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ROBOTIC CALIBRATION ISSUES: ACCURACY, REPEATABILITY AND CALIBRATION

Kevin L. Conrad, Panayiotis S. Shiakolas shiakolas@uta.edu**, T. C. Yih**

Mechanical and Aerospace Eng. Department, and Automation and Robotics Research Institute, The University of Texas at Arlington, Arlington, TX 76019, USA, shiakolas@uta.edu

Abstract. The groundwork for a contact calibration methodology using a touch probe is developed for an articulated robot arm. This solution is framed within current calibration and metrology issues in robotics based upon the kinematical mechanical design of a serial link manipulator. Accuracy, repeatability, and resolution are explored and a simplistic approach is taken. This exercise is intended to lay the groundwork for exploring the feasibility of integrating a commercial product such as a force sensor or touch trigger probe on the end of a robot arm. Candidate processes and/or applications are identified. Findings indicate that an in-process contact calibration methodology that is accurate, repeatable, and cost effective would be a desirable solution.

Key Words. Robotic accuracy, repeatability, calibration, resolution

1 INTRODUCTION

One of the main technological barriers in the robotics industry has been the reduction of error between the tool frame and the goal frame. The sources of this error are readily identified. Modeling differences between the controller and the robot account for most of the error between the base frame and the tool frame. Inaccurate fixturing and manufacturing processes can account for the differences between the station and goal frames. The definition of these frames is depicted in Fig. 1 [1].

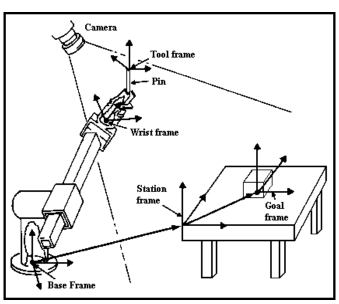

Fig. 1. Standard Robot Frames.

While the obvious solutions of building a better robot, building more rigid and repeatable fixtures, and improving manufacturing processes could help in improving this problem, oftentimes are not feasible due to the lack of available resources.

Compensation for this error through an in-process feedback mechanism is a much more attractive alternative. If the desire is to improve upon the resolution or absolute accuracy of the robot, a precise metrology system is needed to perform these measurements. However, for the majority of industrial applications that require repeatability or positional accuracy in the order of 0.0001", this approach is not necessary. Possibly a contact probe could close the loop without sacrificing the repeatability of the robot.

The identified parameters related to robotics calibration are accuracy, repeatability, and resolution. Each of these depends on the various components used (links, motors, encoders, etc.), the construction procedure, and the capability of the controller. Resolution is defined as the smallest incremental move that the robot can physically produce. Repeatability is a measure of the ability of the robot to move back to the same position and orientation. Accuracy is defined as the ability of the robot to precisely move to a desired position in 3-D space. Fig. 2 shows these concepts graphically.

Absolute accuracy and repeatability describe the ability of a robot to move to a desired location without any deviation. Dynamic accuracy and repeatability describe the ability of a robot to follow a desired trajectory with little or no variance. Additionally, as in all robotic applications zero overshoot is a necessity to avoid disastrous collisions with other parts in the work-cell. Ideally, both the absolute and dynamic accuracy and repeatability can be minimized to the attainable resolution.

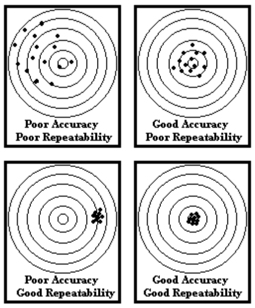

Fig. 2. Accuracy vs. Repeatability.

The biggest effect on the accuracy of the robot comes from the length of the robot links. Manufacturing of these links inevitably introduces some variation in the dimensions from one robot to the next, as well as some variation in the orientation of the joints. The differences between the physical joint zero position reported by the robot controller and the actual physical joint zero position usually has an effect on the accuracy of the robot. For an articulated 6-DOF robot, joints 1, 2, and 3 contribute to the position and joints 4, 5, and 6 contribute primarily to the orientation of the tool frame. A mathematical model within each robot controller assumes that the links on one robot are the same length as the links on another robot of the same type. Additionally, it also assumes that the relative orientations of the joints on one robot are the same as on another robot of the same type. Unfortunately, this is not true. The robot incorrectly estimates where its endpoint is, given a set of joint angles. Another significant factor in the robot positional error is joint compliance. This may be thought of as a factor representing the elasticity of each joint caused by the effects of gravity, payload, and inertia.

