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High Accuracy Articulated Robots with CNC Control Systems

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ABSTRACT

A robotic arm manipulator is often an appealing method to position drills, bolt inserters, automated fiber placement heads, or other end effectors. In a standard robot the flexibility of the cantilevered arm as well as backlash in the drive system lead to large positioning errors. Previous work has greatly reduced this error through the use of secondary scales and a mathematical model of the robot deflection running on a CNC controller. Further research improved upon this model by accounting for linear deformation of each robot link regardless of position. The parameters describing these deformations are determined through a calibration routine and then used in real time to guide the end effector accurately to any reachable pose. In practice this method has been used to achieve total on-part positioning accuracy of better than +/- 0.25mm.

INTRODUCTION

Production implementations of articulated arm robots in the aerospace industry have been active for many years with varying degrees of success. Interest in them derives from their successful implementation in automotive manufacturing. Robots offer airframe manufacturers benefits in both cost and application flexibility. In lieu of traditional pick and place operations, robots are used as static positioners for drilling and fastening, and as dynamic positioners for milling, inspection, composite fiber placement, and so on.

Manufacturers commonly give 1/3rd of the overall assembly tolerance to the automation, and for the vast majority of applications that number is +/-0.25mm. Existing technologies are available for global accuracy improvement to this level. These include real-time guidance via metrology, directly teaching positions, etc. However, these methods either hinder offline programming capability or the automation system must include expensive, sensitive equipment that tend to restrict the working range.

Many robot systems rely on local accuracy which is generally possible even with a marginally-accurate system. Vision systems sync on a group of datum features and within the small volume of the group (e.g. 300 x 300 x 100 mm) the robot can maintain reasonable accuracy. This assumes the orientation of the end of arm (EOA) tooling is not significantly changed, the datum features are accurately placed, and the synchronization system is sufficiently accurate. Though this method is successful, it relies on features that must be placed accurately by some other means and in some cases may not exist. Therefore the ideal solution is one that remains accurate over a large volume with potentially large orientation change.

Electroimpact's *Accurate* Robot technology is built upon the use of an off-the-shelf conventional articulated robot motion platform supplied by KUKA Robotics. To this, secondary feedback on each robot joint is added and the complete system (robot, external axes, EOA, etc.) is controlled using a Siemens 840Dsl CNC. The CNC positions the robot using the external feedback which provides superior repeatability. With descriptive kinematics, the robotic motion platform can provide positioning accuracy on par with machine tools. The kinematic model dictates the theoretical position of the tool center point (TCP) based on, in simplified form, the position of each robot axis. On-part positional accuracy is a function of off-part precision and the ability for the system to counteract external forces. Recent development has been focused on off-part system calibration by the identification of error sources.

ACCURATE ROBOT

To achieve high accuracy with any positioning system it must be repeatable. For a robot, the secondary encoders added to each axis output have reduced error from backlash to a negligible amount. Eliminating uncertainty in axis position allows the possibility to predict the TCP to very high precision if all factors that influence the TCP are known.

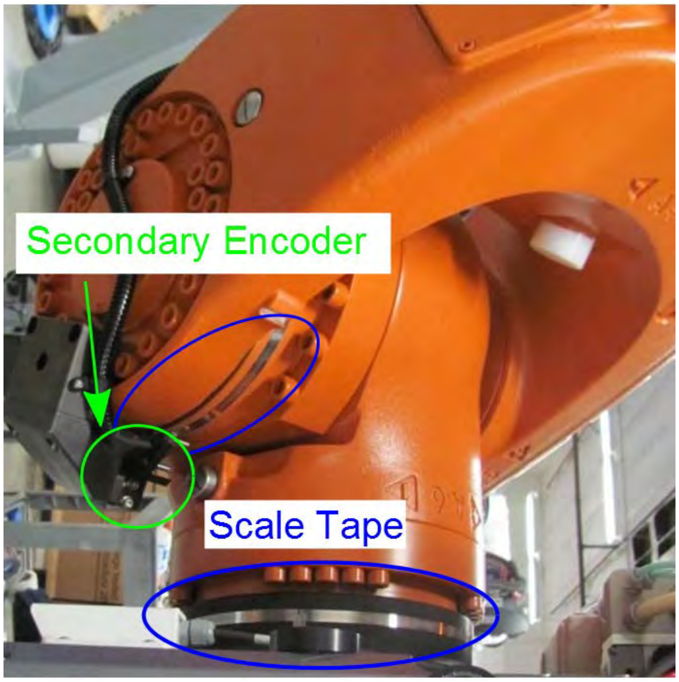

Figure 1: Secondary Encoders

MANIPULATOR ERROR

The following outlines a method of compensation which accounts for geometric offsets and counteracts deformation from the weight of the robot and weight of the payload. In practice this method has been able to position a large serial link robotic arm with ~200kg end effector within 0.15mm (3-sigma error) over a volume of 2m × 3m × 3m.

