Error Modeling for Automated Construction Equipment

by

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ABSTRACT: This paper introduces the statistical error modeling approach for a computer-controlled large-scale manipulator (LSM). The LSM is sufficiently representative of several types of construction equipment to be able to serve as a general test bed. In the analysis, three factors which are measurable in real time: distance, hydraulic pressure, and payload, were varied to determine their influence on position errors in the LSM. It was shown that with an integrated multi-variable regression model, about 30% of the mean positioning error of the LSM can be reduced without the mid of fixed external reference systems.

KEYWORDS: automation; kinematics; manipulator; position error; regression analysis

1. INTRODUCTION

Hydraulically actuated construction equipment is rapidly being retrofitted with robotic control capabilities by several major manufacturers such as dozers, graders, and excavators equipped with various position sensors reflects a movement in the construction industry towards improving productivity, efficiency, and safety [6].

The reduction of the cumulative position error caused by backlash, deflection, sensor error and other factors, however, still remains as one of the key issues in operating autonomous or semi-autonomous construction equipment. Further, large scale construction equipment, particularly the ones actuated hydraulically, possess lower end-point positioning accuracy than electrically actuated robotic devices used in controlled environments.

Understanding the causes and propagation of errors in automated construction equipment is very important for precise operation in a field environment. Large manipulators such as forklifts, excavators, and the LSM pose particularly difficult equipment control problems. Much of the manipulator error is due to accumulated feedback errors of the rotary and prismatic joint sensors, and lost motion due to backlash. Working conditions such as variations in hydraulic pressure supply and presence of large payloads influence the error attributes as well. Kinematic and dynamic states are also an influence.

Most errors arising from the operation of the manipulator are considered random errors which are unavoidable and are usually reduced through stochastic experimentation [1]. Even if it is theoretically possible to derive a mechanistic mode of all sources and their interdependence, it is computationally untenable for real time manipulator control, and sensor requirements for independent input variables are currently unfeasible in a construction environment. Position error of an economically sensor equipped manipulator can be reduced by providing the correction factors resulting from a statistical analysis of on-hand samples. The results can be organized into statistical equations with correction factors for real-time equipment feedback control, much like those used for artillery fire control.

2. OBJECTIVE AND METHODOLOGY

The main objective of the research presented here is to improve automated manipulator positioning capability based on regression modeling of

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manipulator position errors and working conditions.

The methodology pursued includes the following basic steps:

1) Select a set of well distributed known positions in a manipulator's working space,
2) Command a robotically controlled manipulator's end-point to the selected positions,
3) Measure actual positions of the resulting end-point, and calculating position errors,
4) Repeat the above steps for varied working conditions as defined by the following causal factors: distance, hydraulic pressure, and payload,
5) Analyze the results with the regression modeling method, and
6) Develop an algorithm based on the regression modeling and apply the algorithm to adjust the commanded positions to reduce errors.

3. KINEMATICS

Inverse and forward kinematics equations, computer algorithms, feedback encoders, control interfaces were implemented from the previous research efforts for the various control strategies for the LSM [4]. An illustration of the large scale manipulator is shown in Fig. 1. As seen in the figure, the LSM has swing, lift, telescope, rotate, roll, and pivot joints in total 6 degrees of freedom (DOF).

The LSM control system calculates a series of joint angles through which to move the joints in order for the end-effector frame to move from its initial location to its final location. Then, the link transformations can be multiplied together to find the single transformation that relates a frame to another frame. As with vectors and rotation matrices, a symbol T is called a transformation operator [3]. Here, ${}^{Base}_{Pivot}T$ describes Pivot frame relative to Base frame and forms the following transform equation:

$$ {}^{Base}_{Pivot}T = {}^{Base}_{Swing}T \; {}^{Swing}_{Lift}T \; {}^{Lift}_{Tele}T \; {}^{Tele}_{Rotate}T \; {}^{Rotate}_{Roll}T \; {}^{Roll}_{Pivot}T $$

Each joint angle can be computed from the transform equation.

4. ACCURACY TESTS

Accuracy may be defined as the magnitude of the difference between the desired value and actual value of a measurement. In this study, accuracy is measured relative to the manipulator's base coordinate system (see Fig. 2).

4.1 Sample Regression Analysis

There are many existing random error sources affecting the final position of the manipulator's end-effector. Thus, in this study, to predict and to adjust for the position errors from the uncertain random error sources, the sample regression modeling method was selected to determine whether or not a relationship exists between error variables and to predict the nature of the relationship of correlated random variables.

