High-Accuracy Articulated Mobile Robots

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Abstract

The advent of accuracy improvement methods in robotic arm manipulators have allowed these systems to penetrate applications previously reserved for larger, robustly supported machine architectures. A benefit of the relative reduced size of serial-link robotic systems is the potential for their mobilization throughout a manufacturing environment. However, the mobility of a system offers unique challenges in maintaining the high-accuracy requirement of many applications, particularly in aerospace manufacturing. Discussed herein are several aspects of mechanical design, control, and accuracy calibration required to retain accurate motion over large volumes when utilizing mobile articulated robotic systems. A number of mobile robot system architectures and their measured static accuracy performance are provided in support of the particular methods discussed.

Introduction

Articulated robotic arms have seen increased usage in high-accuracy industrial applications as performance levels increase. In particular, aerospace manufacturing techniques have begun to utilize robotic arm systems to perform tasks previously reserved for larger automation platforms due to the potential benefits of reduced cost, minimized permanent infrastructure, and added manufacturing flexibility. The size and packaging benefits provided by robotic arms have also allowed these systems to become mobile in some circumstances. Mobile robotic systems increase flexibility in the manufacturing environment and can facilitate automation in low-rate production environments where an automation system can work on multiple parts in different areas of a factory.

It is necessary in mobile robot applications that accuracy performance not be adversely affected by the system's mobility. Previous work in increased accuracy performance of articulated robot platforms have shown accuracies of ±0.18 mm over a 3m × 3m × 2m volume to be achievable [1]. This is accomplished through the high-order kinematic modeling of error sources and through increased repeatability and stiffness performance provided by secondary feedback methods [2]. Work discussed in this paper addresses particular aspects of maintaining a similar level of accuracy performance in mobile robotic systems.

A variety of mobile robot architectures implemented in manufacturing endeavors are discussed; specifically, challenges associated with the mechanical design, control, and calibration of the systems as these aspects pertain to accuracy performance. The positional accuracy of these systems, measured using a laser tracker, is offered as evidence of the effectiveness of these techniques. The core of all the robotic systems discussed is that of the patented Electroimpact Accurate Robot technology. This consists of a KUKA Robotics-manufactured articulated robot fitted with secondary feedback devices on each robot joint and controlled by a Siemens 840Dsl CNC. All articulated robots discussed consist of six rotary axes, although the principles discussed can be applied to any mobile serial link manipulator.

Articulated Robot Accuracy

Detailed discussion of articulated robot accuracy, calibration methods, and error source modeling to improve large volume accuracy of unguided robots can be found in previous works [1, 3]. In brevity, error sources in articulated robots are discussed here for clarity.

Two of the main sources of robotic manipulator positional error are errors associated with a rigid link, here referred to as kinematic errors, and errors associated with the flexibility of the system. Kinematic errors are the result of deviations in the nominal kinematics of a robot due to manufacturing imperfections and inaccuracy of feedback devices. Flexibility errors are associated with the deflection of links and the base of the robot due to the varying loading conditions system components are subjected to during operation.

For this paper, accuracy performance of a robot is calculated as the vector magnitude deviation from commanded position to actual position of the robot tool point measured using a laser tracker and spherically-mounted retro-reflector (SMR). Vector-magnitude error deviation is the ANSI/RIA standard method of quantifying static performance of robotic systems [4], where each measured tool point location's error deviation (d_i) is calculated as follows:

$$d_i = \sqrt{(X_{ai} - X_{ci})^2 + (Y_{ai} - Y_{ci})^2 + (Z_{ai} - Z_{ci})^2}$$

where X_{ai}, Y_{ai}, Z_{ai} are the Cartesian coordinates of the measured position and X_{ci}, Y_{ci}, Z_{ci} are the commanded coordinates.

Only static positioning accuracy is addressed. Measurement uncertainty of laser tracker and SMR is approximately 0.05mm.

Mobile Robot Accuracy

Outlined here is a discussion of certain facets of mechanical design, control, and calibration pertinent to mobile articulated robots. The automation task typically dictates the mechanical architecture of the system and each architecture comes with unique challenges in maintaining accuracy. As such, several system architectures that are currently utilized in industrial mobile robot applications are provided to facilitate discussion.

Mobile Articulated Robot

The first and simplest mobile articulated robot architecture is that of a six degree of freedom (DOF) robot arm attached to a mobile platform that enables movement through a factory. The platform provides a mounting structure for the robot as well as space for any supplementary systems. Mobility can be achieved by a number of methods. Here, pneumatically actuated casters and air skids provide an efficient means of maneuvering robot and platform.

