Experimental Determination of Kinematic Coupling Repeatability in Industrial and Laboratory Conditions

Patrick J. Willoughby, Anastasios J. Hart, and Alexander H. Slocum (E-mail: slocum@mit.edu),
Dept. of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Abstract

While kinematic couplings are frequently used as components of repeatable interfaces in ideal environments, their use in heavily loaded industrial interfaces is less frequent, as previous studies have validated couplings mostly under modest loads and controlled environmental conditions. On the other hand, the performance of heavily loaded industrial equipment, such as robots used in automotive production, could benefit from highly repeatable interfaces for assembly and replacement of modules. A series of tests was conducted to assess the industrial repeatability performance of large kinematic couplings on an ABB 6400R industrial robot. The interfaces for two of the more frequently detached interfaces—the robot base to the factory floor interface and the robot wrist interface—were tested. For both interfaces, replacements for the existing pin joint interfaces were designed using two forms of kinematic couplings—a three-pin coupling and a canoo-ball coupling. During industrial testing, measurements were taken for each coupling form on the base and wrist interfaces. Both laboratory and industrial experiments demonstrated that the installation procedure is almost as important as the form of coupling itself and that properly mounted kinematic couplings can improve the repeatability of machine interfaces by up to 90%. Laboratory measurements provided best-case canoo-ball coupling repeatability on the order of 0.1 µm and three-pin coupling repeatability of 1 µm. In industrial trials, the canoo-ball coupling repeatability was 0.05 mm for the wrist interface and 0.10 mm for the base interface. The three-pin coupling was capable of 0.11 mm repeatability for the base interface, and limited testing for the wrist interface indicates possible 0.08 mm repeatability.

Keywords: Kinematic Couplings, Robotics, Repeatability, Precision Fixturing

Introduction

In the measurement and instrumentation fields, kinematic couplings are widely used to create very repeatable interfaces for devices such as lenses and probe mounts, which are subjected to small disturbance loads in ideal controlled environments. As kinematic coupling performance has previously been validated for relatively low loads and consistent mounting conditions (Slocum 1992a; Evans 1989), kinematic coupling use in industrial settings has been traditionally limited to environments such as semiconductor production facilities and metrology rooms. Although traditional factory environments present less ideal conditions for kinematic couplings, equipment used in these settings could benefit from improved repeatability of the mounting interfaces. Incorporating kinematic couplings into manufacturing equipment could allow removable interfaces to be more repeatable while minimally increasing the machine cost.

For example, industrial robots are widely used for material handling and automation of processes such as assembly, welding, and painting of vehicles in automotive factories. Geometric differences between the true robot structure and the ideal kinematic model in the robot controller can cause errors greater than a millimeter during production processes, so the robot is calibrated before leaving the production facility. This calibration captures the error of the real structure by fitting error parameters to the kinematic model. However, recalibration is required to correct degradations in robot accuracy due to subsequent discrete alterations to the robot structure, such as replacement of an individual motor, the wrist module, or the complete robot itself. While recalibration can restore robot accuracy, it requires a lengthy process of measuring 100 or more points in the robot workspace with a laser measurement system. The required calibration time can reduce the productivity of an assembly line for several hours, leading to much lost revenue. Incorporating kinematic couplings into the robot’s critical assembly interfaces can reduce the requirements of the calibration measurement procedure by improving device repeatability (Hart, Slocum, and Willoughby 2004).
This paper explores the performance of two forms of kinematic couplings, the “canoe” ball coupling and the “three-pin” coupling on a large industrial robot set in a factory environment. The couplings were tested in three settings with different installation techniques to assess the effect of mounting conditions and procedures on coupling repeatability. The three settings were:

1. Robot wrist in laboratory setting—Robot wrist interface geometry in a laboratory environment under managed preload and gravity loads only.
2. Robot wrist in industrial setting—Medium-scale, moderate-to-high load interface between the robot arm and robot wrist with installation issues and subjected to more complicated external loading.
3. Robot base in industrial setting—Large-scale, high-load interface between the robot and the factory floor subjected to large external loads.

In the factory measurements, the ABB 6400R robot, shown in Figure 1, was used as the test platform.