Each of these, accuracy, repeatability, and resolution, depends upon many different factors that include, but are not limited to, friction, temperature, loading, and manufacturing tolerances. High accuracy is the most difficult to accomplish.

This paper examines the concepts of accuracy, repeatability, and resolution. These principles are framed within the context of the homogeneous transformation, by which a theoretical error analysis is performed using the Puma 560 robot. Calibration and metrology techniques are also introduced. Furthermore, the current state of the automation industry is examined. Issues relating to calibration and metrology techniques are addressed and some popular solutions are identified. Contact calibration is framed as a viable technological application to industrial robotics.

2 BACKGROUND

The first step in improving the accuracy, repeatability, and resolution of industrial robots is to look at the current state of the art. This applies not only to robots themselves, but also to the most advanced metrology systems.

Robot manufacturers, as an industry standard, publish the repeatability of each machine. These specifications are determined by performing stringent experiments in accordance with ISO 9283 [3]. As a general rule of thumb, larger robots have larger errors in repeatability.

More often than not, these repeatability numbers are smaller than process requirements. In those few instances when this is not the case, other solutions must be found. A common approach has been to start from the base of the manipulator to determine if improvements can be made in each link such as machining or assembly improvements or actuator resolution improvements.

2.1 Kinematics

A robot kinematics structure is often represented mathematically using a compact representation of the position and orientation of each joint relative to the previous joint. For demonstration purposes, the modified Denavit-Hartenberg (DH) notation as presented by Craig [1] will be used. The following notation applies:

a_{i-1}= distance from Z_{i-1} to Z_i measured along X_{i-1}; α_{i-1}=angle from Z_{i-1} to Z_i measured about X_{i-1}; d_i = distance from X_{i-1} to X_i measured along Z_i; θ_I = angle from X_{i-1} to X_i measured about Z_i.

The DH notation is commonly referred to as the DH parameters of a robot. 0 provides a graphical representation of how the DH parameters create a link transformation [1]. These parameters are combined into a 4 X 4 matrix called the homogeneous transformation:

$$
{}^{i-1}_{i}T = \begin{bmatrix} \cos q_i & -\sin q_i & 0 & a_{i-1} \\ \sin q_i \cos a_{i-1} & \cos q_i \cos a_{i-1} & -\sin a_{i-1} & -\sin a_{i-1} d_i \\ \sin q_i \sin a_{i-1} & \cos q_i \cos a_{i-1} & \cos a_{i-1} & \cos a_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

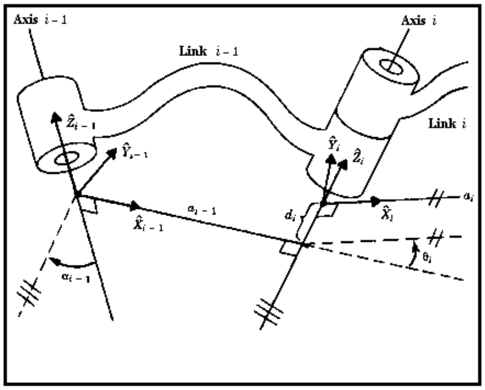

Fig. 3. Link Transformations

To examine how errors between the kinematically as-designed and as-built manipulator affect the overall positioning, an example of a well-studied robot, the Puma 560, will be used. The Puma 560 robot will demonstrate the uncertainty in accurately and repeatably positioning the tool frame with respect to the goal frame. This robot was chosen primarily because so much has been published about it in the past. Table 1 shows the DH parameters of the Puma 560 [1,5].