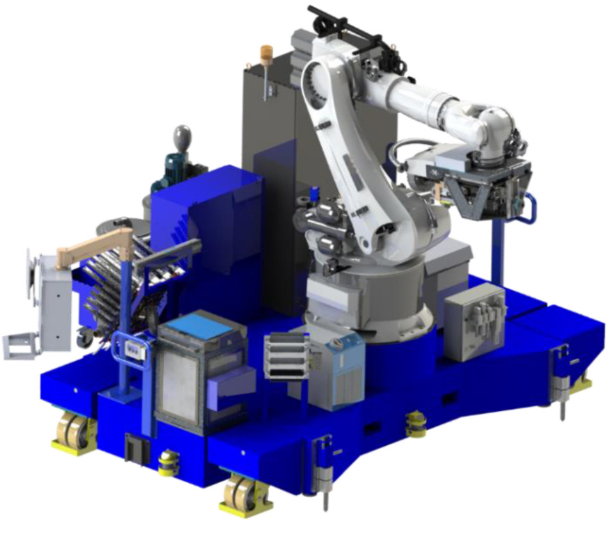

Figure 1. Example Electroimpact mobile platform robot.

Of primary consideration in robot accuracy is the repeatability of the system. Inherently, any accuracy enhancing calibration methods of a system are limited by the repeatability of the system. With a mobile platform, it is possible that the floor interface on which the platform will rest may not be repeatable or precisely controllable from work station to work station. This commonly happens when factory floors are not flush. Differing floor interfaces can cause the mobile platform loading and consequently the robot mounting's stiffness to change at different locations. To overcome this, a three-point-load floor-to-platform interface is utilized. The combination of three contact points and a spherical load bearing interface ensures repeatable loading of the platform regardless of small deviations in floor height.

Similarly, the foundations on which the mobile platform resides in different areas of the factory must be of consistent rigidity. Deflections of the foundation impose significant amounts of error on the robot tool point. While the deflections are accounted for during robot accuracy calibration, consistency in foundation stiffness ensures calibrations at individual work areas are unnecessary.

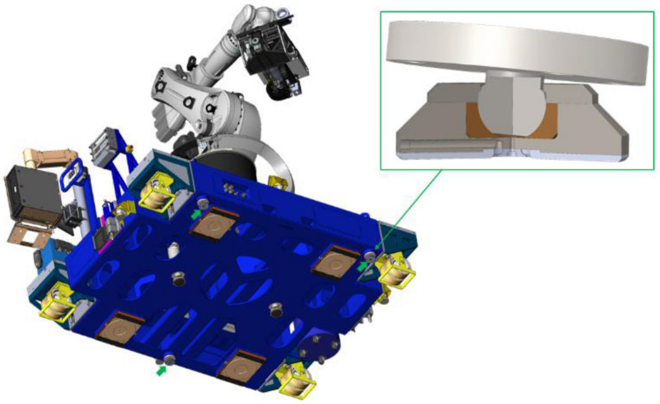

Figure 2. Three-point-load floor-to-platform interface with spherical feet on Electroimpact mobile robot platform.

The mounting interface between mobile platform and robot is also of critical importance. Error sources that are difficult to isolate with accuracy calibration methods can be avoided by considering the stiffness symmetry of the mobile platform and mounting interface. Of particular interest are sources of stiffness asymmetry at the base of the robot. The platform structure is designed such that the stiffness at the base of the robot is minimally dependent on moment direction. This limits deviation from the nominal kinematic description and simplifies calibration methods by making some error terms independent of axis position.

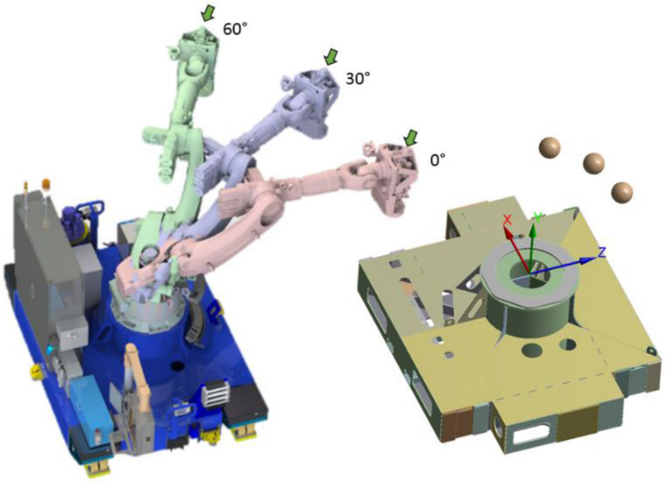

Figure 3. Moment direction alteration as the robot rotates about its base. Finite element analysis of the tool point deflections at different orientations are shown in Figure 4. Robot mass was modeled as a single equivalent point mass in each iteration and the robot model is considered to be rigid.

