Design of a Precision Robot Wrist Interface

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Project Summary

**Problem:** Current bolted robot wrist replacements are inaccurate, causing ~1.0 mm errors at robot tool which are transmitted to the work piece.

**Possible Solutions:**
1. Costly and lengthy calibration procedures
2. Inexpensive classic ball and groove kinematic coupling
3. Very inexpensive three pin coupling
Application: ABB IRB 6400R Robot

- Heavy duty industrial robot
- Six degree of freedom manipulator
- Carrying capacity of 200 kg
- Maximum tool speed of 3 m/s
- Tool position repeatability of 0.1 mm
- Common applications
  - Automotive assembly, welding, and painting
  - Material Handling
Current Wrist Replacement

- Requires $\sim \frac{1}{2}$ hour to do replacement and 2 hours to perform recalibration of robot
- Wrist mass of $\sim 100$kg
- Replacement can cause severe damage to motor
- Concerns for worker safety
**Existing Coupling**

- Uses large surface contact with alignment pins and surfaces
- Repeatability is a function of machining tolerances
- Repeatability of 0.3 mm
- Stiffness derived from friction between interface surfaces

*Interface on Arm*  
*Interface on Wrist*  
*Friction Plate*
Project Requirements and Strategy

1. Improve repeatability of wrist replacement on IRB 6400R
2. Minimize physical changes to existing wrist structure
3. Minimize changes in structural performance of wrist
4. Introduce concepts of exact constraint design and kinematic couplings to ABB

**Strategy:** Develop kinematic coupling adapter plates that can be added to robot to test repeatability
## Overview of Common Coupling Methods

<table>
<thead>
<tr>
<th>Coupling Type</th>
<th>Contact Type</th>
<th>Repeatability</th>
<th>Stiffness</th>
<th>Load Capacity</th>
<th>Industrially Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Pin Joint</td>
<td>Surface</td>
<td>Poor</td>
<td>High</td>
<td>High</td>
<td>Fair</td>
</tr>
<tr>
<td>Elastic Averaging</td>
<td>Surface</td>
<td>Fair</td>
<td>High</td>
<td>High</td>
<td>Good</td>
</tr>
<tr>
<td>Planar Kinematic</td>
<td>Mixed</td>
<td>Good</td>
<td>High</td>
<td>High</td>
<td>Good</td>
</tr>
<tr>
<td>Quasi-Kinematic</td>
<td>Line</td>
<td>Good</td>
<td>Medium to High</td>
<td>High</td>
<td>Good</td>
</tr>
<tr>
<td>Kinematic</td>
<td>Point</td>
<td>Excellent</td>
<td>Low</td>
<td>Varies</td>
<td>Poor</td>
</tr>
</tbody>
</table>

- **Pinned Joints**: No Unique Position
- **Elastic Averaging**: Non-Deterministic
- **Planar Kinematic**: Non-Deterministic
- **Kinematic Couplings**: Kinematic Constraint
Exact Constraint or Kinematic Design

- Each component has an equal number of constrained points to number of degrees of freedom
- If component is over constrained, clearance and high tolerances required to prevent premature failure or assembly incompatibility
- Kinematic design means that the motion is exactly constrained and geometric equations can be written to describe its motion
Ball and Groove Coupling Design

- Uses standard kinematic coupling design of six point constraint in a stable coupling triangle
- Preload applied through ball center to resist static loading
Coupling Stability

- Basic Definition – A stable coupling is one which remains constrained when design loads are applied
- Many factors affect stability:
  - Geometry
  - Friction
  - Preload
  - Disturbance Loads
Hertz Contact Stress Design

- Exact constraint design creates contact at single points or lines, creating high contact stresses
- Managing Hertz contact stresses is the key to successful kinematic coupling design

Contact Mechanics Equations:

Equivalent radius and modulus

\[ R_e = \frac{1}{R_{1\text{major}}} + \frac{1}{R_{1\text{minor}}} + \frac{1}{R_{2\text{major}}} + \frac{1}{R_{2\text{minor}}} \]

\[ E_e = \frac{1}{\frac{1}{E_1} + \frac{1}{E_2}} \]

Deflection of Contact Point

\[ = \left( \frac{2F^2}{3R_eE_e^2} \right)^{1/3} \]

Contact Pressure of Contact Ellipse

\[ q = \frac{3F}{2 \cdot \text{cd}} \]

c & d are diameters of ellipse
Canoe Ball and Groove Design

- "Canoe Ball" Design
  - Places a section of a sphere with radius of 250 mm onto a small block to reduce contact stress
  - Large shallow Hertzian stress zone
  - Repeatability of ¼ micron or on the order of parts’ surface finish
  - Stiffness and load capacity are 100 times that of a normal 1” ball

- Contact stresses determined to be 1/3 of allowable stress

<table>
<thead>
<tr>
<th></th>
<th>Normal Operation</th>
<th>Emergency Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$</td>
<td>7588</td>
<td>9020</td>
</tr>
<tr>
<td>$F_y$</td>
<td>8755</td>
<td>23712</td>
</tr>
<tr>
<td>$F_z$</td>
<td>7542</td>
<td>2321</td>
</tr>
<tr>
<td>$M_x$</td>
<td>3843</td>
<td>5687</td>
</tr>
<tr>
<td>$M_y$</td>
<td>5567</td>
<td>8192</td>
</tr>
<tr>
<td>$M_z$</td>
<td>7362</td>
<td>29320</td>
</tr>
</tbody>
</table>

Units in N or N-m
CAD Model for Ball and Groove Coupling

- Plates are 30mm thick
- Interface plates have negative features to couple with existing interface
- Interface plates installed between wrist and arm
- Tabs added to outside to hold large balls and grooves, coupling features in future can be integrated into wrist

