

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 $\pm 0.25\text{mm}$.

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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 $\pm 0.25\text{mm}$. 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. $300 \times 300 \times 100\text{ mm}$) 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.

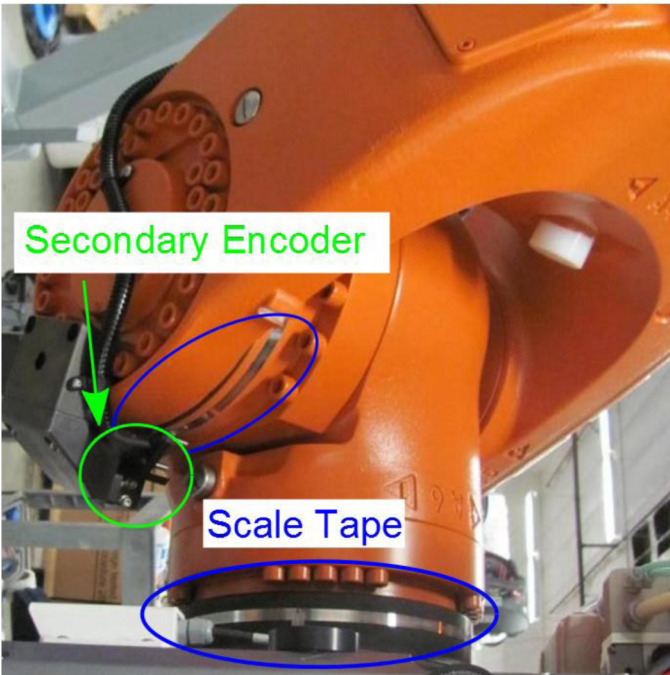


Figure 1. Secondary Encoders

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:

$$\begin{aligned} < x, y, z > \text{positional offsets} \\ < \alpha, \beta, \gamma > \text{rotational offsets} \\ A = < x, y, z, \alpha, \beta, \gamma > \end{aligned}$$

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

$$\begin{aligned} \text{Nominal: } A &= < \tilde{x}, \tilde{y}, \tilde{z}, \tilde{\alpha}, \tilde{\beta}, \tilde{\gamma} > \\ \text{Error: } \Delta A &= < \Delta x, \Delta y, \Delta z, \Delta \alpha, \Delta \beta, \Delta \gamma > \end{aligned}$$

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 $\Theta(\theta)$. Thus the equation for the final transformation is:

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

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

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

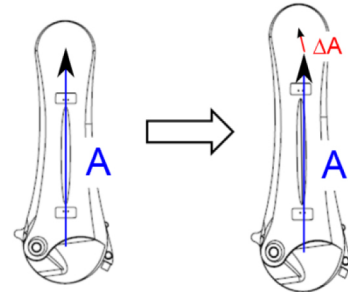


Figure 2. Offset from Nominal

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:

$$\begin{aligned} f &= < f_x, f_y, f_z > \\ \tau &= < \tau_\alpha, \tau_\beta, \tau_\gamma > \\ F &= < f_x, f_y, f_z, \tau_\alpha, \tau_\beta, \tau_\gamma > \end{aligned}$$

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 :

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

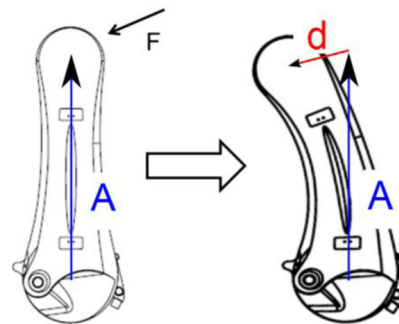


Figure 3. Deformation due to a force

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.