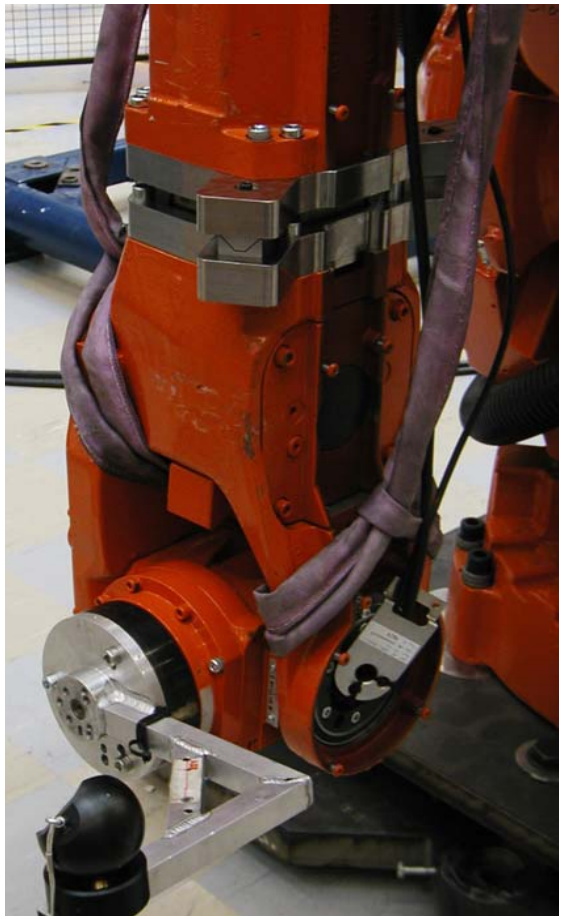
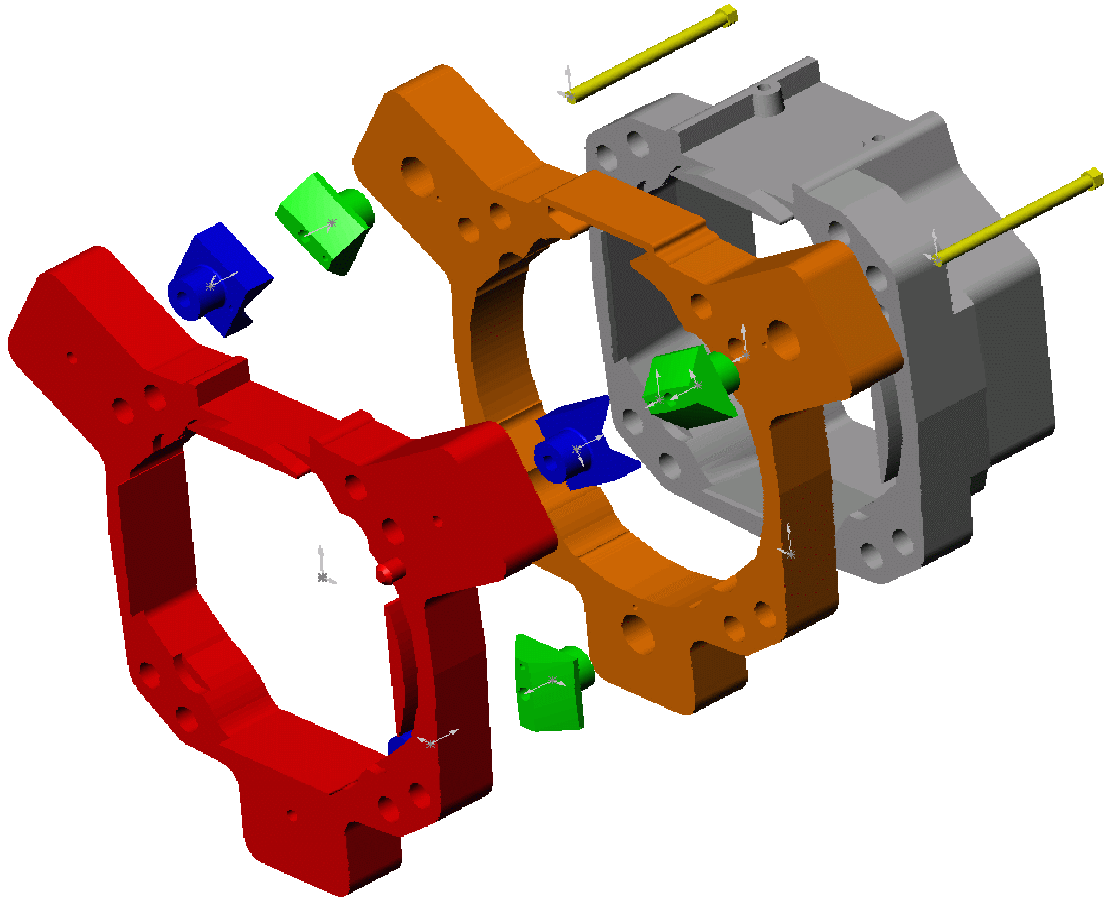
Design of a Precision Robot Wrist Interface