Kinematic Coupling Designs

The traditional kinematic coupling configuration, consisting of three balls or hemispheres on one interface with matching grooves on the corresponding part as shown in Figure 2, constrains six degrees of freedom via a near-exact kinematic constraint resulting from six ball-groove contacts (Slocum 1992b; Smith and Chetwynd 1992). As noted by Schouten, Rosielle, and Schellekens (1997), the traction caused by friction prevents a true kinematic constraint, although flexures can be used to mitigate this effect. Because the ideal equilibrium position of the coupling can be described by six point contacts, closed-loop mathematics deterministically describes the geometric relationship and elastic error motions between the interface halves. In reality, these point contacts must typically tolerate high Hertzian contact stresses caused by the applied load; therefore, the theoretical point contacts deform into ellipses. As the applied load increases, failure of a properly designed coupling occurs in the contact regions, placing a limit on the maximum load capacity of the coupling.

To increase the load capacity of traditional ball-groove couplings, the specialized “canoe ball” element shown in Figure 3 was developed. The canoe-ball coupling replaced the traditional hemispherical contacting element with a trapezoidal block having two sections of large-diameter spheres ground onto the contacting surfaces. By placing the smaller spherical sections onto the block as illustrated, the applied load creates an approximately circular contact area with a large, shallow Hertzian stress zone. The benefit of this design is the compact size of the contacting elements. As the sphere’s virtual diameter is increased, the contact stress is reduced, allowing for increased load capacity without adversely affecting the repeatability. The larger diameter also increases the size of the Hertzian stress zone, reducing the elastic error motions and preserving repeatability. Previous laboratory experiments by Mueller-Held (1999)...

\* The mathematics and design procedure for the canoe-ball coupling was developed using the kinematic coupling design spreadsheet. This spreadsheet is available online at http://pergatory.mit.edu/kinematiccouplings in Excel, MATLAB, and MathCAD formats. These mathematics and a detailed description of the coupling design process can be found in Slocum (1988, 1992a,b), Evans (1989), and Slocum and Donmez (1988).
have shown the repeatability of the canoe-ball couplings to be on the order of 0.1 μm.

Another form of coupling developed to increase load capacity without increasing cost is the quasi-kinematic coupling, which uses a combination of kinematic and surface contacts to optimize the load capacity and stiffness, without greatly reducing repeatability (Culpepper 2004). For the two robot interfaces discussed in this paper, a specialized planar version of a quasi-kinematic coupling called the three-pin coupling was designed in an effort to reduce the cost of implementing a fully kinematic or quasi-kinematic coupling. The three-pin coupling uses three precision pins to constrain the in-plane degrees of freedom and a large surface area to constrain the three out-of-plane degrees of freedom. A basic sketch model of the three-pin coupling is shown in Figure 4. Preload is applied by engaging a set screw or bolt normal to one of the pins to break friction and force the pins into the final mating position. After the in-plane constraint is established, bolts normal to the interface can then be heavily tightened to guarantee contact of the interface surfaces and provide support for dynamic loading of the interface.

For the couplings investigated, the kinematic coupling design methodology outlined in Slocum (1988, 1992b) and Slocum and Donnez (1988) was used to design the canoe-ball coupling elements. This methodology provides estimations of Hertzian stresses, deformations, and error motions. Additional finite element analysis was performed as required, as well as a Monte Carlo statistical analysis to determine interchangeability of coupling elements (Hart, Slocum, and Willoughby 2004). For the three-pin coupling, an existing set of mathematics was not available; however, the generalized process described in kinematic coupling references could be applied. In addition to contact stress and stiffness analyses, it is necessary to do a force and moment balance on the three-pin coupling to ensure that the in-plane preload is sufficient to break interface friction and that the out-of-plane preload is able to resist any applied load.

**Experimental Procedure—Laboratory Setting**

To evaluate the performance of the canoe ball and three-pin couplings in both industrial and laboratory circumstances, three experiments were performed by varying the preload and mounting conditions and then measuring the repeatability. The first experiments were performed in a laboratory setting. These experi-
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
displacement of the bottom coupling and the bed plate, and two probes measured the relative displacement between the coupling halves. Each capacitance probe was operated in high-resolution mode, allowing for a resolution of 3.5 nm RMS over a span of 75 to 125 μm between the probe tip and part surface. All measurements were controlled and recorded automatically using LabView with a National Instruments E-Series 16-bit DAQ card, which has a resolution of 152 μV or an equivalent measurement resolution of 0.5 nm.

