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# Improved Accuracy of Unguided Articulated Robots

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## ABSTRACT

The effectiveness of serial link articulated robots in aerospace drilling and fastening is largely limited by positional accuracy. Unguided production robotic systems are practically limited to +/-0.5mm, whereas the majority of aerospace applications call for tolerances in the +/-0.25mm range. The precision with which holes are placed on an aircraft structure is affected by two main criteria; the volumetric accuracy of the positioner, and how the system is affected when an external load is applied. Production use and testing of off-the-shelf robots has highlighted the major contributor to reduced stiffness and accuracy as being error ahead of the joint position feedback such as backlash and belt stretch. These factors affect the omni-directional repeatability, thus limiting accuracy, and also contribute to deflection of the tool point when process forces are applied. Drawing from common axis configuration in machine tool design, an industrial robot integrated with secondary encoders yields tighter control on axis position and increases system rigidity, thus creating a more repeatable system and, in turn, a system than can be compensated to high accuracies.

## INTRODUCTION

Investment in aerospace factory automation is met with high performance expectations and low cost demands. Manufacturers wish to deploy systems that can be programmed offline without teaching using minimal operator intervention. Automating the assembly of aerospace structures, specifically drilling, countersinking, and inspection, using traditional automotive-style articulated robots makes for a particularly attractive solution with unique design challenges. The articulated arm offers a large working envelope capable of reaching 6-degree of freedom (DOF) poses along highly curved surfaces and can navigate into tight spaces due to its compact design. Because robots are produced in high volume, they typically prove to be a much lower cost motion platform as compared to tailored positioning systems. And, within the last 5 to 10 years, significant mechanical and control improvements have made the articulated arm a viable option for lower accuracy (e.g. +/-0.75mm) aerospace assembly processes.

The defense aerospace industry has been interested in the use of articulated arm robots in aerospace production operation for many years. This interest in the use of industrial robots has its roots in the successful implementation of industrial robots in automotive plants. The use of industrial articulated robots offers airframe manufacturers significant potential benefits in both cost and flexibility when employed for assembly and manufacturing tasks. Implementation of articulated-arm robotic drilling and inspection technology has the can significantly reduce production non-recurring costs, assembly span time and aircraft Unit Recurring Flyaway cost by reducing hole drilling time, improving hole quality and reducing the ergonomic challenges. A robotic drilling cell can also improve assembly line footprint requirements and drilling accessibility, contributing to span time reduction.

Typical drilling applications in defense aerospace have consisted of large gantry style drilling systems requiring

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significant facility footprints and clear access to the product. The gantry monuments limit head and spindle accessibility to the product whereas with a robot often numerous spindles can be applied within a similar volume resulting in a reduced quantity of cells to reach full rate. In addition, stem-walls or columns are typically not required because the robots are able to reach up and out over the product during cycle and move away from the product when out of cycle for manual operations. When confronted with the high demands required for aerospace assembly however, the robot systems have typically not been able to meet customer requirements.

Fundamentally, currently available industrial robots are designed for lower tolerance, high-speed work such as palletizing, picking and placing, welding, etc. and they perform these tasks quite well. However, tailoring for these operations have presented difficulties. Because the links on the robot are serial, error from the first joint is carried to the second, and from the second to the third, and so on. This produces a cascading effect on the error which magnifies what may be a small displacement at the joint into a large displacement at the tool center point (TCP). For a typical 3 meter reach robot, this caps the positional accuracy to, at best, a global tolerance of +/-0.5mm which significantly limits the potential applications of the technology. Although systems for guiding the TCP to its location via external metrology are available, these often present line of sight and cycle time issues, as well as additional maintenance and cost burdens that are preferably avoided wherever possible. However, it should be noted that the guidance process is significantly streamlined if the base system is accurate and rigid, essentially getting to or very near the target position in its initial approach. The ultimate desire is to rely solely on the global accuracy of the motion platform. To that end, careful analysis of the sources of error as well as significant production experience have highlighted areas of significant accuracy loss which can effectively be eliminated by direct measurement using standard, integrated sensor technology. Implementing this technology in conjunction with an accurate, rigid multi-function process head enables the application of affordable automation to a much broader range of higher tolerance aerospace components.