To ensure a consistent test process, six different kinematic states of the LSM were chosen as known target positions (Table 1). They were chosen to represent the full range of configuration that was anticipated to affect the various random error sources under the different conditions of the chosen three independent variables: distance, hydraulic pressure, and payload.

4.1.1 Accuracy with respect to Distance

Errors with respect to the distance variable were analyzed under several different conditions: five different payloads and five different hydraulic pressures in the six fixed positions.

In this study, the distance is defined as the Cartesian positional difference between a base point (0,0,0) of the LSM's test bed and the kinematically calculated position (x, y, z) of the end-effector.

The accuracy test result for individual axial accuracies with signed values were tested by distances ranging from 0 to 4.5 m. The desired position was calculated from the kinematics equations, and the actual position was manually measured. Then, the actual positions of the end-effector were compared to the kinematically calculated positions. Then the directional (axial) error attributes with respect to the distance variable were analyzed with collected sample data (see Table 2). Here, n indicates the sample size (5 pressures × 6 positions + 5 payloads × 6 positions = 60 samples).

While distance increased, as results, the directional errors in the Z axis increased, which relates to or is explained by the fact that angular joint error increases with respect to distance. Correlation analysis might be useful to determine the deflection in z coordinates according to the directional distance in X and Y axes ($\sqrt{(x^2 + y^2)}$) which describes how far the arm is cantilevered out.

4.1.2 Accuracy with respect to Hydraulic Pressure

The current LSM's hydraulic system configuration is a single power source that feeds a parallel network of actuators, with a single branch for each joint. The computer control signal determines the strength of the current to the valve solenoids and thus the opening of the control valve. This determines the flow rate of fluid into the actuator. According to the LSM payload and location in workspace, the control signal strength changes and thus the flow rate. To keep the joint moving at a steady speed under an increasing load, the valve opening increases as the load increases. This can be done by the pressure compensation valve. So even with an increasing load, the LSM's pressure compensation valve keeps the actuator velocity steady [5].

Even with the advanced hydraulic flow control system, the LSM still exhibits more stiction, slop, and backlash in the joints and hydraulic actuators than conventional industrial robots which are small, fast, electrically actuated. Besides, the LSM can be manufactured to lower tolerances than can be the industrial robots. Thus, as another variable, hydraulic oil pressure was selected to be examined in order to find the error attributes of the LSM. Due to maintenance concerns, hydraulic pressure was limited to a maximum of 10345 kPa (1500 psi).

LSM Table 3 shows the directional error attributes with respect to the hydraulic pressure. All the linear regression equations indicate the error decreases toward zero while the hydraulic pressure increases.

Similar to the previous accuracy test toward distance, hydraulic pressure showed some relationship with the directional error in the Z axis. The directional error in the Z axis decreased while hydraulic pressure increased. The increased hydraulic strength increases the joint speed, which might ultimately reduce the error caused from stiction and load. In a sense, the system is stiffer as well.

4.1.3 Accuracy with respect to Payload

As another variable, payload was examined in order to find the error attributes of the LSM. Payload affects the inertia and speed of the manipulator, which can yield an overshoot error and more deflection. Four different pipes were used for this test. The weight of the pipes ranged from 40 kg to 386 kg.

To ensure a consistent test process, the experiment was performed under 8276 kPa (1200 psi) of hydraulic pressure. Each pipe was lifted into the chosen kinematic states of the LSM. Fig. 3 shows one of the chosen kinematic states.

The directional (axial) error attributes with respect to the payload variable were analyzed and summarized in Table 4.

The coefficient of determination r^2 for the X axis (0.507) and the Z axis (0.531) indicate that the payload significantly affects the accuracy of the X axis and the Z axis. It is clear that payload accentuates the deflection which explains the increased error in Z coordinates. In addition, payload makes the LSM move sluggish which might cause in more errors toward the X axis which has a 4.5 m range than toward the Y axis which has 2.2 m range. Payload makes the lifting and telescoping motions more sluggish, which might ultimately cause some systematic relationship with errors in x and z coordinates. Also, x and z coordinates relate to degree of cantilever and therefore deflection.

Although there was almost no relationship between payload and the directional error in the Y axis, the systematically increased conditional variance of accuracy in the Y axis might be caused from erratically applied error sources such as stiction and overshoot to the swing joint.