During measurements, the threads and heads of all preload bolts were cleaned and lubricated after each removal of the top coupling half. Contact regions on each interface of the canoe balls and the pins were cleaned with methanol and lubricated with WD-40 after every five measurements. In addition, a separate test was conducted to determine the effect of a grease layer between the interfaces of the three-pin coupling. Preload bolts were replaced after 10 cycles during the canoe-ball measurements; however, a separate examination of preload bolt replacement was performed during the three-pin measurements to determine the effect of repeated loadings on the brass-tipped setscrew. Preloads were applied in a stepped fashion using a precision torque wrench (hand-tight, then 10%, 50%, and 100% of final preload within 4%) to break static friction and in a consistent order to prevent asymmetric bending moments across the part. A preload torque of 15 N-m was applied to the bolts for the canoe-ball couplings, while the preload torque for the three-pin coupling’s in-plane bolt was 0.3 N-m.

Measurements were taken at each step of the preload process to estimate the repeatability at the different preloads and to ensure proper preloading of the couplings. In addition, a final measurement was taken after removal of the preload force to determine how the deformations relaxed. The top coupling half was removed and replaced by hand using insulated gloves and stand-offs to prevent thermal errors from body heat. Typically, low-frequency vibration dithering of kinematic couplings assists the breaking of friction during preloading and hence improves repeatability. However, initial testing demonstrated that vibration dithering negatively affected measurements for this setup by introducing motion in the measurement structure and was therefore not used during testing.

Experimental Procedure—Industrial Setting

The industrial setting for the second and third experiments was an ABB IRB6400R industrial robot, shown in Figure 1. With full six-degree-of-freedom control, the 6400R is capable of positioning and orienting a 150 kg load while maintaining 1 mm accuracy along the path at 1 m/s or 0.1 mm point-to-point accuracy. One goal for this series of experiments was to determine if kinematic couplings were capable of providing repeatability better than the point-to-point accuracy of the robot. The point-to-point accuracy is affected by the accuracy of the calibration measurement system and numerous attributes of the robot, including structural compliance, backlash in the gearboxes, and accuracy of the error model in the robot controller.

Wrist Interface

Two separate mechanical interfaces of the IRB 6400R are of interest: the interface between the wrist and upper arm and the interface between the robot and the factory floor. The wrist unit of the robot contains two motors for the last two degrees of freedom of the robot’s six degrees of freedom and provides the interface for mounting a tool to the robot. The current wrist coupling, shown in Figure 7, consists of a series of four rounded tabs used to constrain in-plane translation of the wrist and an out-of-plane pin to constrain rotation. Eight M12 bolts perpendicular to the interface secure the interfaces and support a large portion of the interface loads, while a thin metal friction plate is placed between the interface surfaces to transfer the in-plane loads across the interface. As the interface is essentially a pinned joint, the interface repeatability is determined by the tolerances of the interface features and the accuracy of the interface placement during installation.

During robot operation, the wrist interface experiences dynamic forces up to 30 kN and moments up to 30 kN-m over an interface contained by an approximately 200 mm by 200 mm perimeter (ABB Product Manual). However, the load is transmitted only over a small ring on the outer edge of the wrist, as the center section is hollowed to allow the main wrist motor to fit into the upper arm. This size constraint was a concern for the placement of the canoe-ball elements when designing the new prototype couplings. Because the robot structure could not be
modified for testing prototype interfaces, the couplings were mounted to separate interface plates, as shown in Figure 8. These interface plates were bolted to the existing interfaces for the duration of the industrial experiments and were used separately in the laboratory measurements. Three protruding wings were added to the wrist interface plates to allow sufficient space for each of the elements, although the elements must be fully integrated into the wrist geometry in a finalized design. The wings were sufficiently thick to prevent bending caused by the weight of the wrist module. Less significant changes to the interface were required to incorporate the three-pin coupling, as only two of the existing rounded tabs had to be removed and one in-plane hole was required for securing the coupling.

