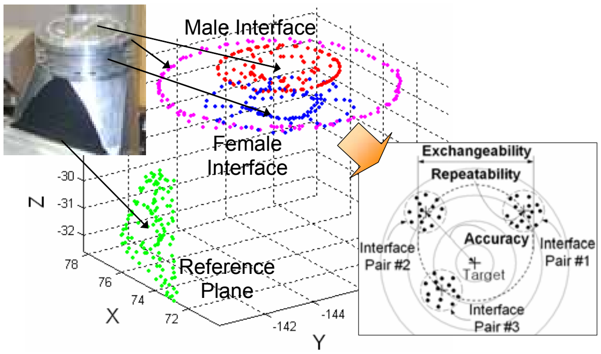

Fig. 9. Scanned point cloud for interface testing

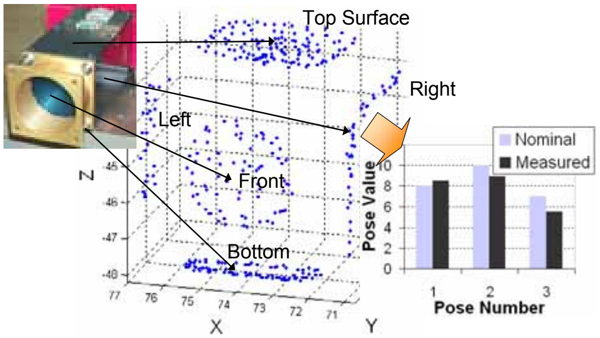

Fig. 10. Scanned point cloud for actuator metrology

plane. The other frame is determined using the same procedure on the male side. By repeatedly measuring these two frames, the distribution of differences between the two frames provides the connection accuracy, repeatability, and exchangeability. This information can be used to predict the overall accuracy of an assembled modular structure with error mapping. The pre-measured data of the interface connections could be written to a serial number on the interface serving as a database key to the calibration data.

Similarly, the 3D Probe could also be used for metrology of actuator joint/link modules and assembled modular robots. Figures 10 and 11 show experimentally measured point clouds needed to determine input/output or base/end-effector frames. A robot's accuracy and repeatability could then be determined based on the ISO and ANSI standard procedures as shown in Fig. 12 [6,7].

5. Conclusion

The 3D Probe prototype presented here is the first model. Thus, a simple design has been chosen for ease of manufacturing. An extensive optimization and analysis will be performed on the next prototype with control buttons and visibility/scanning mode indicators for easy operation. The second prototype will solve the problems found on the first model. Nonetheless, it turned out to be a convenient hand-held device that an operator can carry and use for OAS metrology. The 3D Probe has been successfully used and will continue to be used for interface, actuator, robot, and manufacturing workcell performance tests. This will help us understand the nonlinear phenomena of accuracy error sources and deal with them more effectively.

Acknowledgement

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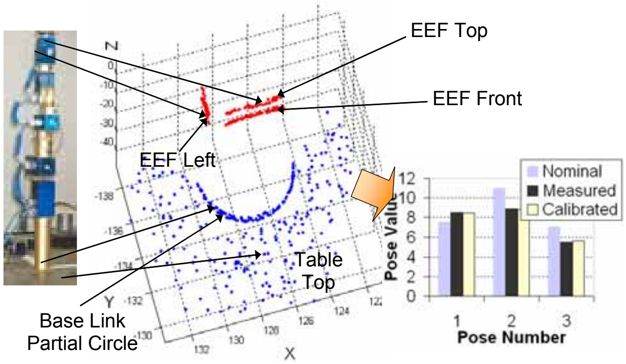

Fig. 11. Scanned point cloud for robot metrology

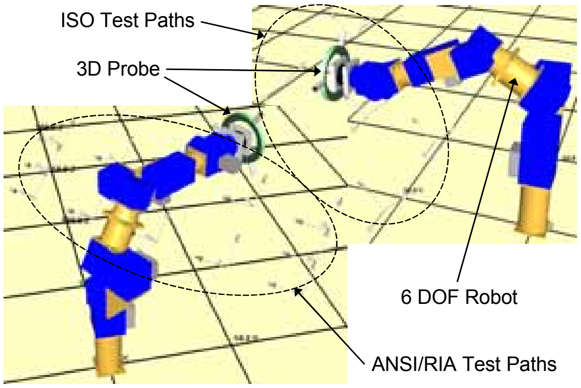

Fig. 12. ISO and ANSI/RIA standard test paths [6, 7]