4.2 Error Adjustment with Multi-variable Regression Models

The multi-variable regression analysis of the LSM's position with respect to distance, hydraulic oil pressure, and payload was modeled to adjust the error of each axis of the end-effector as follows:

$\Delta X=-1.229+0.182D_{istance} + 0.0000528P_{ressure} - 0.00264\,P_{ayload}$, ($r^2=0.262$)

$\Delta Y=0.627-0.1D_{istance} - 0.000018P_{ressure} + 0.0000988P_{ayload}$, ($r^2=0.028$)

$\Delta Z= -0.884 - 0.141\,D_{istance} + 0.0001075\,P_{ressure} - 0.00397\,P_{ayload}$, ($r^2=0.483$)

Here, ΔX, ΔY, and ΔZ indicate the regression of the multi-variable model on the LSM's axial position error

By applying the three multi-variable equations to the same data set obtained from the LSM's position accuracy test, given the three conditional variables, there were some error reductions (30.7%) in the overall accuracy shown in Table 5. In a theory, the substantial number of the unsolved errors (69.3%) may be statistically solved by adding more conditional variables.

While the average errors of the X axis and the Z axis were reduced by 18.88% and 50.55% respectively, the average error of the Y axis somewhat increased by using the multi-variable equations. This means that the multi-variable equation (ΔY) does not explain the Y axis errors very well. Also, it can be inferred from the equation in which r^2 is 0.028, that the multiple variables have little effect on the Y axis accuracy. Therefore, while adjusting the X and Z axis values based on Equation ΔX and Equation ΔZ, the kinematically calculated original Y axis value was not adjusted.

4.3 Final Performance Test

The obtained three equations were then applied to the original forward kinematics equations to adjust for the original x-y-z coordinates. Then, the inverse kinematics provides adjusted six joints angles based on the adjusted position data. To verify the error attributes found from the error modeling tests, several material placement tests were conducted on the LSM's test bed. This paper introduces one of the tests here.

A stylus was attached to the test load (386 kg) in the LSM's jaws pointing toward a target (see Fig.4). By using a developed laser rangefinder system and string encoders [2], a Cartesian coordinates of a center of cross hairs on a target plane was measured (325.63cm, 10.77cm, 77.09cm). The purpose of this test was to compare the LSM's accuracy when its error was adjusted and unadjusted under a certain working condition (with 3.348m distance, a 386 kg test load, and a 8276 kPa (1200 psi) hydraulic pressure supply). A test result shows that the LSM has better accuracy when a commanded position was modified based on the developed error modeling as follows:

a) Error without adjustment: 4.29 cm
b) Error with adjustment: 1.97 cm

Here, the errors were measured by the distance between the center of the cross hairs and the end of the stylus.

5. CONCLUSION

The error attributes of a hydraulically actuated large scale manipulator were analyzed by using regression analysis. In the regression analysis, three variables, distance, hydraulic pressure, and payload, were individually varied to find the position error attributes of the LSM. Distance had a somewhat significant effect on the directional error in the Z axis (as distance increased, random errors in the Z axis increased). Hydraulic pressure and payload had significant effect on the overall error (as hydraulic pressure decreased and payload increased, random error increased). Although, the testing was performed in a small working volume due to the limited mobility of the LSM on its fixed frame, this study reduced about 30% of the average positioning errors of the LSM with an integrated multi-variable regression model. Thus, it is sufficient to indicate whether a descriptive model or a regression model is feasible. The substantial number of the unsolved errors (about 70%) may be statistically solved by adding more conditional variables which possibly affect the manipulator’s position errors.

6. REFERENCES

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Table 1. Chosen Kinematic States

Kinematic States					Calculated Global Position of End-effector (cm)		
Swing (°)		Lift (°)	Telescope (cm)	Rotate (°)	X	Y	Z
(1)	-20	11	0	20	157.9992	-54.0685	73.5178
(2)	5	50	30.48	0	364.4036	31.8821	186.7875
(3)	-10	36	60.96	0	321.0855	-56.6166	95.7560
(4)	-2	31	16.76	-10	276.6731	-11.3020	112.2213
(5)	10	21	0	0	216.2586	38.1335	95.5121
(6)	0	54	48.77	0	393.9296	0	197.3946

(The values of Roll and Pivot joints are 0°)

Table 2. Directional (Axial) Error Attributes with respect to Distance

Axis	Regression Model	n	r^2
X	$\Delta x = -0.962+0.180\ D_{istance}$	60	0.059
Y	$\Delta y=0.493-0.1\ D_{istance}$	60	0.026
Z	$\Delta z=0.0318-0.2411\ D_{istance}$	60	0.122