The canoe balls were preloaded using M6 bolts that pass through clearance holes in the center of each coupling element and are threaded into the interface plates. An M6 setscrew with a brass tip was used to preload the three-pin coupling. Both coupling types used M12 bolts to secure the coupling plates to the robot and act as an additional precaution in case the preload bolts or couplings fail. During experimentation, it was discovered that the M6 bolts could not provide sufficient preload to prevent the canoe-ball couplings from exhibiting some undesired compliance. Therefore, additional precise preload was applied at the four off-center securing bolts using a torque wrench, and imprecise preload was applied along the axis of the preload bolts using "C" clamps.

The final variable measured during the wrist measurements was the effect of the installation angle. Traditionally, a wrist replacement is performed with the arm at an angle of 45 degrees to the ground. In this position, installation of the wrist was difficult as the wrist tended to rotate about the carrying straps and bind inside the arm. This installation position was especially problematic during three-pin coupling replacement, as the preload pin damaged the receptacle on the opposing coupling and prevented repeatable measurements of the coupling. To alleviate this problem, wrist replacements were performed with the arm normal to the ground, allowing for straight access to the arm with minimal rotation of the wrist.

Base Interface

For the base interface between the robot and the factory floor, ABB uses several different methods to attach the robot to the factory floor, depending on customer requirements. The configuration available during measurements consisted of a tubular pallet bolted to anchors fixed in the floor. To attach the robot to the pallet, two pins on the pallet are aligned to precision holes in the robot base and eight M20 bolts are tightened to anchor the robot to the pallet. The robot base occupies a total footprint of less than 1 m by 1 m and supports loads of 30 kN and moments of 45 kN-m during normal operation. To adapt the existing base to the new couplings, 1.2 m square interface plates were added that could accommodate both the canoe-ball and three-pin couplings. The existing base interface and new coupling interface plates are shown in Figure 9. The top interface plate was bolted to the robot foot using the existing eight mounting holes and received the ball elements or pin elements, while the bottom plate was bolted to the floor anchors and received the groove elements or provided engagement surfaces for the three pins.
physical size and geometry on the removal and replacement of the parts. To measure the \((x, y, z)\) location of the robot end effector while calibrating the system, ABB used the Leica LTD500 laser-tracking measurement system. For the coupling repeatability measurements, the LTD500 was used to measure the location of a retroreflector mounted on the robot’s tool flange with an accuracy of 0.01 mm per meter between the retroreflector and the motorized laser-tracking device. The retroreflector was located approximately 0.5 m from the wrist coupling and 2.5 m from the base coupling. The Leica system also includes a temperature correction system to adjust for thermal drift of the laser over the course of the measurements.

A series of measurements was performed for each interface using a basic installation procedure, which involved removal of the preload bolts, separation of the interfaces, replacement of the parts, and direct application of design torque to the preload bolts. In addition, a series of measurements was taken to assess the benefit of a more careful, refined installation. The refined installation procedure consisted of the following five steps:

1. Remove preload bolts and separate coupling interfaces using an overhead crane for support.
2. Inspect and carefully clean the contacting surfaces with methanol. Surfaces are not lubricated during the experiments.
3. Clean and lubricate all threads and undersides of bolt heads.
4. Engage coupling interfaces with special attention to alignment of elements using an overhead crane for support.
5. Replace bolts and tighten to design specification in a stepped fashion following a consistent pattern.

After securing the coupling, the overhead crane support was released, placing the full static load on the coupling. The location of the retroreflector was then measured with the robot in the coupling installation position, as well as at five additional stationary positions throughout the workspace of the robot.

Industrial Measurement Procedure

The industrial measurement procedures for the wrist experiments and base experiments were similar, with differences due primarily to the effect of
These additional positions were chosen to emphasize the effects of the coupling stiffness from dynamic motion, such as the changing gravity vectors and braking forces. To ensure that the robot did not experience excessively large forces, the robot’s motion was restricted to a speed of 250 mm/s. Between three and 15 measurements were taken for each variation in coupling type or installation procedure.