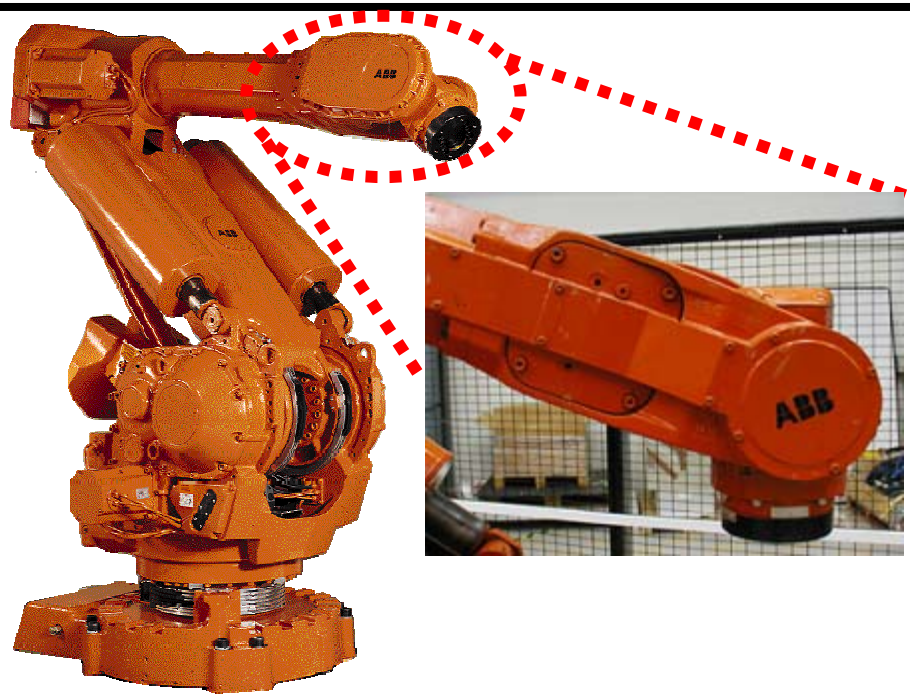
Patrick Willoughby

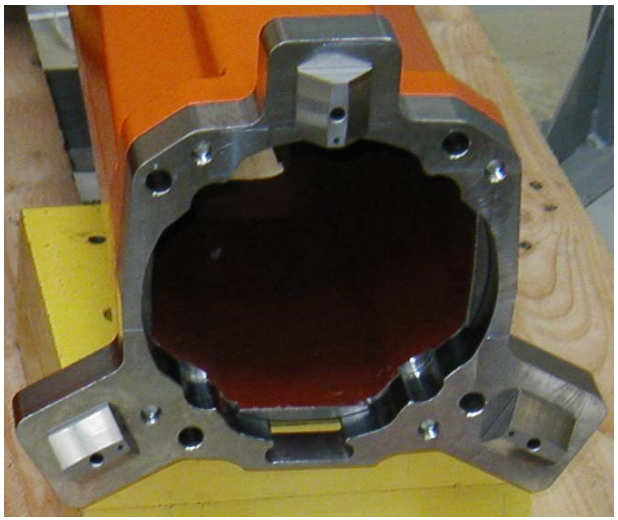
Advisor: Alexander Slocum

MIT Precision Engineering Research Group

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.