Error Associated with a Rigid Link

Every link of a robot manipulator can be described by 6 parameters that define a transformation between the two connection points of the link:

$$\langle x, y, z \rangle \text{ positional offsets}$$
$$\langle \alpha, \beta, \gamma \rangle \text{ rotational offsets}$$
$$A = \langle x, y, z, \alpha, \beta, \gamma \rangle$$

Each of these terms has nominal value and an offset error:

$$\text{Nominal: } A = \langle \tilde{x}, \tilde{y}, \tilde{z}, \tilde{\alpha}, \tilde{\beta}, \tilde{\gamma} \rangle$$
$$\text{Error: } \Delta A = \langle \Delta x, \Delta y, \Delta z, \Delta\alpha, \Delta\beta, \Delta\gamma \rangle$$

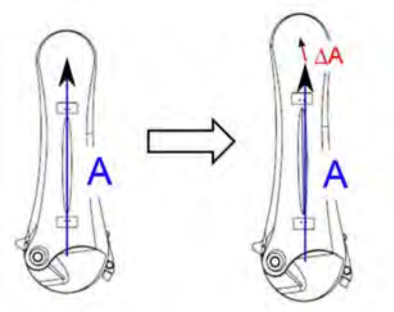

Figure 2: Offset from Nominal

In a rigid link there is exactly one free parameter, θ, allowing motion. In all cases examined here θ is a pure rotation, though in general a translational component is also possible. In the simplest case the measurement of theta is exactly the motion of the link offset, however in the general case the offset is Θ(θ). Thus the equation for the final transformation is:

$$A_{Rigid}(\theta) = A + \Delta A + \Theta(\theta)$$

As an example, in the specific case of rotation about γ the parameters are defined as:

$$x = \tilde{x} + \Delta x;\ y = \tilde{y} + \Delta y,\ \ldots\ \gamma = \theta + (\tilde{\gamma} + \Delta\gamma)$$

Additional Error Associated with a Flexible Link

One of the added challenges of a serial link robotic manipulator over a conventional linear machine is the links of a robotic manipulator are both flexible and experience a large range of forces and torques dependent on position:

$$f = \langle f_x, f_y, f_z \rangle$$
$$\tau = \langle \tau_\alpha, \tau_\beta, \tau_\gamma \rangle$$
$$F = \langle f_x, f_y, f_z, \tau_\alpha, \tau_\beta, \tau_\gamma \rangle$$

These forces and torques cause an additional deflection d(F). In the generalized link geometry, for small deformations there is a linear relationship between each element of force or torque and each element of positional or rotational offsets. Defining J_d as the Jacobian of d(F) with respect to F:

$$d(F) = J_d * F$$

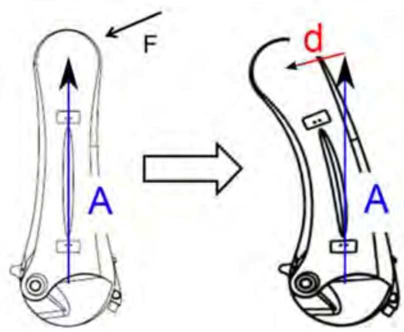

Figure 3: Deformation due to a force

While this error depends on force, it is otherwise independent of the robot position. Adding this error, the equation for the transformation of a non-rigid link becomes:

$$A(\theta, F) = A + \Delta A + \Theta(\theta) + J_d * F$$

F for any link and robot position can be computed as the sum of weights and torques applied from the other links, $F(X_1, X_2, X_3, ...)$, however since the deformations are small the equations can be written in closed form as $F_{approx}(\theta_1, \theta_2, \theta_3, ...)$. Thus the full transformation for the link is:

$$A \approx A(\theta_1, \theta_2, \theta_3, ...) = \underline{A + \Delta A + \Theta(\theta) + J_d * F_{approx}}$$