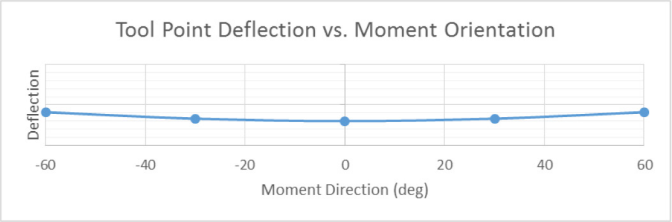

Figure 4. Approximate independence of robot tool point deflection from moment direction due to mobile platform compliance.

Utilizing these design principles and accuracy calibration techniques similar to those described in previous works [1], robotic systems of this mobile architecture have displayed measured off-part static accuracies of ±0.125mm (3-sigma) in a 3.5m × 2m × 1m volume.

In mobile robot applications, it becomes of particular importance to also consider accuracy relative to a static coordinate system with which the robot will interface as well as the now mobile robot-motion-defined coordinate system. Most industrial applications require the mobile robot to be positioned in front of a statically located work piece, register the location of that work piece, and perform a task fully automated and without accuracy degradation. Several methods can be utilized to reliably orient the robot relative to a work piece with most consisting of a mechanical rough alignment to the work piece followed by a precision part location determination.

Coarse alignment through mechanical means is achieved through work piece mechanical interlocks or floor index mechanisms. In either of these cases a static indexing interlock is used to roughly align the mobile robot relative to the work piece in the three degrees of freedom not already controlled inherently by the floor interface. Tapered pin-in-bushing and actuated-hook indexes have proven reliable and robust methods of coarse alignment. Static machine vision targets and floor facing cameras have also been used to calculate rough robot to work piece coordinate transforms [5].

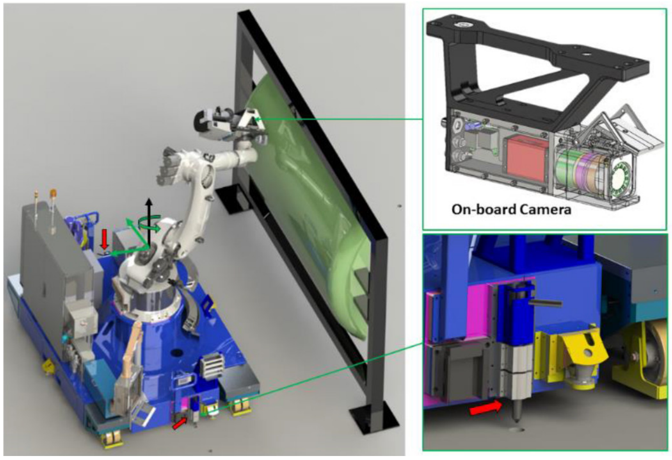

Figure 5. Example of pin-in-bushing rough alignment and precise part registration using on-board vision with an Electroimpact mobile robot.

Precise alignment to a work piece is achieved using on-board machine vision or metrology inspection touch probes. Either of these methods provide precise locations of work piece datum features from which a robot to work piece transform can be calculated.

Mobile Robot with Mobile External Axes

In many applications, it is convenient to increase working volume by mounting the robot to an external linear axis. Mobilizing the linear axis brings with it a multitude of mechanical design challenges and further complicates maintaining accurate motion.

With a mobile external axis, the principles remain consistent with the previously discussed mobile platform architecture. Consistent loading of the mobile structure is required to maintain repeatable motion. For a horizontal external axis, substantially increasing the working volume quickly makes three-pointing the floor-to-structure interface impractical as the robot's center of gravity will likely move outside the platform's stability triangle resulting in carrying the mass of the robot cantilevered. In this case, a grid of planar contact points provides a robust support interface for the mobile platform while maintaining repeatable loading of the platform between work stations. Planarity of the interface is ensured by precisely setting the height of each contact using a laser tracker.

