Achieving Fine Absolute Positioning Accuracy in Large Powerful Manipulators

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Abstract

Important robotic tasks could be most effectively done by powerful and accurate manipulators. However, high accuracy is generally unattainable in manipulators capable of producing high task forces due to such factors as high joint, actuator, and transmission friction and link elastic and geometric distortions. A method called Base Sensor Control (BSC) has been developed to compensate for nonlinear joint characteristics, such as high joint friction, to improve system repeatability. A method to identify and compensate for system geometric and elastic distortion positioning errors in large manipulators has also been recently proposed to improve absolute accuracy in systems with good repeatability using a wrist force/torque sensor. This technique is called Geometric and Elastic Error Compensation (GEC). Here, it is shown experimentally that the two techniques can be effectively combined to enable strong manipulators to achieve high absolute positioning accuracy while performing tasks requiring high forces.

1 Introduction

Large robotic manipulators are needed in nuclear maintenance, field, undersea and medical applications to perform high accuracy tasks requiring the manipulation of heavy payloads. Hydraulic robot's high load carrying capacity is attractive for such applications, but high joint friction and actuator nonlinearities make them difficult to control. The nozzle dam positioning task for maintenance of a nuclear power plant steam generator is an example of a task that requires a strong manipulator with very fine absolute positioning accuracy [14]. Absolute accuracy, rather than simple repeatability, is required for autonomous operation or for teleoperation with advanced virtual aides, such as virtual viewing.

A number of approaches exist for improving fine motion manipulator performance through friction compensation. Some of these require modeling of the difficult to characterize joint frictional behavior [1, 10]. Some require the use of specially designed manipulators that contain complex internal joint-torque sensors [11].

A simple, yet effective control method has been developed that is modeless and does not require internal joint sensors [5, 9]. The method, called Base Sensor Control (BSC), estimates manipulator joint torques from a self-contained external six-axis force/torque sensor placed under the manipulator's base. The joint torque estimates allow for accurate joint torque control that has been shown to greatly improve repeatability of both hydraulic and electric manipulators.

Even with improved repeatability, high absolute positioning accuracy is still difficult to achieve with a strong manipulator. Two principal error sources create this problem. The first is kinematic errors due to the non-ideal geometry of the links and joints of manipulators. These errors are often called geometric errors. Task constraints often make it impossible to use direct end-point sensing to compensate for these errors. Therefore, there is a need for model-based error identification. Research has been done in this area, commonly referred to as robot calibration [4, 12].

The second error source that often limits the absolute accuracy of a large manipulator is the elastic errors due to the distortion of a manipulator's mechanical components under large task loads. Methods have been developed to deal with this problem [13]. These methods depend upon detailed and difficult to obtain analytical models of the manipulator.

Recent work has resulted in methods that can correct for errors in the end-effector position and orientation caused by geometric and elastic errors in large manipulators [2, 7]. The similar methods, called Geometric and Elastic Error Compensation (GEC), yield measurement based error compensation algorithms that predict the manipulator's end-point position and orientation as a function of the configuration of the system and the task forces. Given the task loads from a conventional wrist force/torque sensor and the joint angles of the manipulator, the algorithm compensates for the combined elastic and geometric errors. They do not require detailed modeling of the manipulator's structural properties. Instead they use a relatively small set of offline end-point experimental measurements to build a "generalized error" representation of the system [6]. These methods can substantially reduce the absolute errors in manipulators with good inherent repeatability.

In this research, an approach is developed that substantially improves the absolute accuracy in strong powerful manipulators lacking good repeatability and having significant geometric and elastic errors. The method uses base force/torque sensor information to apply BSC in concert with GEC, which uses wrist sensor information to achieve greatly improved absolute accuracy in a strong manipulator exerting high task loads. Its effectiveness is shown experimentally on a large powerful hydraulic industrial manipulator. While strong, robust and reliable, this manipulator does not inherently have fine repeatability and absolute accuracy. The algorithm does not require joint velocity or acceleration measurements, a model of the actuators or friction, or the knowledge of manipulator mass parameters or link stiffnesses, yet it is able to substantially improve its absolute positioning accuracy.

2 Analytical Background

2.1 Base Sensor Control (BSC)

Here the basis for BSC is briefly reviewed. The complete development is presented in [9]. A simplified version of the algorithm sufficient and effective for fine-motion control is formulated in [5].