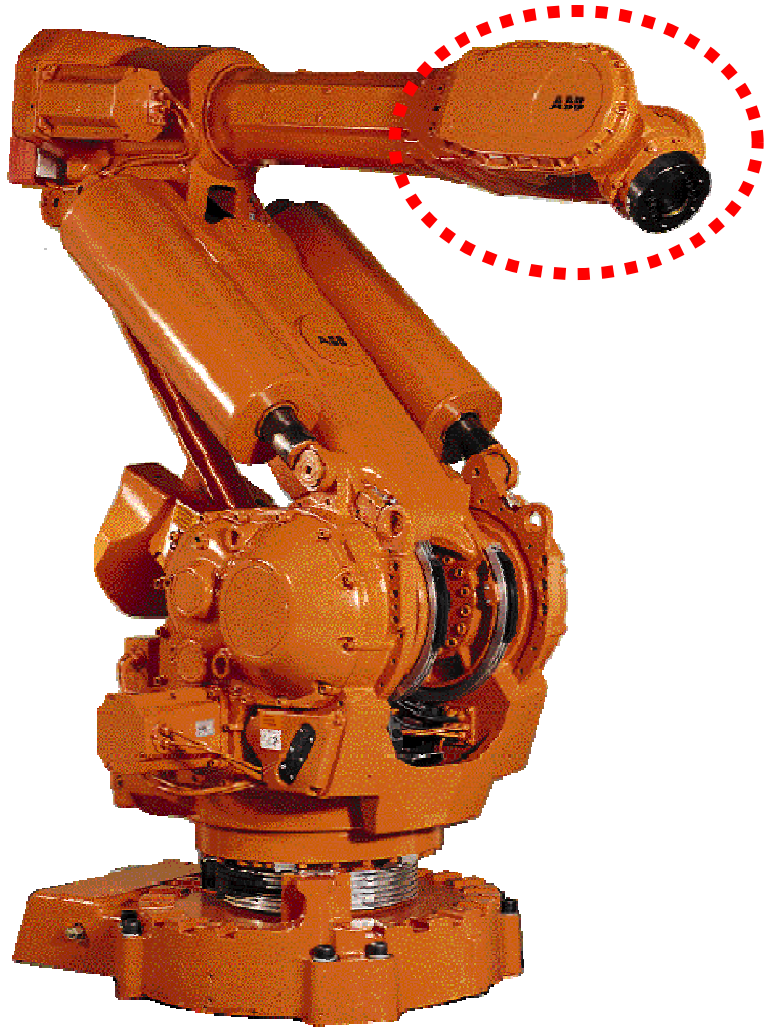


Possible Solutions:

1. Costly and lengthy calibration procedures
2. Inexpensive classic ball and groove kinematic coupling
3. Very inexpensive three pin coupling