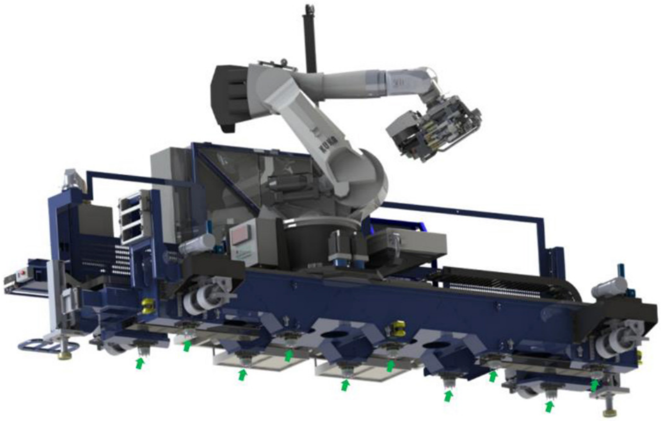

Figure 6. Electroimpact horizontal external axis mobile robot system architecture with multi-point-planar contact floor interface.

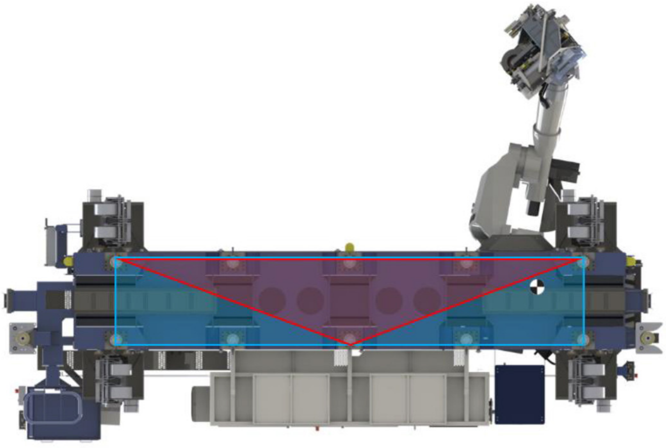

Figure 7. Structural support and stability benefits of a multi-point planar floor interface over three-point contact.

Alternatively, some work piece sizes require the expansion of the working volume vertically. In this case, three pointing the mobile platform typically remains a viable solution since the motion of the external axis does not significantly alter the center of gravity of the system relative to the support structure. In some cases, other design requirements force a platform geometry that requires more than three points of contact to the floor. Here, two of the contact points are connected via a single point of rotation so the platform is functionally three-point loaded but four points remain in contact with the floor.

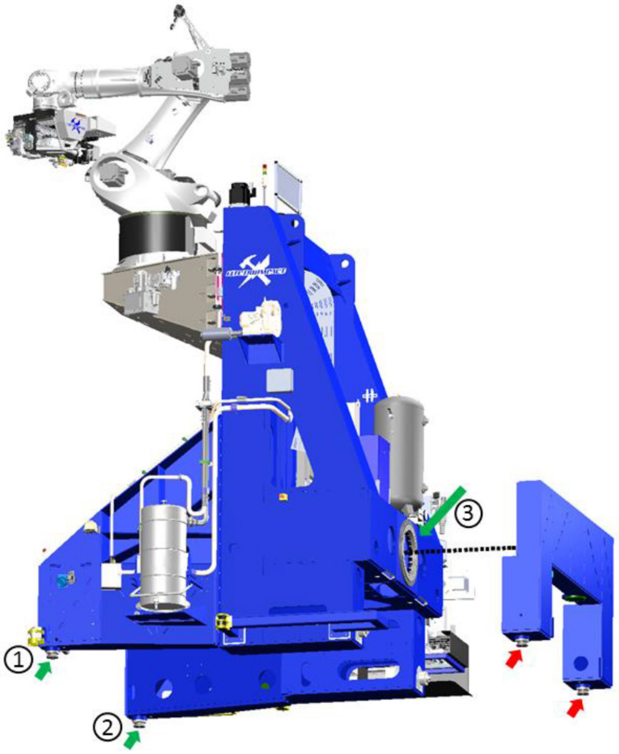

Figure 8. Consistent structural loading by three-point support with four floor contact points. Demonstrated by Electroimpact vertical external axis mobile robot.