## MAIN SECTION

### ANALYSIS OF MECHANICAL SYSTEM

In a drilling application, the accuracy in which a hole is placed relative to some coordinate reference is largely the function of two performance criteria; 1) The positional accuracy of the motion platform in free space, and 2) The ability of the motion platform to remain in position when external loads are applied (e.g. clamp pressure, drilling, etc.).

The pose of the TCP is obtained by driving the robot axes to a calculated angular position based on the

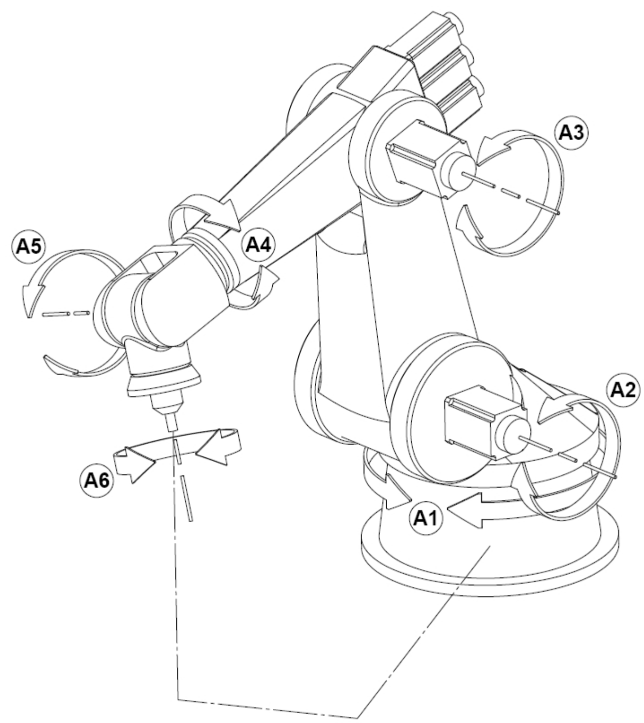


**Figure 1.** Typical serial link 6-axis robot

kinematic model of the arm (Figure 1). On a typical 3m reach arm, the nominal model, which is based on ideal link lengths, offsets, and rotations exhibits an accuracy of about +/- 2 to 4mm within its working volume. Because the physical robot never matches the nominal model due to manufacturing and assembly tolerances, a unique higher order model can be developed to better describe each individual arm. This model can also include parameters for drooping affects from the masses of the links and payload and has been shown to achieve a positional accuracy of ~ +/-0.5mm in a restricted range. With any model, no matter how perfect, the ultimate TCP pose is a function of the 6 robot joints angles. The position feedback for each robot axis is located at their respective servo motors. Ahead of the feedback are numerous sources of error, such as backlash in gearing and u-joints, belt stretch, shaft twist, scaling error, etc. To further complicate, the wrist axes are often mechanically coupled, meaning movement of one affects the position of another, therefore a means for calculating for and correcting coupled axes must be implemented. Joints that are farther from the tool point have a more significant affect on error with the first axis being the worst as it is typically not actively preloaded nor loaded via gravity. Although the uni-directional repeatability of robots is generally good, omni-directional is significantly more substantial. Testing of omni-directional repeatability using a standard robot in typical working volumes has demonstrated magnitudes of up to 0.5mm. Poor repeatability can be attributed to uncertainty in the joint position. Because the system's accuracy can only be as good as it's repeatability, the best a standard system could ever achieve in ideal conditions is TP 0.5mm. Therefore, fundamental to system accuracy is knowing the position of each axis.

The location of the axis feedback on a standard robot (at the servo motor, Figure 2) also limits the stiffness of the mechanical unit.