As shown in Figure 1, the wrench, $\mathbf{W_b}$, exerted by the manipulator on its base sensor can be expressed as the sum of three components:

$$\mathbf{W_b} = \mathbf{W_g} + \mathbf{W_d} + \mathbf{W_e} \tag{1}$$

where $\mathbf{W_g}$ is the robot gravity component, $\mathbf{W_d}$ is caused by manipulator motion, and $\mathbf{W_e}$ is the wrench exerted by the payload on the end-effector. Note that joint friction does not appear in the measured base sensor wrench. In the fine-motion case, it is assumed that the gravity wrench is essentially constant, and this wrench can be approximated by the initial value measured by the base sensor. Hence, the complexity of computing the gravitational wrench, such as identification of link weights and a static manipulator model, is eliminated. Under this assumption, the Newton Euler equations of the first i links are:

$$\begin{cases} \mathbf{W_{0\to 1}} = -\mathbf{W_b} \\ \mathbf{W_{1\to 2}} = \mathbf{W_{0\to 1}} - \mathbf{W_{d_1}} \\ \vdots \\ \mathbf{W_{i\to i+1}} = \mathbf{W_{i-1\to i}} - \mathbf{W_{d_i}} \\ \vdots \\ -\mathbf{W_e} = \mathbf{W_{n-1\to n}} - \mathbf{W_{d_n}} \end{cases} \tag{2}$$

where $\mathbf{W_{i\to i+1}}$ is the wrench exerted by link i on link i+1, and $\mathbf{W_{d_i}}$ is the dynamic wrench for link i.

For fine tasks it is assumed that the manipulator moves very slowly so that $\mathbf{W_d}$ can be neglected. Therefore, for slow, fine motions, only the measured wrench at the base

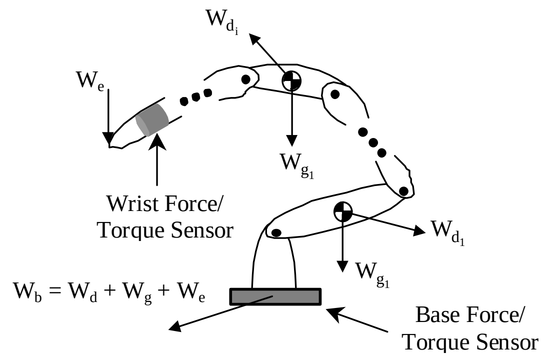

Figure 1 - External and Dynamic Wrenches

is used to estimate the torque in joint i+1. The estimated torque in joint i+1 is obtained by projecting the moment vector at the origin O_i of the i^{th} reference frame along the joint axis z_i:

$$\tau_{i+1} = -z_i^T \cdot \mathbf{W_b}^{O_i} \tag{3}$$

The value of τ_{i+1} depends only on the robot's kinematic parameters, joint angles and base sensor measurements.

With estimates of the joint torque, it is possible to perform high performance torque control that can greatly reduce the effects of joint friction and nonlinearities. This results in greatly improved repeatability. This method will not compensate for sources of random repeatability errors, such as limited encoder resolution. In addition, a manipulator with good repeatability may not have fine absolute position accuracy.

2.2 Geometric and Elastic Error Compensation (GEC)

The main sources of absolute accuracy errors in a manipulator with good repeatability are mechanical system errors (resulting from machining and assembly tolerances), elastic deformations of the manipulator links, and joint errors (bearing run-out). These can be grouped into geometric and elastic errors. Although these physical errors are relatively small, their influence on the end-effector position of a large manipulator can be significant. A brief review of the error compensation method used here is presented below.

The end-effector position and orientation error, $\mathbf{\Delta X}$, is defined as the 6x1 vector that represents the difference between the real position and orientation of the end-effector and the ideal or desired one:

$$\mathbf{\Delta X} = \mathbf{X^r} - \mathbf{X^i} \tag{4}$$

where $\mathbf{X^r}$ and $\mathbf{X^i}$ are 6x1 vectors composed of the three positions and three orientations of the end-effector reference frame in the inertial reference system for the real and ideal cases respectively.