In both the vertical and horizontal external axis mobile robot system architectures the principle of stiffness axis independence remains paramount. However, with these architectures it becomes more difficult to ensure consistent stiffness as the robot's mass traverses the mobile external axis. In these cases, the stiffness, or alternatively, the compliance, c, of the external axis can be characterized as a function of that axis's position, θ. This function can be continuous or discretized and interpolated.

$$c = c(\theta)$$

Note that this compliance model assumes that the small deflections associated with link flexibility are linear and directly proportional to the force or torque applied to the axis. A convenient way to express this mathematically is to represent the generalized force as its linear and angular components acting at a point on the axis. The generalized force / moment pair, referred to as a wrench, F, is expressed as a six element vector [6].

$$f = < f_x, f_y, f_z >$$

$$\tau = < \tau_x, \tau_y, \tau_z >$$

$$F = \begin{bmatrix} f \\ \tau \end{bmatrix}$$

The Jacobian J_d of the deflection $d(F)$ with respect to the wrench F now becomes a function of axis position, θ.

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

The terms of the deflection Jacobian are determined experimentally.

In the case of the vertical external axis mobile robot, the stiffness of the platform at the base of the robot is also dependent on the position on the feedback mechanism. As the robot orientation changes the resultant moment applied to the robot mounting location alters direction and magnitude. This causes deflection of the platform and a visible motion at the feedback device.

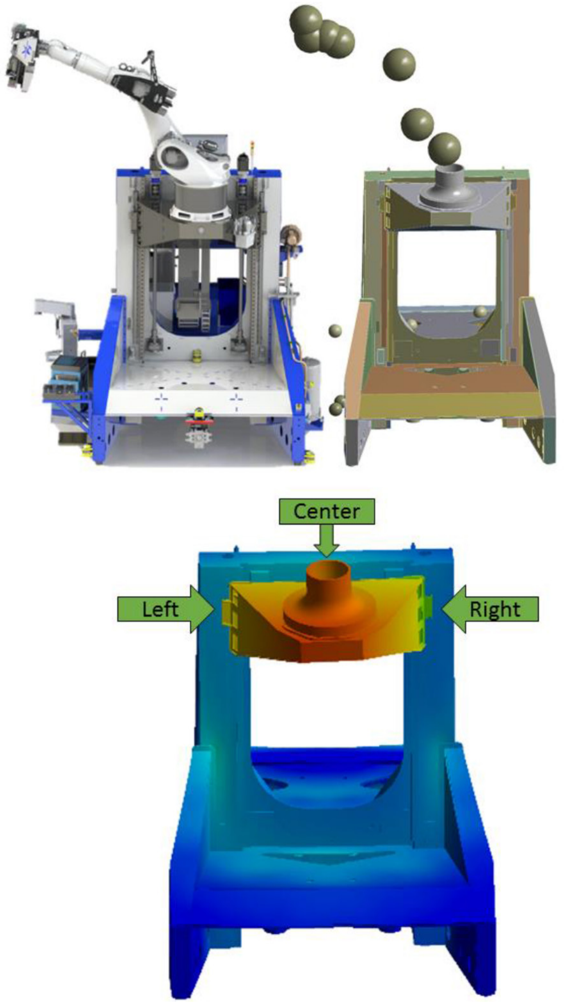

Figure 9. Deflection of a vertical external axis mobile robot platform with possible feedback device locations indicated. Deflections calculated using finite element analysis with the robot mass simulated as equivalent point masses.

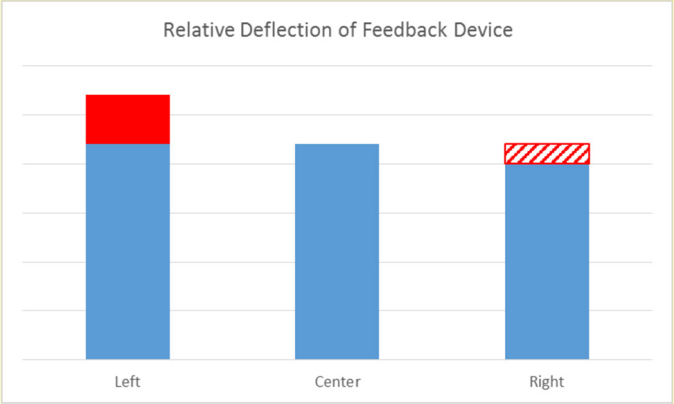

Figure 10. Relative displacement of feedback device positions. Red indicates the unobservable difference in deflection if the feedback device is centrally located.