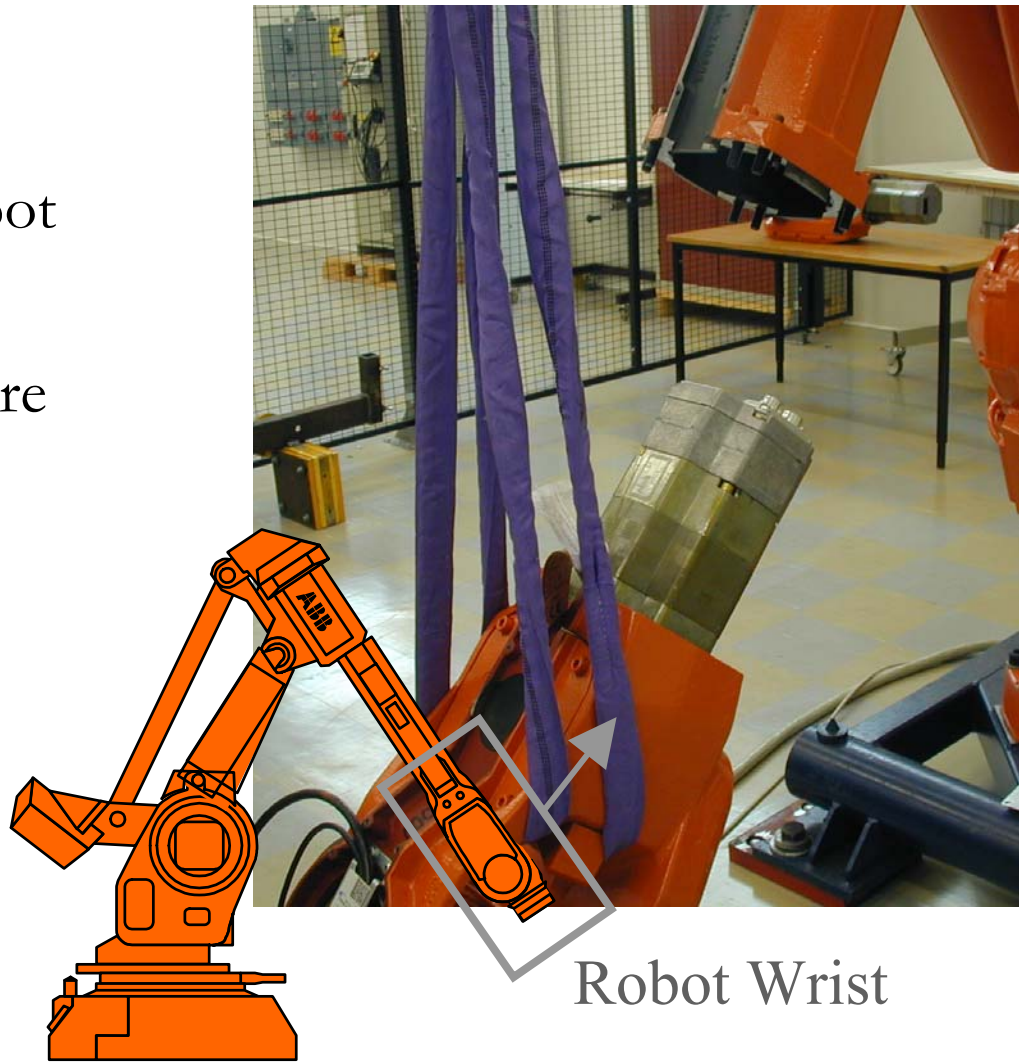
Application: ABB IRB 6400R Robot

- 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 ~½ hour to do replacement and 2 hours to perform recalibration of robot
- Wrist mass of ~100kg
- Replacement can cause severe damage to motor
- Concerns for worker safety