Table 1. Puma 560 DH Parameters

I	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	-90°	0	0	θ_2
3	0	a_2	d_3	θ_3
4	-90°	a_3	d_4	θ_4
5	90°	0	0	θ_5
6	-90°	0	0	θ_6

where: a_2 = 431.8 mm, a_3 = 20.32 mm, d_3 = 124.46 mm, d_4 = 431.8 mm

Solving for the final transformation from the base frame to the tool frame, we obtain:

$$ {}^0_6T = {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T\,{}^4_5T\,{}^5_6T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & tp_x \\ r_{21} & r_{22} & r_{23} & tp_y \\ r_{31} & r_{32} & r_{33} & tp_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

This research is concerned only with the positioning of a robot. The theoretical positional components, tp_x, tp_y, and tp_z, provide the equations for which the following positional analysis is based:

$tp_x = \cos\theta_1[a_2\cos\theta_2 + a_3(\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3) - d_4(\cos\theta_2\sin\theta_3 + \sin\theta_2\cos\theta_3)] - d_3\sin\theta_1$

$tp_y = \sin\theta_1[a_2\cos\theta_2 + a_3(\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3) - d_4(\cos\theta_2\sin\theta_3 + \sin\theta_2\cos\theta_3)] - d_3\cos\theta_1$

$tp_z = -a_2(\cos\theta_2\sin\theta_3 + \sin\theta_2\cos\theta_3) - a_2\sin\theta_2 - d_4(\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3)$

2.2 Error Budget

Accuracy and repeatability can be derived from the preceding equations. Let the theoretical position be calculated from the above equations for tp_x, tp_y, and tp_z. Substitution of the preceding values for the DH parameters and zeroes for the joint values, θ_i, give the theoretical zero position. The actual position of the robot is a function of the DH parameters and the corresponding individual variations or "errors" mainly due to machining or manufacturing tolerances or component limitations (encoder resolution). These variations are indicated as a Δ value for each DH variable. Let us define the actual position by p_x, p_y, and p_z.

The position error, pos_err, is defined as the norm of the individual position error for each axis. This is computed by the following equation:

$$ \begin{aligned} pos\_err &= \text{norm}\{e_x, e_y, e_z\} \\ &= \{(p_x - tp_x)^2 + (p_y - tp_y)^2 + (p_z - tp_z)^2\}^{1/2} \end{aligned} $$

A "rough" estimate of the accuracy is calculated as the positional error when there exist both angular and length variations. Repeatability, on the other hand, is calculated by assuming no variation in the length parameters. This is due to the fact that after a manipulator has been built not all components change dynamically, only the DH joint variables will vary.

For a sample analysis, assume an angular tolerance of ± 0.000375° and a machining (length) tolerance of ± 0.005 inches. The expected accuracy and repeatability can be evaluated by substituting these values into the respective equations. Let the repeatability and accuracy be defined as:

repeatability, pos_err = $f(a_i, d_i, \theta_i, \Delta\theta_i)$
accuracy, pos_err = $f(a_i, \Delta a_i, d_i, \Delta d_i, \theta_i, \Delta\theta_i)$

Using the DH values for a PUMA 560 in Table 2, zero for the joint variables and the tolerances defined above, we evaluate the repeatability and accuracy as

repeatability = ± 0.00028 inches
accuracy = 0.0118 ± 0.00028 inches

Note that these calculations are performed without accounting for any temperature variations or external loading. By only using the previously described concept for accuracy and repeatability, it has been shown that in this instance, 97% of the positional error is due to errors in the robot zero position. If we can eliminate any error associated with the length of the links, the servo system can position the robot to within a volume of 3% of the total volume seen when these errors are present. It should also be noted, that although this analysis is performed for an articulated manipulator, it can easily be extrapolated to other robot topologies.

Over the past decade, great strides have been made in accurately positioning robots. High precision motors, zero backlash gear sets, and dynamic encoders have compensated for many of the structural and dynamic errors identified in Fig. 4, and made robots into the finely tuned machines they are today. Coupled with the speed of microprocessors in today's robots, it becomes clear that manufacturers around the world are spoiled by 'real-time' operations.

Another issue of concern is the signature of the robot. Each manipulator, due in part to manufacturing tolerances, has a different signature. This means that the absolute accuracy and repeatability of a robot vary from point to point within the work volume. This makes sense in that the joint configuration can greatly affect the loading and resulting deflections of each link. In addition, due to various attainable kinematics configurations, accuracy and repeatability can also vary for what the controller considers the same point. This fact has led researchers to examine calibration and metrology techniques to determine or compensate for this error.