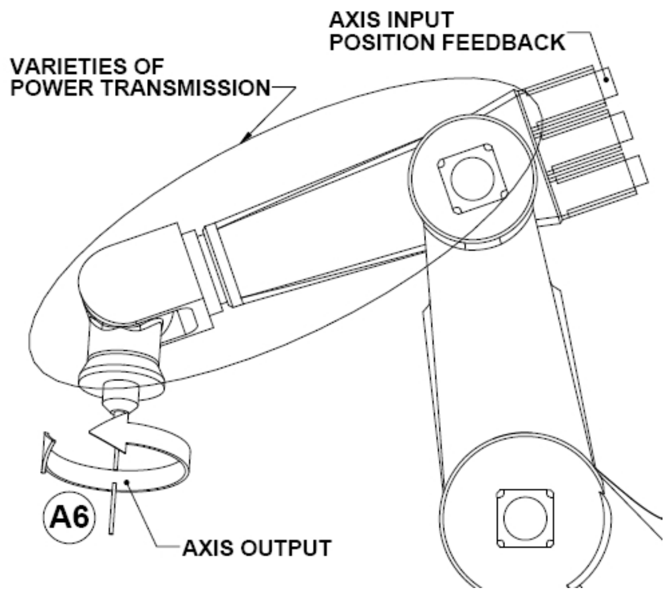


**Figure 2.** Standard location for position feedback

Because the axis position is held at its input, compliance, backlash, and non-linearities go unaccounted for. This results in poor joint stiffness which yields significant TCP deflection when moments are applied to the joints. Joint moments result both from the masses of the links and from externally applied process forces. If not compensated, droop from the link masses and payload can exceed 3mm at the TCP. Even ignoring this, pressure applied at the TCP (as is common in drilling or cutting applications) can send the TCP out of position up to 2mm for relatively low loads (<200 kgf) with a good portion of this deflection coming directly from the joints.

SECONDARY ENCODERS

In the machine tool world, secondary position encoders are commonly used for this exact reason. The secondary encoder is mounted at the output of the axis, rather than the input. Sensors are typically very high resolution and exhibit high repeatability with little to no measureable hysteresis. Taking this same technology and applying it to a robot yields much tighter control on axis position, thus creating a far more repeatable system and, in turn, a system that can be compensated to high accuracies (Figures 3 and 4). Fundamentally, this differs from the machine tool where the secondary encoders are primarily linear and are used to directly measure the Cartesian position of the TCP. On the articulated robot, the secondary encoders improve the accuracy of the joint angle which when input thru the serial kinematic chain, improves the Cartesian position of the TCP.

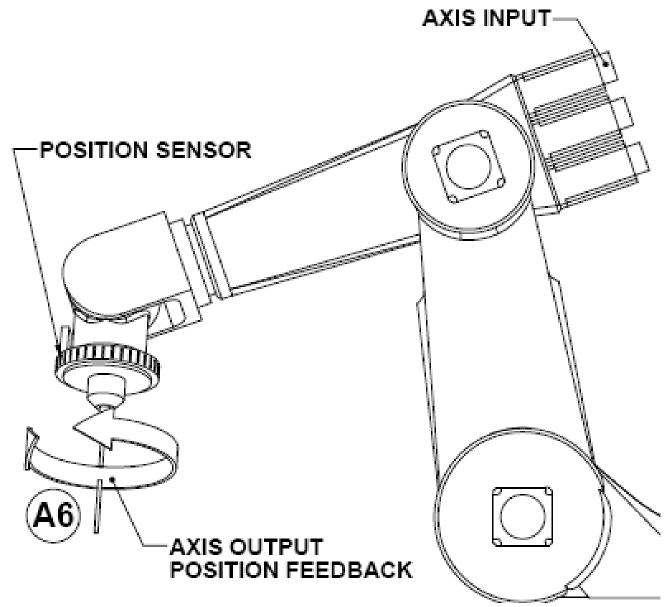


**Figure 3.** Secondary feedback at joint output

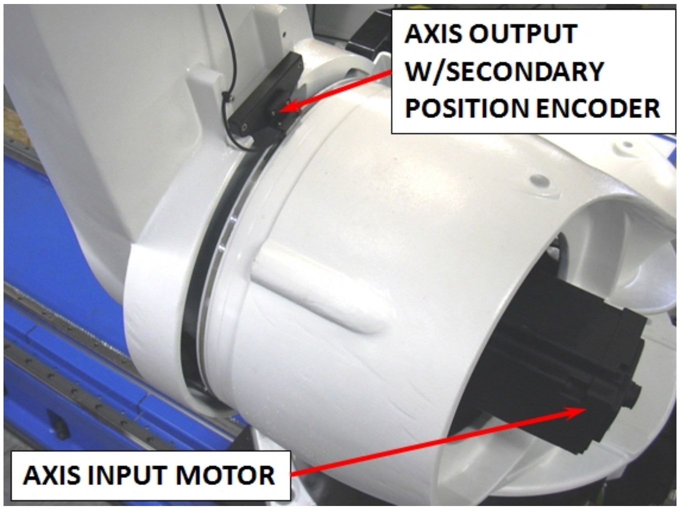


**Figure 4.** Applied secondary feedback at joint output

Sensor Selection - There are many factors to consider in selecting encoders. These factors include operating principle, resolution, accuracy, and signal type. Consideration of all factors needs to be used to select the best one for robot secondary feedback.