**Results—Laboratory Setting for Wrist Geometry**

Before taking coupling repeatability measurements in a laboratory setting, static measurements of the fixed canoe-ball couplings were taken to estimate the thermal drift of the coupling and measurement structures. Over a span of 22 hours, the canoe-ball coupling exhibited an approximately 1 μm drift for a 1° C change, as shown in Figure 10. Similar temperature-deflection profiles were measured for the three-pin coupling. Due to the large thermal drift, special care was taken during laboratory measurements to ensure that the thermal error was not a significant influence on the repeatability.

**Canoe-Ball Coupling Results**

The first laboratory repeatability data, shown in Figure 11, represents the canoe-ball coupling under gravity preload alone, without the preload bolts engaged. Repeatability for these measurements is defined as the difference between the current measurement and the first measurement as expressed by the
standard deviation of the measurement set. In addition, average location shifts are presented, which give the accuracy of the individual coupling pair. Thermal drift significantly affected the repeatability, even for the slight temperature increase over 200 mounting cycles. In Figure 12, the same measurement set is presented, however, the variation between the current test and the immediately previous test are shown. By reducing the measurement sample size from that shown in Figure 11 to a selection such as the region labeled "linear," repeatability measurements begin to approach the test-to-test variation shown in Figure 12. This trend indicates that a large portion of apparent coupling repeatability error is caused by drift errors, in this case largely thermal error. Even with the presence of this thermal error, the gravity preloaded canoe-ball coupling can achieve an average location shift of -0.04 μm with a standard deviation of 0.14 μm.

In the next series of measurements, data were taken under five different preloading conditions: loose bolts, hand-tightened bolts, bolt torque of 7.5 N-m, bolt torque of 15 N-m (90% of bolt yield), and unloaded bolts. Due to the large number of data points, summarized repeatability data is presented in Figure 13 as the average of the location shift with error bars of plus/minus three standard deviations. Measurements from the laboratory experiments may have positive or negative average location shift as the measurements are direct displacements, while measurements for the industrial experiments are magnitudes only and will have only positive average location shift. For measurements taken using the right probes, location shift improved as the preload was increased and worsened on preload removal. The left probe displayed location shift on the same order of magnitude; however, the expected trend did not occur. The reasons for this difference are not known, although measurements from the lower probe were consistently greater for all measurements, which could indicate some relative movement between the probe stand or bottom coupling and the base. At the design preload of 15 N-m, the coupling provided average location shift of -0.24 μm with a standard deviation of 0.55 μm for the right
Three-Pin Coupling Results

Turning to the three-pin coupling, the first repeatability measurements mirrored the above preloading process, as measurements were taken with hand-tightened bolts, bolts tightened to 0.1 N-m, 0.2 N-m, and 0.3 N-m using a torque wrench, and after unloading the bolts. Results shown in Figure 14 indicate that the three-pin coupling can achieve average x and y location shift at levels comparable to the unloaded canoe-ball coupling. However, the variability of the three-pin measurements is much greater, as shown by the large error bars on the plot. At the design preload of 0.3 N-m, the coupling provided an average location shift of ~0.09 μm with a standard deviation of 1.01 μm for the right probe and an average location shift of ~0.05 μm with a standard deviation of 0.92 μm for the left probe. An interesting result of the measurements is that repeatability is relatively independent of the applied preload, after sufficient preload is applied to break friction and bring the interface surfaces into contact. To help reduce this friction, a thin layer of white zinc grease was applied across the interface and at the contact points, and the previous measurements were repeated. Instead of improving repeatability, the grease layer degraded the average three-pin coupling location shift at design preload to ~0.54 μm with a standard deviation of 1.06 μm for the right probe and 2.32 μm with a standard deviation of 1.73 μm for the left probe. As shown in Figure 15, increasing the preload past 0.1 N-m causes the average location shift to deteriorate, while the variability remains relatively constant for all preloads.