Modeling the Full Robot

A typical robotic manipulator is made of multiple serial flexible links. The transformation through multiple links is generated by successively applying the transform through each link. Common methods for storing and applying these transforms use either homogeneous matrices or dual quaternions. Using this model, a function is created for TCP position as a function of the joint angles.

$$P_{TCP} = A_1 * A_2 * A_3 * ... * A_N$$

For each link the nominal transform is known, and ΔA, J_d, and $\Theta(\theta)$ are determined from a calibration routine. Though the secondary measuring system is intended to measure θ directly, the function $\Theta(\theta)$ includes terms to account for non-concentric measuring system and link axes.

One or more laser tracker spherically-mounted retro-reflectors (SMRs) are mounted on the end-effector enabling a laser tracker to measure the position of the points with a margin of error of approximately 0.05mm. A large set of axis positions are generated that present the robot in a pose that lies inside a chosen working volume. For each robot pose, nominal coordinates for each SMR is generated assuming ΔA and J_d are zero. The robot is driven to each pose and the position is measured with the laser tracker. Using a least squares non-linear iterative solver the parameters used to describe ΔA, J_d and $\Theta(\theta)$ for each link are determined to minimize the absolute error. These solved parameters, along with the nominal parameters, ultimately form the kinematic description of the robot. The forward and inverse kinematics are executed in real-time using the CNC, correcting for any predicted error.

Progression of Calibration and Accuracy

Full development of the *Accurate* Robot commenced in 2008. Since then, there have been notable iterations – each presenting solutions to prior limitations.

Initial Development System

The prototype *Accurate* Robot was built upon a KUKA KR360-2 robot. The robot was fitted with magnetic tape scales on the output of each axis and the controls were exchanged with a Siemens 840Dsl CNC to enable direct use of the added scale feedback. Early calibrations utilized a single SMR located at the TCP for data collection. Testing showed that in practice the EOA orientation accuracy was relatively poor, and for systems utilizing multiple TCPs, the model was not acceptable.

To improve on the accuracy of orientation, two additional SMRs were added to the EOA for data collection to provide a 6 degree of freedom (DOF) position measurement. 50 randomly generated robot poses were used to solve for the selected kinematic parameters. The working volume (~1.5m x 1.5m x 0.5m) and axis ranges were limited - not allowing for large orientation variability, and poses were used that mimicked a general drilling application. Applying an abbreviated variation of the model described resulted in a solved accuracy of +/-0.25mm. In practice, the validity of the model was limited to positions well inside the calibrated volume and the validated accuracy was found to be worse than the solved accuracy. It did, however, provide a good starting point with high optimism for improvement.

Initial Production Implementation

A number of items were revisited for the production variant of the *Accurate* Robot in order to bring the true working accuracy down to a comfortable level below +/-0.25mm.

The secondary feedback encoder resolution was increased 50x, going from a 1mm signal period to 0.02mm (not including interpolation). To bring the functional accuracy in line with the solved accuracy, more data was needed for calibration. The number of robot poses used was increased from 50 to 200. Flexible link terms were included for major structures, such as the robot base, and the first and second main links. An empirical minimization process was performed to reduce the number of flexibility terms to eight.

Results showed significant improvement in accuracy and an increase in the calibrated volume. In a 2m x 2m x 1m volume, the 3-sigma accuracy ranged from +/-0.1mm to +/-0.2mm, including significant EOA orientation change (+/-90 degrees). Orientation accuracy was sufficient yielding a combined accuracy of +/-0.2mm using two TCP locations 150mm apart.

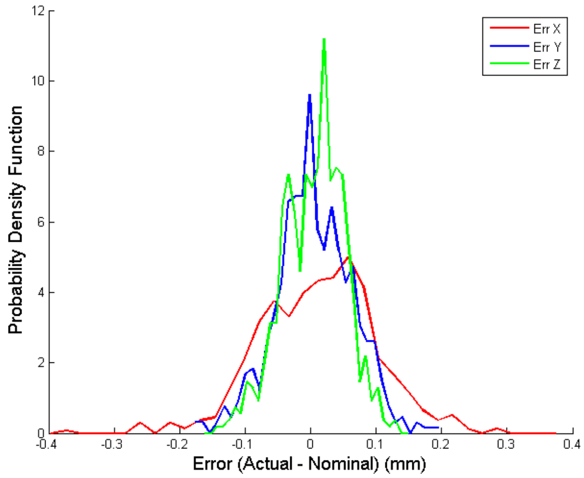

Figure 4:
Error After Calibration
Of Initial Implementation

Latest Production Implementation

The latest implementation of the *Accurate* Robot utilizes absolute secondary position feedback which was previously not compatible with the CNC. Though no improvement in accuracy was noted due to these encoders, the ease of setup and reliability due to generous alignment tolerances and the elimination of axis position referencing have proven to be a significant upgrade.