The error compensation method assumes that physical errors slightly displace manipulator joint frames from

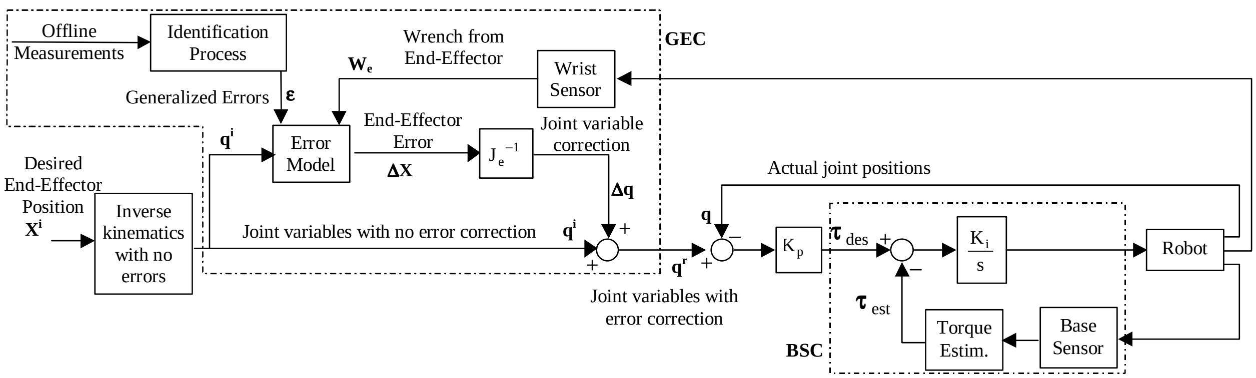

Figure 2 - Base Sensor Control and Error Compensation Scheme

their expected, ideal locations [7]. The real, or actual, position and orientation of each frame with respect to its ideal location is represented by three consecutive rotations and three translational coordinates. These 6 parameters are called here "generalized error" parameters. For an n^{th} degree of freedom manipulator, there are 6n generalized errors represented by a vector $\boldsymbol{\varepsilon}$. When the generalized errors are included in the model,

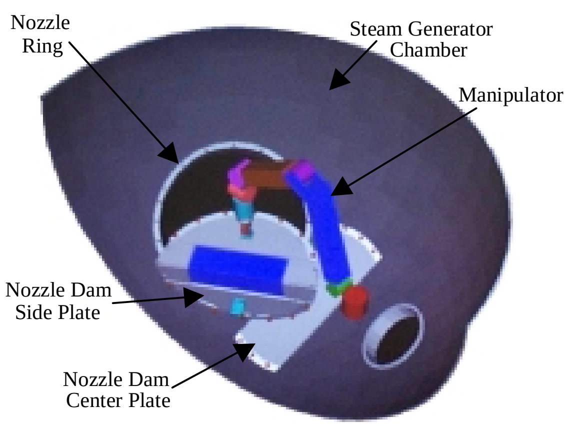

Figure 3 - Simulated Robotic Nozzle Dam Task

the six coordinates of the real end-effector position vector $\mathbf{X^r}$ can be written in a general form:

$$\mathbf{X^r} = \mathbf{f}^{\mathbf{r}}(\mathbf{q}, \boldsymbol{\varepsilon}, \mathbf{s}) \qquad (5)$$

where $\mathbf{f^r}$ is a vector non-linear function of the configuration parameters $\mathbf{q}$, the generalized errors $\boldsymbol{\varepsilon}$, and the structural parameters $\mathbf{s}$. In general, the generalized errors depend on the manipulator configuration $\mathbf{q}$ and the end-effector wrench $\mathbf{W}_e$, or $\boldsymbol{\varepsilon}(\mathbf{q}, \mathbf{W}_e)$. To predict the behavior of the manipulator in a given configuration, the task wrench is necessary to calculate the generalized errors from previous offline measurements. For simplicity, the i^{th} element of vector $\boldsymbol{\varepsilon}$ is approximated by a polynomial series expansion of the form:

$$\varepsilon_{\mathbf{i}} = \sum_{\mathbf{j}} \varepsilon_{\mathbf{i}}^{(\mathbf{j})} \cdot (q_1^{a_1^{(j)}} \cdot q_2^{a_2^{(j)}} \cdot ... \cdot q_n^{a_n^{(j)}} \cdot w_m^{b^{(j)}}) \qquad (6)$$