The final experiment on the three-pin coupling assessed the effect of changing the preload pin with each measurement. In the previous experiments, the brass tip of the preload bolt deformed with each application of preload. After approximately three applications, the brass tip reached a constant state of deformation, as shown in Figure 16. Without this break-in process on the preload tip, average location shift worsened to 1.58 μm with a standard deviation of 1.08 μm at the right probe, and 1.58 μm with a standard deviation of 1.16 μm at the left probe.
Results—Industrial Setting

Wrist Coupling Results

Before beginning in-situ measurements of the couplings on the industrial robot wrist, repeatability measurements were taken for the existing wrist coupling. In field measurements, ABB found that the current wrist design can provide an average repeatability of approximately 0.3 mm. No variability information from these trials was available. A second set of baseline measurements was taken for the current wrist design using the robot unit tested with the new coupling designs. Because of the care taken during measurements, the original wrist coupling’s average location shift improved to 0.12 mm with a standard deviation of 0.05 mm.

The first series of prototype measurements was taken by securing the canoe-ball coupling on the robot, moving the robot to five points throughout the workspace, and recording the (x, y, z) location of the tool interface at each point (Willoughby 2002). Results presented in Figure 17 show the mean location shift averaged over the five points of interest. The first measurements were taken with 15 N·m of preload torque applied to the preload bolts using the basic installation procedure. However, this preload was insufficient to maintain the stiffness of the joint, and hence, additional preload was applied via off-center bolts located around the wrist perimeter.

A separate series of measurements was taken for each additional torque value of 15 N·m, 50 N·m, 75 N·m, and 120 N·m. As the preload torque reached 50 N·m, the repeatability approached an average location shift of 0.10 mm with a standard deviation of 0.06 mm. Above this torque, the three wings of the coupling began to deflect, causing the location of the contact points to change, which degraded the repeatability.

In an attempt to further improve repeatability, several alterations to the installation procedure were tested, with results shown in Figure 18. The first alteration was to perform the wrist replacement with the robot’s arm at 90° to the ground. While this had only a minor effect on the average location shift and a worsening effect for the standard deviation when compared to the current wrist design, the angular change markedly decreased both the average and standard deviation when compared to the same replacement at 45°. The second alteration retained the 45° installation, but all installations occurred using the refined procedure discussed previously. With these changes, the average location shift improved significantly over the existing wrist to a location shift of 0.06 mm with a standard deviation of 0.03 mm. Combining the 90° installation and refined techniques, repeatability improved slightly to an average location shift of 0.05 mm with a standard deviation of 0.02 mm. By restricting measurements
to the robot arm in one position, the best possible repeatability in industrial experiments is achieved with an average location shift of less than 0.05 mm and a standard deviation of 0.02 mm.

The final series of measurements on the wrist interface was taken using the three-pin coupling and is shown in Figure 19. Initially, measurements were taken with the wrist in the 45° position. However, after five measurements, the preload pin scraped the matching receptacle, damaging the contact surfaces. Displacement measurements following the damage steadily worsened from 0.08 mm to 0.98 mm, at which point it was decided that the damage was significantly affecting the measurements in this position. Three additional measurements were taken with the wrist in the 90° position with promising results, but further testing is required to accurately determine the repeatability of the three-pin coupling on the wrist. Except for the damage noted, only minor scratches were left on the interface surfaces for both the three-pin and canoe-ball wrist couplings.

**Base Coupling Results**

For the base interface coupling, a total of three groups of measurements were taken—reference repeatability using the blue pallet base, experimental repeatability for the three-pin coupling, and experimental repeatability for the canoe-ball couplings. Measurements with the three-pin and canoe-ball couplings were taken with both the basic and refined installation procedures, with the results shown in Figure 20 (Hart 2001). The baseline repeatability of the blue pallet base was measured to have an average location shift of 1.60 mm with a standard deviation of 0.50 mm. The three-pin coupling without the refined installation procedure showed an 89% improvement over the conventional bolted pallet. The refined installation procedure improved this repeatability to an average location shift of 0.10 mm with a standard deviation of 0.04 mm. For the basic installation procedure, the canoe-ball couplings achieved an improvement in repeatability of 93%. With the addition of the refined installation procedure, the canoe-ball couplings demonstrated only a
Slight improvement over the refined three-pin mounting with an average location shift of 0.11 mm and standard deviation of 0.03 mm. Physically, the three-pin couplings showed very little signs of wear, while the canoe-ball couplings had clearly visible scratches or burnish marks caused by the rather inexact placement process. The canoe-ball elements also exhibited dark spots approximately 15 mm in diameter, corresponding to the elastic deformation region of the contact interfaces. It should be noted that it is likely that particles would have become trapped between the contacting surfaces in the factory environment if a thorough cleaning process had not been followed.