Robot Wrist

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



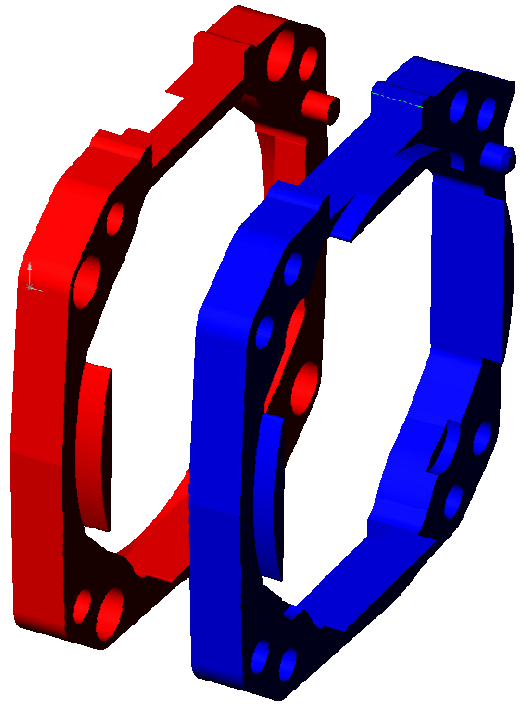
Interface on Wrist



Friction Plate

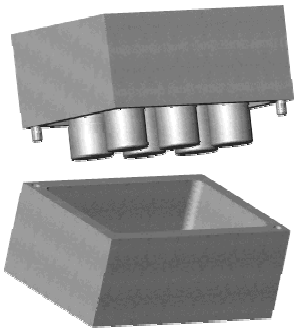
Project Requirements and Strategy

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



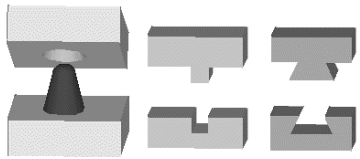
Strategy: Develop kinematic coupling adapter plates that can be added to robot to test repeatability

Overview of Common Coupling Methods



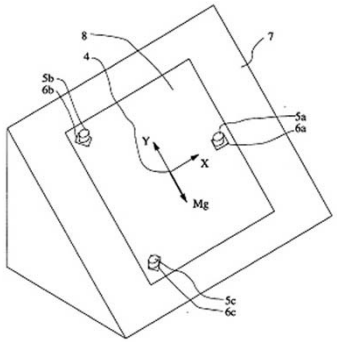
Pinned Joints

No Unique Position



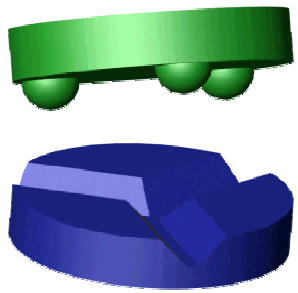
Elastic Averaging

Non-Deterministic



Planar Kinematic

Non-Deterministic



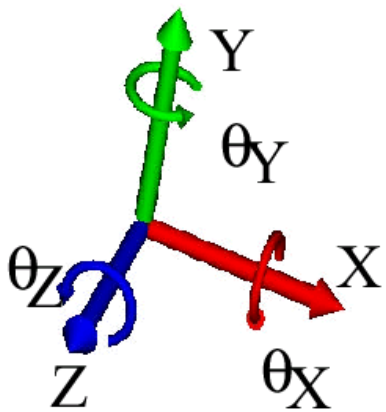
Kinematic Couplings

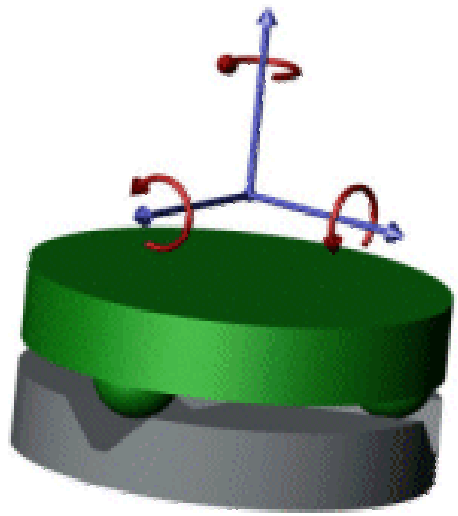
Kinematic Constraint

Coupling Type	Contact Type	Repeatability	Stiffness	Load Capacity	Industrially Ideal
Basic Pin Joint	Surface	Poor	High	High	Fair
Elastic Averaging	Surface	Fair	High	High	Good
Planar Kinematic	Mixed	Good	High	High	Good
Quasi-Kinematic	Line	Good	Medium to High	High	Good
Kinematic	Point	Excellent	Low	Varies	Poor

Exact Constraint or Kinematic Design

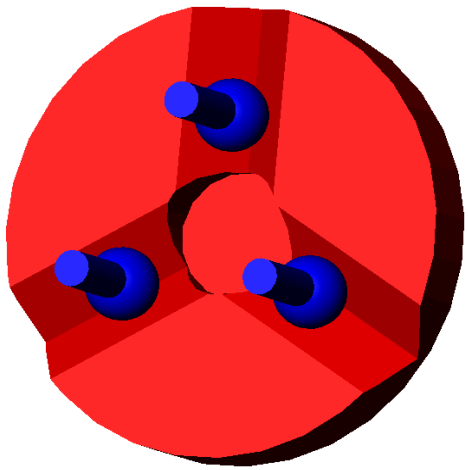
- Each component has an equal number of constrained points to number of degrees of freedom
- If component is over constrained, clearance and high tolerances required to prevent premature failure or assembly incompatibility
- Kinematic design means that the motion is exactly constrained and geometric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