The addition of dual drive control of the external axis with separate feedback devices make the left and right relative deflections shown in Figure 10 observable and enable counteraction. A centrally-located feedback device can only view and counteract a single DOF deflection. Dual drives allow an additional rotational DOF deflection to be observed and counteracted.

Utilizing these design principles and accuracy calibration methods, mobile robots with vertical external axes have displayed off-part accuracies of ±0.20mm (3-sigma) over a 4m × 2.5m × 2m volume. A mobile robot with a horizontal external axis demonstrated an accuracy of ±0.18mm (3-sigma) in a 3m × 2m × 1m volume.

Mobile Robot with Static External Axes

In some automation cases there are functional and financial benefits for the work-volume enhancing external axes of a robotic system to remain in place while the robot maintains its mobility. In this case, any combination of mobile robot and static external axis can occur. This architecture provides several unique challenges in maintaining robot accuracy.

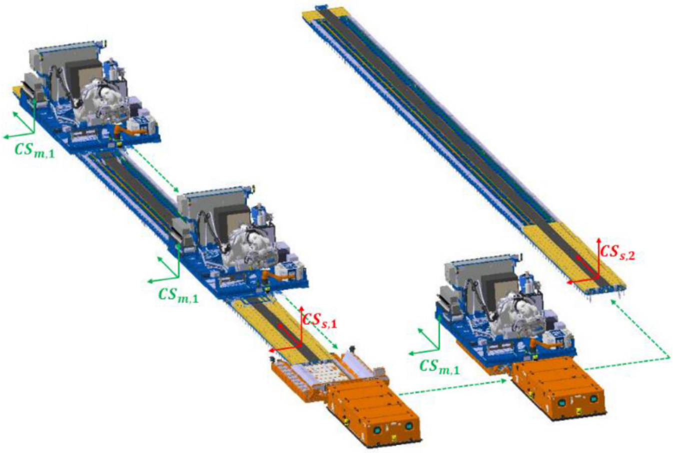

Figure 11. Electroimpact mobile robot with multiple static external axes.

To facilitate interchangeability, error sources of static and mobile components of the system are isolated during the robot accuracy calibration process; i.e. accuracy calibration is performed in such a manner that the error models describing either mobile or static components of the system retain their superposition property. The high-dimension error model suffers from issues of observability in the 6 DOF measured output of the system. Because of this, it becomes difficult to isolate and differentiate the effects of individual system components if all of those components are used to drive tool point location.

A simple workaround for this issue it to measure tool point error in batches where only static or mobile components affect tool point location. Multiple discrete error models can then be superimposed, mimicking the actual topology of the mechanical system where the cumulative error, E, is the sum of any i^{th} static or mobile system component's error model, $e_{s,i}$ and $e_{m,i}$, respectively.

$$E = e_{s,i} + e_{m,i}$$

Note that when determining individual system component error models, relative tool point error must be measured rather than absolute tool point error. Furthermore, it is usually necessary to measure error of static and mobile components in different coordinate systems; one local Cartesian coordinate system for the static system components and one mobile coordinate system for the mobile robot components. From this, the complete system error in the static coordinate system, E_s, becomes:

$$E_s = e_{s,i} + T_m^s e_{m,i}$$

where T_m^s is the transform from static to mobile coordinate systems.

This method of system component error isolation during accuracy calibration has demonstrated off-part accuracy of ±0.25mm (3-sigma) over multiple 4m × 1m × 3m volumes with a single mobile robot utilizing multiple static horizontal external axes.

Conclusion

Articulated robotic arms have penetrated high-accuracy industrial manufacturing tasks through the enhanced capabilities of novel system feedback architectures and high-order error modeling. Mobilizing these high-accuracy robot systems has provided manufacturers flexible automation solutions for tasks where mobility is necessary or where rates do not require a dedicated system. With mobility, special considerations in design and accuracy calibration methods must be made to maintain accurate motion. These include consistent structural loading, consistent foundation compliance, characterization of variable stiffness components, and the isolation of error terms describing mobile and static system components. With these additional complexities of high-accuracy mobile robots accounted for, functional off-part accuracies of various mobile robot system architectures have measured ±0.25 mm (3-sigma) or better over volumes from 6 to 20 cubic meters.

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Definitions/Abbreviations

CS - Coordinate System

DOF - Degree of freedom

SMR - Spherical-mounted retro-reflector

Wrench - A six-element vector consisting of forces and torques in a Cartesian coordinate system.

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