Conclusions

The primary conclusion from measurements of kinematic coupling performance in both industrial and laboratory settings is that proper mounting of a kinematic coupling is equally as important as the presence of the kinematic interface. Careful attention to mounting conditions is required to ensure high repeatability for high-load interfaces in industrial settings: A factor of two to three improvement in interface repeatability is possible simply by switching from a basic mounting procedure to a refined installation procedure with proper preloading and lubrication. Within the refined installation procedure, preload application is one of the most critical actions. Without properly applied sufficient preload, frictional effects adversely affect interface position and optimal repeatability cannot be achieved (Slocum and Donmez 1988).

In industrial trials, the canoe-ball coupling was able to improve repeatability of the robot wrist interface by about 60% and of the base interface by about 90%. The three-pin coupling was capable of improving the wrist interface repeatability by about 30% and was able to improve the base interface repeatability by about 90%. Because of the interface damage, the three-pin coupling on the wrist interface must undergo further industrial measurements to properly characterize repeatability. Summary results are shown in Table 1. The trends in the measurements indicate that the three-pin coupling
is a lower cost but less repeatable alternative to the higher cost, more repeatable canoe-ball couplings; however, as the physical size and scale of loading increase, this trend becomes less significant. In the case of the base couplings, the controller will include a structural model to estimate errors due to dynamic forces on the base, which will help to improve the effective stiffness.

While measurements for the laboratory experiments were taken at the center of stiffness, measurements for the industrial couplings were taken at a fixed distance (0.5 m) from the coupling center under changing loads.

A simple approximation for the repeatability of the industrial couplings at the center of stiffness of each coupling indicates that the theoretical repeatability could be an order of magnitude better than the measured results. In general, both the three-pin and canoe-ball couplings measured in this study result in an order of magnitude improvement in coupling repeatability over the current overconstrained designs commonly used in industry. These trends indicate that the canoe-ball and three-pin coupling designs are promising for industrial applications; however, further testing is required to show statistical significance for the potential range of operating conditions and across multiple coupling pairs.

Acknowledgments

This work was sponsored by research grants from ABB Corporate Research and the Ford-MIT Alliance. The authors thank Alec Robertson of ABB Robotics for his assistance in completing the repeatability measurements for the robot base and wrist, and Gerry Wentworth of the MIT LMP machine shop for his assistance in manufacturing the prototype wrist interface plates.

References


Authors' Biographies

Patrick Willoughby is currently an R&D mechanical engineer in the Cardiac Rhythm Management division of the Guidant Corp. He holds a B.S. (2000) from the University of Pittsburgh and did his graduate work in the Dept. of Mechanical Engineering at the Massachusetts Institute of Technology, including an M.S. (2002) and a Ph.D. (2005). His doctoral research was on modeling of elastic averaging for a fiber optic connector and development of the silicon insert molded plastic process. His interests include design of biomedical devices, biomaterials, machine design, and the engineering design process.

Anastasio John Hart is a PhD candidate in the Dept. of Mechanical Engineering at MIT. His doctoral research is on synthesis of carbon nanotubes, and his interests include nanostructured and composite materials, machine design, microsystems, and energy production and conversion. John holds an MS (2002) from MIT and a BSE (2000) from the University of Michigan, both in mechanical engineering, and he has industry experience at General Motors Corp.

Alex Sloucum did his undergraduate and graduate work at MIT. While at the National Bureau of Standards, he earned 12 superior service awards and a Department of Commerce Bronze Medal. He is now a professor of mechanical engineering at MIT and a MacVicar Faculty Fellow. He has more than 60 patents issued/pending. He has been involved in nine products gaining R&D 100 awards and is the recipient of the SME Frederick W. Taylor Research Medal and the ASME Leonardo daVinci Award. His current interests focus on the development of precision machines and instruments, MEMS, nanotechnology, and consumer products.