Table 3. Directional (Axial) Error Attributes with respect to the Hydraulic Pressure

Axis	Regression Model	n	r^2
X	$\Delta x=-0.58+0.00001412\ P_{ressure}$	30	0.003
Y	$\Delta y=0.549-0.000043\ P_{ressure}$	30	0.033
Z	$\Delta z=-1.29+0.00008942\ P_{ressure}$	30	0.178

Table 4. Directional (Axial) Error Attributes with respect to the Payload

Axis	Regression Model	n	r^2
X	$\Delta x=0.151-0.00397\ P_{ayload}$	30	0.507
Y	$\Delta y=0.124+0.0002431\ P_{ayload}$	30	0.003
Z	$\Delta z=-0.267-0.00459\ P_{ayload}$	30	0.531

Table 5. Axial Error Adjustment for Test Data Set

Average Accuracy	X	Y	Z	Total Accuracy
Before Adjusted (cm)	0.5731	0.3859	0.7309	1.1717
After Adjusted (cm)	0.4649	0.4009	0.3614	0.8115
% Reduced	18.88	-3.66	50.55	30.74

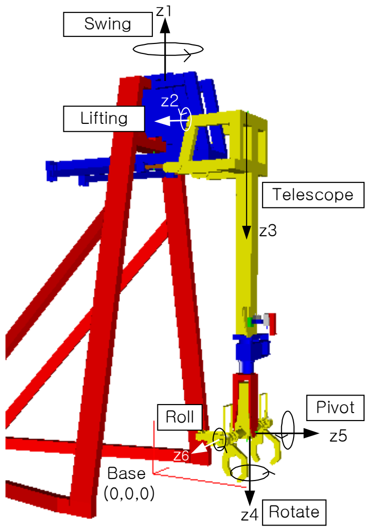

Fig. 1. 6 DOF Kinematic Configuration for the LSM

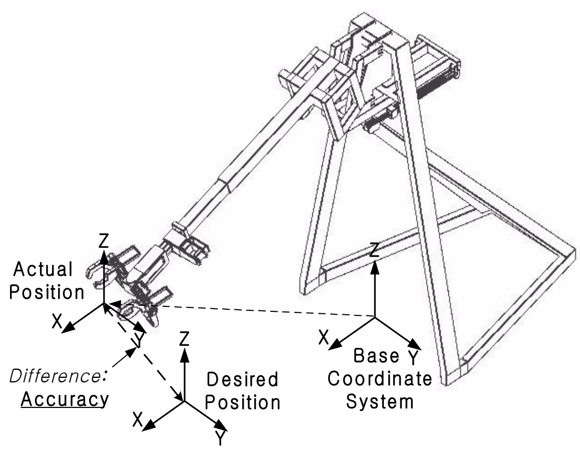

Fig.2. Illustration of the Accuracy Method relative to the Base Coordinate System

Fig. 3. One of the chosen Kinematic States

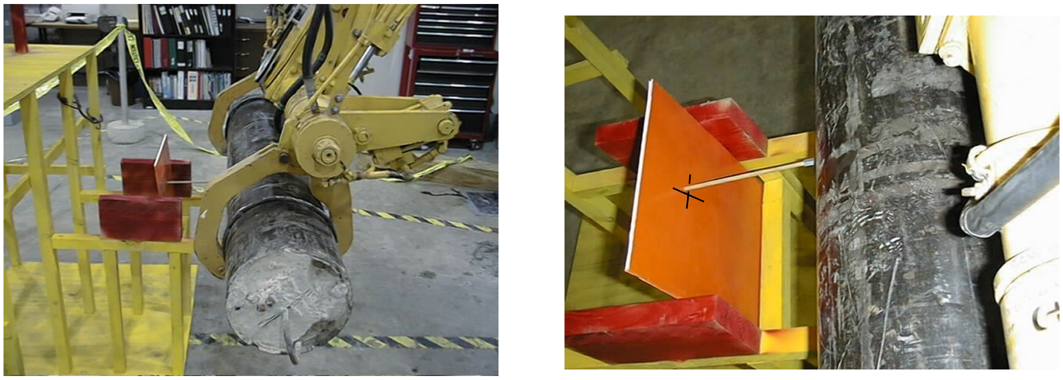

Fig. 4. The Accuracy Test was conducted with a Stylus and a Test Load