The most common operating principles of standard sensors are magnetic, inductive and optical. Magnetic sensors operate on a tape scale with alternating north and south poles. Inductive sensors use a steel scale with a ladder like shape. Optical sensors use a steel scale with etched markings. All three types of scales interpolate the distance between graduations to get resolutions much greater than the pitch of the tape scale graduations.

Two signal types considered were absolute and incremental. Absolute encoders read a unique pattern from the scale which allows it to send data corresponding to its position along the scale. There are various formats for absolute encoder data, so they need to be carefully selected to ensure compatibility with the motion controller. Incremental encoders output pulses as they move along the scale. A counter module is used to interpret the pulses to track the position of the encoder. When the encoder or counter module are without power any motion will be lost. Therefore, incremental encoders require referencing after cycling power on the machine. Incremental encoders are also limited in speed to ensure that the counter module does not miss any pulses. An advantage of incremental encoders is that the output is standardized, so it is well supported by most controllers.

Accuracy is obviously a driving factor in the selection of encoders. Since the tool point can be a large distance away from the axis, small angular errors at the scale are greatly magnified. It is also important the scales have good linearity and small hysteresis. Testing of sensors from various manufacturers for each of the operating principles was executed to provide a baseline of performance data. Besides repeatability, accuracy, and linearity, environmental factors must be considered as each operating principle is susceptible to "contamination", whether it be particulate, magnetic, or other. Consideration must also be given to the physical mounting as some sensors are more lenient than others with regard to alignment tolerances. Sensor housings and form factors vary as well. Tests were performed using (3) methods; 1) Simultaneous signal acquisition from multiple scales mounted to a precision drum, with the angle of the drum being measured via calibrated sealed angular encoder, 2) Laser tracker data acquisition for long (1+ meter) linear moves, and 3) Laser tracker data acquisition for omni-directional repeatability with sensors mounted to rotary axis and data collected at a center distance of ~2.5m. Results from each test were used to compile a table of selection criteria vs. observed data to best select the right sensor for the given application.

Controls Integration - The way in which the robot controller uses the signals from the secondary sensors has a direct affect on the system's dynamic behavior. In a standard system, the servo motor for each axis contains a rotary position sensor which is used to close both the position and velocity loops in the control. This closed-loop system typically runs at about 1ms to ensure high stability with minimal lag. Depending upon the controller, there can exist limitations as far as how the sensor feedback makes its way into the position loop. The input can be directly part of the servo loop (Figure 5), one level up from the servo loop in the motion planning stage (Figure 6), or thru a software package that converts the sensor signals into offsets then inserts these offsets into the motion planning stage (Figure 7).