With 600 points in the calibration data set, it was desirable to minimize the duration of data collection to limit affects from temperature change and degradation in laser tracker accuracy. As a result, the laser tracker was integrated with the CNC which minimized delay between measurement completion and robot motion execution. Collection of 600 points in 200 robot poses was reduced to 2-3 hours.

Continued testing and development indicated the kinematic model remained sensitive to the selected working volume and calibrated axis ranges. It was determined that some of the geometric error terms were artificially compensating for what were actually errors due to link flexibility. This led to the development of a more accurate flexibility model, and a reduction in usage of non-linear geometric terms. Flexibility was shown to be significant in areas that were initially assumed very rigid. With a higher dependence on modeling the robot's flexibility, the latest implementation has proven to be far less sensitive to the working volume. Joints can be fully exercised. In practice, this method has been shown to provide an off-part accuracy of +/-0.13mm to +/-0.18mm in a 3m x 3m x 2m volume with no restriction on EOA orientation.

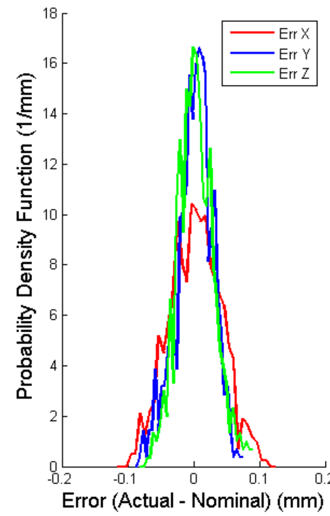

Figure 6:
Error After Calibration
Of Latest Implementation

Additional Axes and Other Sources of Error

To increase the working volume of robotic positioning systems, the robot is often mounted to external axes. In most cases, external axes are linear, though rotary positioners are possible. To maintain acceptable accuracy, these external axes must be calibrated.

Figure 7: A Robotic Arm Mounted
On a Linear Axis

Using a single linear axis as an example, the robot is mounted to a servo-controlled sled. Misalignment of guide rails, deflection of the bedway, gear/rack error, and so on, contribute directly to error at the EOA. In many cases, the error is magnified. For short axes, a continuous function for the error can be valid, where:

$$\Delta A(x) = < \Delta x(x), \Delta y(x), \Delta z(x), \Delta\alpha(x), \Delta\beta(x), \Delta\gamma(x) >$$

However, longer axes may exhibit discontinuous error or contain local anomalies. Modeling of external axes is included in the forward kinematic chain:

$$P_{TCPwithExAx} = A_{ExAx} * \Delta A_{ExAx} * A1 * A2 * A3 * ... * AN$$

Other sources of error can still exist depending upon the installation site and machine configuration, however many are difficult to predict or potentially require a network of sensors to detect. These can include foundation stability, external forces from tugging or dragging cable management systems, significant temperature variation, and so on.

CONCLUSION

The robotic arm is an appealing method to position process heads used for aerospace assembly tasks. Without calibration, large positioning errors are typical using a standard robot due to the flexibility of the links and backlash in the drive system. Global accuracy is ideal without external metrology sources. Previous work has greatly reduced positioning error through the use of secondary scales and a mathematical model of the robot deflection. Further research has improved accuracy and decreased the need to limit the robot's working volume by accounting for linear deformation of robot links regardless of robot position. These parameters are determined through a calibration routine and utilized in real-time as the forward kinematic model in the CNC controller. In practice, this method has been shown to provide an off-part accuracy of +/- 0.13mm to +/-0.18mm in a 3m x 3m x 2m volume with no restriction on EOA orientation.

REFERENCES

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DEFINITIONS/ABBREVIATIONS

TCP	tool center point
EOA	end of arm