Grey – Robot Structure
Orange – Arm Interface Plate
Green – Canoe Balls
Blue – Grooves
Red – Wrist Interface Plate
Yellow – Preload Bolts
Not Shown – Wrist Unit
CAD Model for Ball and Groove Coupling

- Uses separately machined canoe balls and grooves secured to plates
- Bolting Pattern
  - Four bolts used to secure each plate to robot structure
  - Four bolts to connect coupling
  - Three separate preload bolts
- Expensive canoe features on permanent structure, cheaper grooves on “disposable” wrist
- Predicted laboratory repeatability in microns
Prototypes for Ball and Groove Coupling
Planar Kinematic Coupling Design

- Uses a new type of coupling: *Three Pin Coupling*
- Constraint Pattern:
  - Three Degrees of Freedom on Large Surface Contact
  - Three Degrees of Freedom using Line Contacts on Pins
- In plane preload required to set coupling against friction
- Out of plane preload required to close interface and carry loads
Planar Kinematic Coupling Design

Four step design process:
1. Determine interface geometry and method of preload.
2. Determine in plane preload to set coupling against interface friction using free body diagram of static load case.
3. Determine out of plane preload to maintain interface stiffness using free body diagram of disturbance load case.
4. Size pins to withstand contact and bending stresses with necessary safety factors.
CAD Model of Planar Kinematic Coupling

- Plates are ~20mm thick
- Interface plates have negative features to couple with existing interface
- Interface plates installed between wrist and arm

Grey – Upper Arm
Red – Arm Interface Plate with Pins for Coupling
Blue – Wrist Interface Plate with Receptacles
Wrist – Not Shown
CAD Model of Planar Kinematic Coupling

- All features are integral to the interface plates
- Bolting Pattern
  - Four bolts used to secure each plate to robot structure
  - Four bolts to connect coupling
  - One in-plane preload bolt
- Changes to existing robot are minimal, replace control pin and add preload pin
Operation of Planar Kinematic Coupling

Two “Pins” on Arm Plate

Third Pin on Arm Plate

Two “Holes” on Wrist Plate

Pill Shaped Hole for Pin in Wrist Plate

Preload Bolt - Steel bolt with brass tip
Prototypes for Planar Kinematic Coupling
Prototype Wrist Plate Mounting

Tests at ABB Robotics Västerås, Sweden July 2001:

- Tested existing coupling as well as the canoe ball and three pin wrist prototypes
- Test static and dynamic (5-point path) repeatability of canoe ball
- Test variety of preloads (canoe balls)
- Replacement in two orientations (45 and 90 degrees to ground)
- Measure tool point motion using Leica LTD500 Laser Tracker
- Repeatability of robot path + measurement system approximately 20 to 30 microns
Repeatability Performance of KC

<table>
<thead>
<tr>
<th>Installation Angle</th>
<th>Additional Preload</th>
<th>Measurement Type</th>
<th>Bolting</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>0 Nm</td>
<td>5 pt</td>
<td>Plain</td>
</tr>
<tr>
<td>45°</td>
<td>15 Nm</td>
<td>5 pt</td>
<td>Plain</td>
</tr>
<tr>
<td>45°</td>
<td>50 Nm</td>
<td>5 pt</td>
<td>Plain</td>
</tr>
<tr>
<td>45°</td>
<td>75 Nm</td>
<td>5 pt</td>
<td>Plain</td>
</tr>
<tr>
<td>45°</td>
<td>120 Nm</td>
<td>5 pt</td>
<td>Plain</td>
</tr>
<tr>
<td>90°</td>
<td>0 Nm</td>
<td>5 pt</td>
<td>Refined</td>
</tr>
<tr>
<td>90°</td>
<td>Clamps</td>
<td>5 pt</td>
<td>Refined</td>
</tr>
<tr>
<td>90°</td>
<td>Clamps</td>
<td>Static</td>
<td>Refined</td>
</tr>
</tbody>
</table>
Repeatability Performance of Three Pin

1. Normal Wrist
2. 5 point measurement with 45° inclination
3. 5 point measurement with 90° inclination
4. 5 point measurement with 45° inclination

Installation Issues:
- Preload could not be accurately applied as equipment was unavailable
- Damage occurred to alignment features caused by wrist twisting at interface during exchange

Damage!!
Positions of Robot for 5pt Measurement

1 3
2 5
4

[Images of robot positions 1 to 5]
Repeatability Results and Conclusions

- Performance of Different Coupling Designs
  - Canoe balls vs. Normal Wrist @ 45° = 35% reduction
  - Canoe balls vs. Normal Wrist @ 90° = 64% reduction
  - Potential Three-pin vs. Normal Wrist @ 45° = 44% reduction

- Performance of Different Installation Procedures for Canoe Ball Coupling
  - Refined bolting procedure improved repeatability from 0.180 mm to 0.065 mm
  - Mounting process at 90° improved repeatability from 0.180 mm to 0.074 mm
  - Refined bolting procedure and mounting process at 90° improved repeatability from 0.180 mm to 0.062 mm
Project Conclusions

- Kinematic couplings can work in an industrial setting
  - Classic ball and groove formation requires minor modifications for space restrictions and load capacity
  - Three pin coupling requires further testing to verify results
- Industrial applications require more attention on actual installation procedure
- Some further work is required to develop a final product
Recommended Next Steps

- Adapt canoe ball design to fit into space of wrist
- Suggest production designs for different concepts
- Investigate:
  - Three pin coupling in 90 degree position
  - Effect of friction reduction using TiN coated elements or lubrication
  - Coupling design independent of mounting position
  - Applicability quasi-kinematic couplings
- Evaluate long-term dynamic performance