where q_1, q_2, ..., q_n are the manipulator joint parameters, w_m is an element of the task wrench, and $\varepsilon_i^{(j)}$ are the polynomial coefficients. It has been found that good accuracy can be obtained using only a few terms in the above expansion. The coefficients of these $\varepsilon_i^{(j)}$ terms are constants and become the unknowns of the problem.
Since the generalized errors are small, $\Delta\mathbf{X}$ can be calculated by the following linear equation in $\boldsymbol{\varepsilon}$:

$$\Delta\mathbf{X}(\mathbf{q}, \mathbf{W_e}) = \mathbf{J_e} \cdot \boldsymbol{\varepsilon} \qquad (7)$$

where $\mathbf{J}_e$ is the 6x6n Jacobian matrix of the function $\mathbf{f}^{\mathbf{r}}$ with respect to the elements of the generalized error vector $\boldsymbol{\varepsilon}$. The matrix $\mathbf{J}_e$ depends on the system configuration, geometry, and task wrench.
Once the generalized errors, $\boldsymbol{\varepsilon}$, are identified, the end-effector position and orientation error can be calculated using Equation (7). Assuming all six components of $\Delta\mathbf{X}$ can be measured, for an n^{th} degree of freedom manipulator, its 6n generalized errors $\boldsymbol{\varepsilon}$ can be calculated by fully measuring vector $\Delta\mathbf{X}$ at n different configurations. To increase the accuracy of the calculated generalized errors, additional measurements are made and a least mean square procedure is used. All repeatable errors are identified regardless of their source.
Figure 2 summarizes how an error model of the type of Equation (7) can be used in an error compensation algorithm, and how the corrected joint angles can be commanded in a Base Sensor Control scheme.

3 The Task and Experimental System

3.1 The Task

The precision control algorithms presented in this paper are being developed for a task in the nuclear power industry. In order for workers to inspect and repair a nuclear power plant's steam generator, two very large pipes (1 meter in diameter) must be sealed with a device called a nozzle dam. The center section of the nozzle dam weighs approximately 60 kg and it must be inserted into a ring with clearances of a few millimeters. In this operation, workers receive high doses of radiation. Hence, performing this task with a robotic manipulator would be very desirable. A simulated robotic nozzle dam placement can be see in Figure 3, where the manipulator is moving the nozzle dam side plate into its position in the nozzle ring. The center plate will then be inserted within the side plate.

Attempts to place the dam with a manipulator have taken too long because of the combination of poor operator visibility and lack of manipulator accuracy. It costs tens of thousands of dollars per hour to keep a nuclear power plant offline. Improving manipulator accuracy is a key to shortening this time. The typical repeatability of manipulators capable of handling the required load is in the range of 10 to 20 mm. The absolute accuracy can be several times these amounts. The automation of this task would require absolute accuracy of a few mm. In this work, the combined BSC/GEC method was experimentally evaluated for this application.

3.2 Experimental System

Figure 4 shows the experimental test-bed constructed for this study. The manipulator chosen for this system is a Schilling Titan II, a six DOF hydraulic robot capable of handling payloads in excess of 100 kg. Its position accuracy is approximately 40 mm (RMS), many times the specification of a few mm. A good part of its lack of accuracy is due to its underlying lack of repeatability. This can be traced to high seal friction in its joints. It has been found that this friction is very difficult to characterize [3, 8]. Hence, model based friction methods are difficult to apply successfully. This system is a good candidate for BSC to improve its repeatability. For this experimental system, the achievable repeatability is limited by the particular control electronics used for the experimental system. The joint resolver signals, standard on the Schilling, are converted to quadrature encoder waveforms using a special purpose Delta Tau Data/PMAC controller design. The joint angle resolution of this configuration is limited to ±0.087 degree, which leads to as much as ±5 mm errors in the end-effector positioning.

A 6-axis force/torque base sensor is mounted under the manipulator to provide wrench measurements for the BSC algorithm. A 15 kg replica of the nozzle dam center-plate was built along with an adjustable plate receptacle that permits the clearances to be varied from interference to several cm. An algorithm to successfully place the rectangular center plate within the receptacle would be easily extendable to perform the other high precision tasks necessary to complete the entire nozzle dam installation, either through teleoperation or as an autonomous subtask.

A pair of Pentax optical theodolites were used to accurately locate the end-effector in 3D space to generate the correction matrix, evaluate weight dependent deflections, and verify the algorithm performance. The resolution of the theodolites was 30 arc seconds, leading to measurement errors of 0.29 mm.