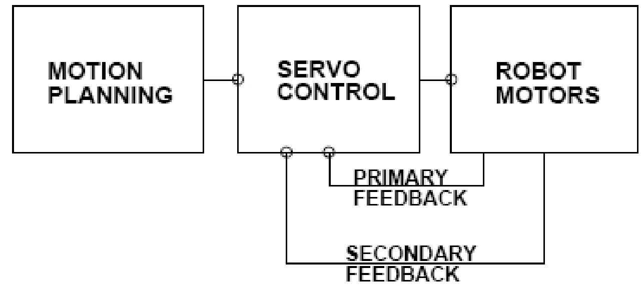


**Figure 5.** Direct use of secondary feedback

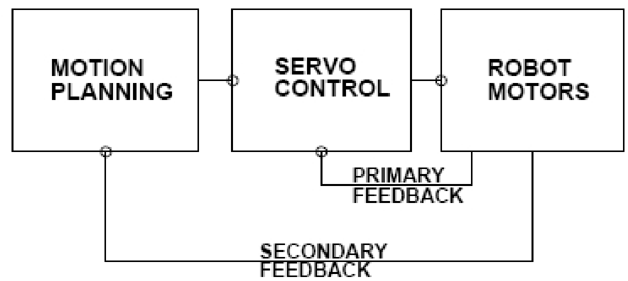


**Figure 6.** Secondary feedback sent to motion planner

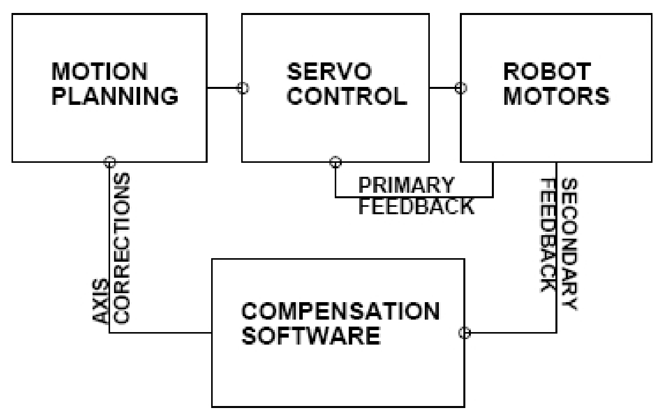


**Figure 7.** Secondary feedback collected and conditioned via software program, then sent to motion planner

These (3) methods have been ordered from fastest to slowest response. For point-to-point (PTP) use, as in a drilling application, the differences become less important, however it is necessary that the system be capable of remaining in position rigidly given externally applied process forces and can hold path accurately should TCP corrections be required (normalize, offset, etc.). For applications requiring high path accuracy, having the position loop closed at the servo level ensures minimal deviation from the target path, given proper tuning.

Testing of Enhanced System - As described above, the precision with which holes are placed on an aircraft structure is affected by two main performance criteria; 1) the volumetric accuracy of the positioner in space, and 2) how the system is affected when an external load is applied. Both factors must be well-managed to meet the +/-0.25mm accuracy target. Affecting process speed, there exists a third criterion related to the stiffness of the platform. The magnitude and time it takes to allow the system to damp out oscillations set up by either moving from location to location and/or by shuttling the process tools on the end effector directly affects the throughput of the machine. Each of the three criteria were evaluated.

The positioning system is limited in accuracy by its repeatability. With the fitment of secondary encoders, the repeatability was expected to drop to nearly zero. Sensor resolution plays a major role on axes that are far from the tool point. For example, given a 3m reach robot, to achieve a resolution of 0.025mm at the tool point requires a sensor that produces at least 1,000,000 counts per revolution at its first axis. Additional limiting factors exist, such as in-position tolerances, sensor hysteresis, and mechanical shifting (e.g. flopping bearings, etc.). Systems were tested for repeatability using two methods; 1) dial indictor, and 2) laser tracker. The dial indicator test was used to evaluate each individual axis during setup. Since the indicator has a higher resolution than a laser tracker, it was ideal for short range testing. The laser tracker was used to test the repeatability of the combined effects from moving all axes, as would occur in normal operation. To best simulate the mechanical system, an end effector that exhibited the weight, CG, and overall dimensions of a typical multi-function drilling head was used. For this test, the tracker's retro-reflector was placed at the TCP and the robot was moved out of position by driving each of the six axes one direction, then driving each of the axes in the opposite direction and back. The magnitude of the joint move was +/-5 degrees. Each time the robot returned to its original location, position data was collected. This was repeated (6) times to get an average value from both approaches and was conducted for various robot positions. As expected, the results for omni-directional repeatability using secondary encoders showed a maximum deviations of less that 0.05mm, or an improvement of 10x.

With the repeatability in check, an initial investigation into system accuracy was performed. Because no robot's kinematic parameters (link lengths, etc.) truly match the nominal design, compensation is required to attain good positional accuracy. Other major contributors to error besides static variables are link and bearing stiffness, base mounting stiffness, runouts, etc. If not directly measured, these parameters can be obtained using common estimation methods.

The end effector was fitted with (3) retro-reflector nests, one in the tool point and the other (2) located on the rigid end effector base. Each robot was then sent to ~50 unique "random" positions that covered the basic working range of the system. The intent was to exercise each joint beyond its maximum anticipated range to better fit the parameters and to avoid extrapolation. At each of the ~50 points, the Cartesian position of each of the (3) targets was valued relative to the robot's base coordinate system. The data from these 50 points were used to estimate the kinematic parameters. Then, an additional set of 24 positions were exercised and data was again collected at each of the (3) targets. This 24 point set was used as validation for the enhanced kinematic chain. The 3-sigma error between actual and nominal was then calculated and served as an initial look at what we could expect at the present time. The results were very encouraging with accuracy showing < +/-0.25mm 3-sigma.