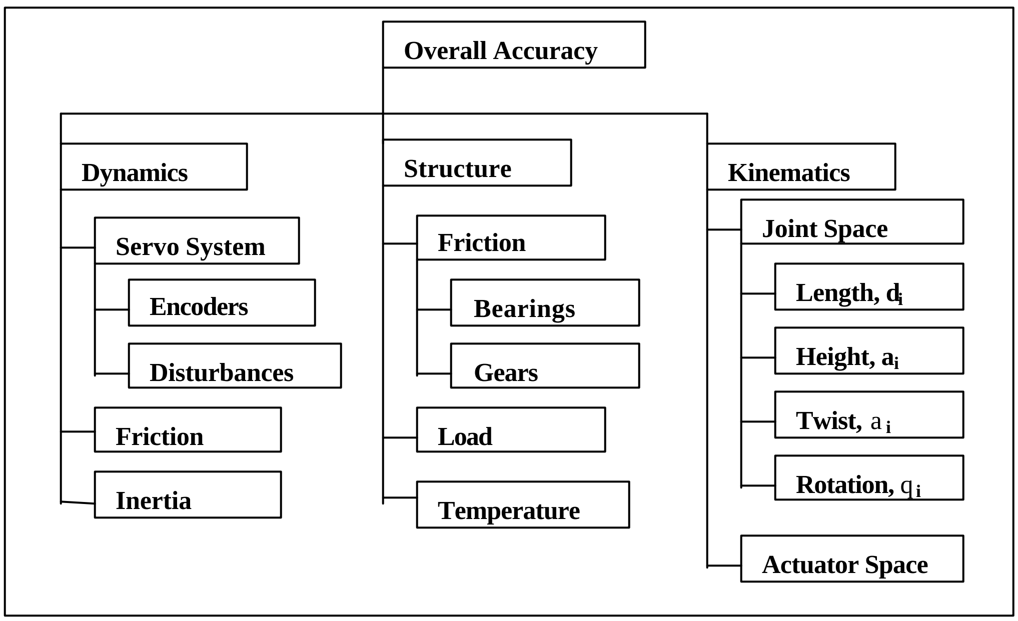

Fig. 4. Error Tree.

2.3 Calibration

Since on the order of 97% of the positional error is due to the error in the robot zero position, often times full calibration is not necessary. Remastering is accomplished by returning the robot to its home position and resetting the encoder values. This is often performed by the manufacturer before the robot is shipped to the end customer. The manufacturer may also recommend that the process be repeated on a regular basis beginning with the initial installation.

Many traditional methods of programming involve using a teach-pendant. In these instances the end user does not depend on the accuracy of the manipulator but relies solely on its repeatability. However, as robots become more popular and the applications for them increase, end users are beginning to demand that a robot be accurate as well as repeatable [6]. When remastering a robot does not provide the end user with the accuracy required by the process, the robot must then be calibrated. Most robot calibration methods compare teach-point positions of a robot with measurements relating the tool to an independent 3-D measuring device [7]. The DH parameters in the mathematical model are then changed so that the distance between where the robot thinks it is and where the robot actually rests is minimized. The modified model (the controller or otherwise) depends on the complexity of the calibration technique.

The recent advances in off-line programming (OLP) packages update the robot model within the software to match the parameters recorded from calibrating the robot [8]. This robot can then be used in multiple work-cells without recalibration. It is only necessary to use the calibrated model. OLP systems that claim to offer such a solution are Workspace4 and IGRIP. The complexities and extent to which this is done will not be addressed here, but such solutions are included for completeness.

In addition to the above-mentioned methods, robot calibration is accomplished using both contact and non-contact probing methods. Non-contact methods include using laser proximity sensors, beam breakers, high-resolution cameras, visual servoing, etc. These methods can provide high accuracies they can be relatively expensive; both in acquiring the calibration equipment and in the time required for setup and interfacing with the robot controller. Cost drivers in industry force users to incorporate much cruder contact methods. These can include the use of dummy parts, compliant devices, and precision styli.

2.4 Metrology

Metrology is very similar to calibration. Metrology, however, implies that an actual measurement is taken to quantify robot performance. Measurements characterizing robot performance are taken in accordance with ISO 9283 [3]. A list of metrology calibration approaches as presented in an ISO technical report is included for completeness [9].