A fixed reference frame, F_0, is used to express the coordinates of all points. The origin of this reference lies at the intersection of the top of the base sensor and the joint 1 axis. Its z-axis is vertical and its x-axis is defined by a specific horizontal reference direction.

A PC based graphical user interface provides the operator with workspace visualization as well as manipulator control functionality. For all experiments, the sampling rate was ten milliseconds, which was sufficiently fast for the experiments.

4 Results

The objective of the experiment was to see if the method outlined in Figure 2 could be applied to the experimental system to improve its repeatability and its absolute

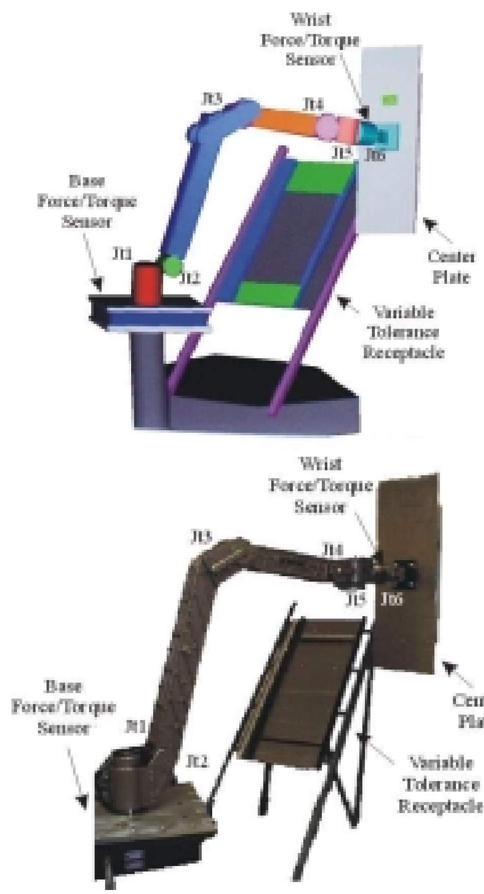

Figure 4 - Simulated and Real Experimental System

accuracy. The object was to have the residual error approach the limit set by the position sensing resolution of the system. In this work, 400 measurements were used to evaluate the basic accuracy of the Schilling. Different payloads were used, with weights up to 45 kg. Most of the measurements focused on two specific payloads: one with no weight and another with a 18 kg weight (the replica nozzle dam plate).

End-effector measurements of the manipulator under PI control determined the baseline uncompensated system repeatability and accuracy. The relative positioning root mean square error was used as a measure of the system repeatability. Recall that the 12-bit discretization of the resolver signal leads to random errors up to 5.0 mm, and imposes a lower limit of 2.0 mm (RMS) on the system repeatability, which sets the accuracy limit of any error compensation algorithm.

The results show that the BSC algorithm was able to reduce the repeatability errors by a factor of 4.73 over PI control. Data was taken by moving the manipulator an arbitrary distance from the test point and then commanding it back to its original position. Figure 5 shows the distributions of the repeatability error with and without BSC. The maximum errors without BSC were 21.0 mm, and the repeatability was 14.3 mm (RMS). BSC reduced the maximum errors to 5.5 mm with a repeatability of only 3.0 mm (RMS).

Although the BSC algorithm greatly reduced the repeatability errors, there are still 35 mm (RMS) errors in absolute accuracy. Since BSC reduced the system repeatability to 3.0 mm, a model based error correction method can be applied to reduce the accuracy errors.

In order to implement GEC, the geometric and elastic deformation correction matrix was calculated using approximately 350 measurements of the end-effector in different configurations and with different payloads. The remaining points were used to verify the efficiency of the GEC method.

From the system kinematic model with no errors, the ideal coordinates of the end-effector were calculated and subtracted from the experimentally measured values to yield the vector $\mathbf{\Delta X(q,W_e)}$ in Equation (7). By treating generalized errors as constant in their respective frames, the system absolute accuracy was improved to 13.4 mm (RMS). Since the GEC method allows for the use of polynomials to describe each generalized error, second order polynomials achieved an absolute accuracy of 7.3 mm (RMS), an additional 100% improvement.