The next step in achieving accuracy on the part is to evaluate where the robot goes when an external load is applied. In order to maintain tight control on the drilling and countersinking process, one-sided pressure is applied to the part via the end effector. This is commonly known as "clamp" force. Depending upon the material and drilled hole size, a typical clamp force range is 50 to 400 lbs. Because the articulated arm is not infinitely stiff, deflection occurs when an external force is applied. This deflection results in "skidding" along the part and can very quickly put the tool point outside the tolerance band. As described earlier, the majority of this deflection occurs at the joint given a normally-equipped robot. With secondary encoders at each axis, local joint error is now negligible, however deflection still occurs in the links, bearings, base mounting plate, etc. Because skidding is partially friction-based, predicting where the tool will go is not trivial. Preferred is a platform that exhibits high stiffness so the level of compensation can remain low.

To evaluate the comparative stiffness of the system with and without secondary encoders, clamping trials were executed in various robot positions and deflection data was acquired via laser tracker. The top plate of the head was fitted with (3) retro-reflector targets. Clamping was performed at maximum anticipated load (200 kgf) to obtain the best resolution and deflection is assumed to be linear as a function of applied load. The positions of each of the (3) targets were valued in both the loaded and unloaded state. This test was repeated to obtain an average and was also conducted in other drilling positions. The data from the (3) points were used to generate a 6 degree of freedom transformation that described the deflection of the head. The position of the tool point was then transformed to yield the 3-dimensional skid vector. Direct measurement of TCP deflection is not valid since it includes movement of the head itself which, for this analysis, should be ignored. Results from testing various articulated arms showed that the deflection at the joint makes up 50-80% of the total TCP deflection and confirmed that maintaining position using secondary sensors at the axis output effectively makes the axes rigid as any induced deflections are automatically corrected for in the control loop.

## CONCLUSION

In order to develop production capable solutions, a variety of equipment must be integrated to meet the technical requirements. Optimal cell configurations, required equipment upgrades, necessary software development and all other aspects of a production robotic drilling system must be considered. Initial application of the precision robotic technology is expected on the F-35 Lightning II program known as the Robotic Applied Drilling System (RADS). The RADS system is expected to be implemented in the NGC F35 Integrated Assembly Line as the business case will demonstrate significant savings and provide the best value versus the current process and expected comparable future drill cell capabilities. The program objective for RADS is to capture 100% of the holes in the selected work stations currently drilled by their respective auto drill systems. The RADS solution and business cases will utilize a combination of robotic drilling and manual processes to achieve the optimal cost and span time reduction and to achieve the accuracy required.

RADS will investigate the following key risk reduction activities while ensuring a successful technical and business case solution:

- Inclusion of precision hardware and components to robot platform
- Development of robotic kinematic models for volumetric compensation
- Reduced local coordinate system working volumes
- Integration of necessary metrology systems
- System simulation and process validation
- Drill skidding/skating compensation

The RADS team will demonstrate a production representative prototype system with production representative tooling and production representative process testing. The demonstration cell will include future production process considerations such as, but not limited to tool changing, tool identification and verification, hole position inspection, environmental compensation, escape routines, safety considerations, and coordinating robots as required. The RADS team will demonstrate the drilling cells' capabilities by drilling flat and contoured test coupons and full scale representative test articles in the production representative cell. They will inspect, validate and report results of all test drilling as to location, size and quality of the drilled holes. Demonstrated cell stations priority may change dependent on factory rearrangement schedules and the technical maturity of RADS. While priority is to demonstrate production representative cells, provisions will be made for the demonstration cell and tooling to allow flexibility and/or reconfiguring for potential demonstrations of other cell configurations.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

**3-Sigma**: Measure of accuracy, +/- (average + 3 * Stdev)

**CG**: Center of gravity (mass)

**DOF**: Degrees of freedom

**NGC**: Northrop Grumman Company

**PTP**: Point to point (motion trajectory)

**RADS**: Robotic Applied Drilling System

**TCP**: Tool center point