- Positioning test probe methods [9]
- Path comparison methods [9]
- Trilateration methods [9]
- Polar coordinate measuring methods [9]
- Triangulation method [9]
- Optical tracking methods [2,10]
- Inertial measuring methods [11]
- Cartesian coordinate measuring methods [9].
- Path drawing methods [9]

The presence of such a wide range of metrology solutions suggests that industry has yet to settle on any single method. Each offers a slightly different approach to a similar problem. Therefore the most appropriate solution is subjected to the parameters each individual process requires.

3 INDUSTRY APPLICATIONS

When considering a calibration or metrology solution, many factors must be considered. These include cost, accuracy, repeatability, resolution, bandwidth, setup time, type of measurement (1-, 2-, or 3-D), sampling rate, calibration requirements, contact vs. non-contact, required software, and controller interface. However, cost is the major decision driver.

3.1 Industrial Calibration and Metrology

Due to the high costs of many metrology systems, and their under-utilization in the field of robotics, many manufacturers and researchers have steered away from these concepts. Industry trends, rather, have been leaning toward macro-micro manipulation as well as other additional robot topologies. These include large Gantry or Cartesian type robots used for rough positioning while smaller articulated robot arms, parallel manipulators (Stewart platforms), and SCARA robots are used for precise positioning. For many large-scale applications, this approach has worked well. For smaller applications, it has proven to be too costly.

Costs associated with different metrology systems and some of their other capabilities are presented in [12]. These researchers concluded, "…the development of a system that could combine these characteristics, but at a low-cost, would fill an important void in the automation industry [12]."

3.2 State of Automation Industry

Many current automation industry solutions focus on the ideas of broadening the market to include applications now covered by both man and machine. "The need for smaller, more precise assemblies will stimulate major changes in assembly technology during the year 2000 and beyond [13]."

The idea of a flexible automation approach, although relatively new, is quickly leaving its mark on the robotics industry. In the 1998 Robotics International Industry Trends prepared by Robotics International of SME, flexible automation was identified as both a market driver for robot-based automation as well as a robotic business trend. "A standard flexible automated assembly cell can compete very well in the future. It is essential that such cells apply better product-design engineering tools, greater tooling automation, and simpler engineering content in parts-feeding fixtures [14]."

Concepts of a layered systems architecture are presented in [15]. Soft tooling methodologies and approaches bypassing the hard automation approach were developed, experimented, and preliminarily demonstrated for robotically automated surface finishing [16,17].

3.3 Our Application and Continued Research

This research was initiated in order to identify methodologies and techniques and assess the state of the art in robotic calibration methods. The actual application that this and subsequent research are to be applied is proprietary and can not be discussed in detail or reveal the real names of the various components.

However, we will attempt to give a flavor of the actual application using the schematics in Fig. 5. The schematics show two concentric cylinders with an array of holes on their surface. The holes on each cylinder are of different diameters and they are through holes. The co linearity of the axes is accurate to machine tool accuracies. The application requires the insertion of a component that is machined with high accuracy through both holes as shown in Fig. 5. This application is similar to that of inserting a peg though not one but two holes with the additional difficulty of identifying the axis between the two centers and maintaining the alignment of the part to be inserted along this axis.

Quantitative measurements for a hole as well as the tooling ball should be made in a more appropriate environment.

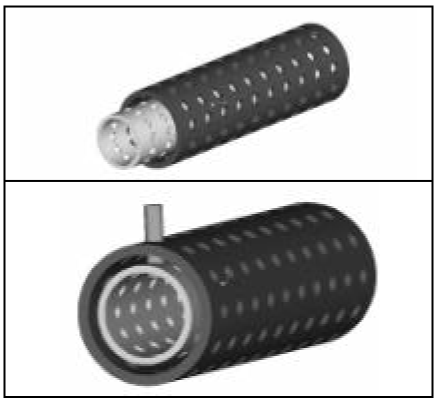

Fig. 5. Pictorial Representation of Our Application

4 CONCLUSIONS

In this work we identified an error tree with sources that contribute to the accuracy and repeatability of serial manipulators. Measures of accuracy and repeatability were derived and calculated indicating that high repeatability is a more desirable than high accuracy in daily applications with industrial robots. A survey of calibration techniques was contacted and it was decided that the costs of obtaining and implementing any of them are prohibitive for common operations. These factors lead us to the conclusion that there must be a better approach of implementing real time in process calibration. Each methodology, if proven accurate, repeatable, and reliable will be a desirable viable low-cost solution to real time robot positioning problems.

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