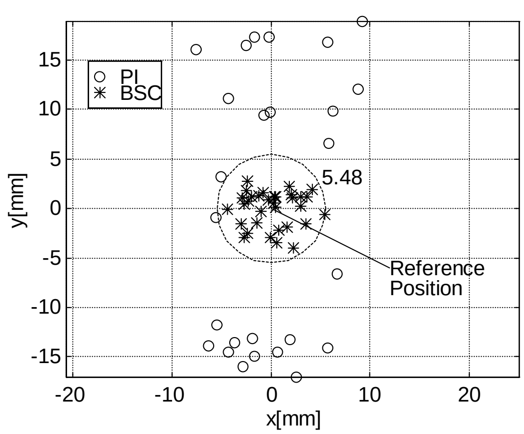

Figure 5 - Repeatability with and without BSC

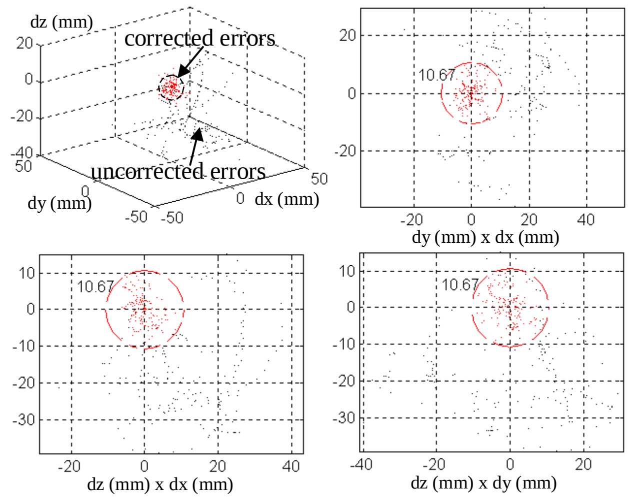

Figure 6 - Measured and Residual Errors After Compensation

Figure 6 shows the convergence of original positioning errors as large as 55.1 mm (34.3 mm RMS) to corrected errors of less than 10.7 mm (7.3 mm RMS) with respect to the base frame F_0. This demonstrates an overall factor of nearly 4.7 improvement in absolute accuracy by using the GEC algorithm.

An experiment was conducted to demonstrate the application of the joint BSC and GEC algorithm. The Schilling was commanded to a series of 11 points in the same plane under pure BSC control and then with the addition of two forms of the GEC method. The uncorrected data showed absolute accuracy errors of 29.5 mm (RMS), which are of the same order as the 34.3 mm (RMS) error found from the theodolite measurements. The implementation of GEC with constant generalized errors in their frames resulted in errors being reduced to 11.4 mm (RMS). By expanding the GEC algorithm to include second order polynomials, absolute positioning errors were reduced even further to a RMS value of 8.2 mm.

Figure 7 shows the dramatic improvement in absolute position tracking by using a polynomial GEC algorithm over the uncorrected method. Each ideal point is enclosed by a 5 mm radius circle, since the absolute position accuracy is limited by the resolution of the position sensors. The GEC algorithm also corrected for errors perpendicular to the plane of the points, and these values were measured and included in the error calculations. It can be seen that residual errors are approaching the levels of the resolver electronics. With this improvement in performance, it should make feasible such tasks as the nozzle dam insertion.

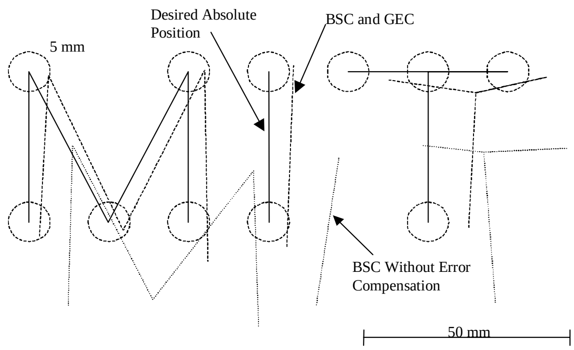

Figure 7 - Uncorrected and Corrected Accuracy

5 Conclusions

In this paper, the simplified, model-free form of Base Sensor Control (BSC) is applied to a hydraulic manipulator. The BSC uses a base force/torque sensor to accurately control joint torques, thereby compensating for joint friction. This in turn, substantially improves the manipulator's poor position repeatability. The BSC controller is then combined with a method, called GEC, that compensates for geometric and elastic errors that degrade the absolute positioning accuracy in large manipulators with inherently good repeatability. The results showed that applying the combined error compensation algorithm improved the absolute accuracy of the manipulator by a factor of 4.7 over pure BSC.

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