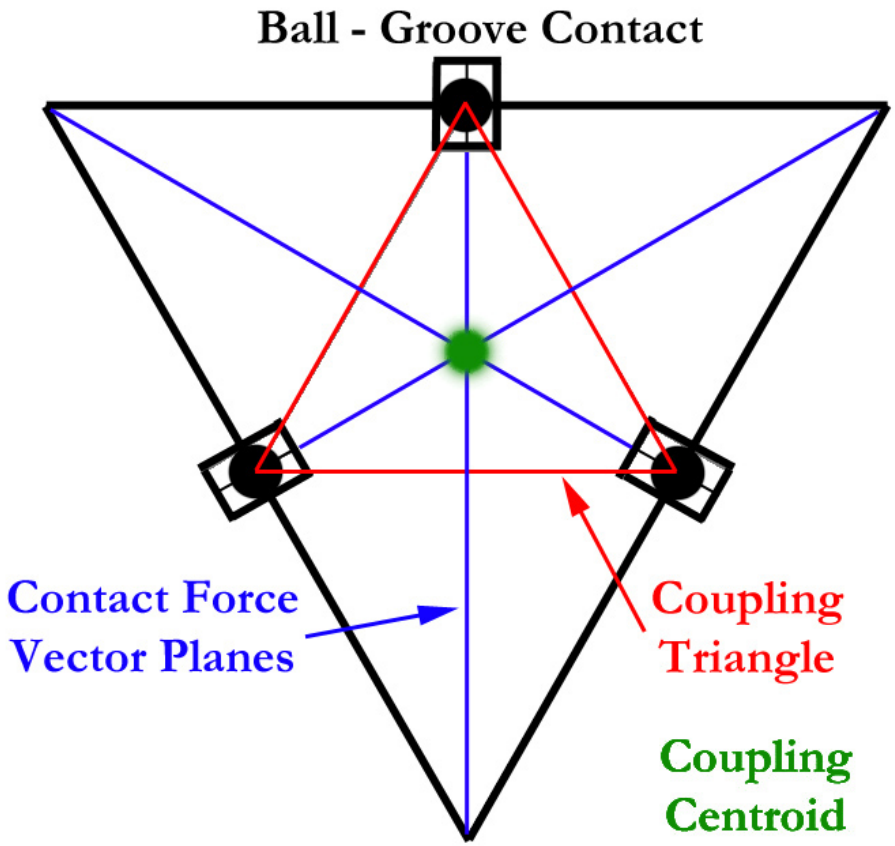




Ball and Groove Coupling Design

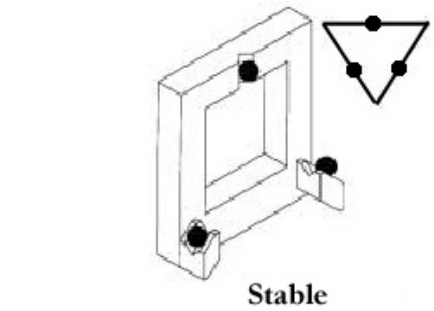
- Uses standard kinematic coupling design of six point constraint in a stable coupling triangle
- Preload applied through ball center to resist static loading

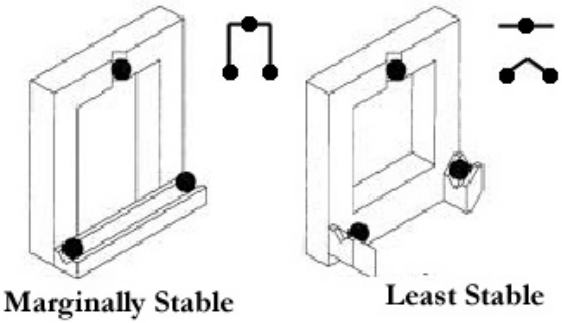


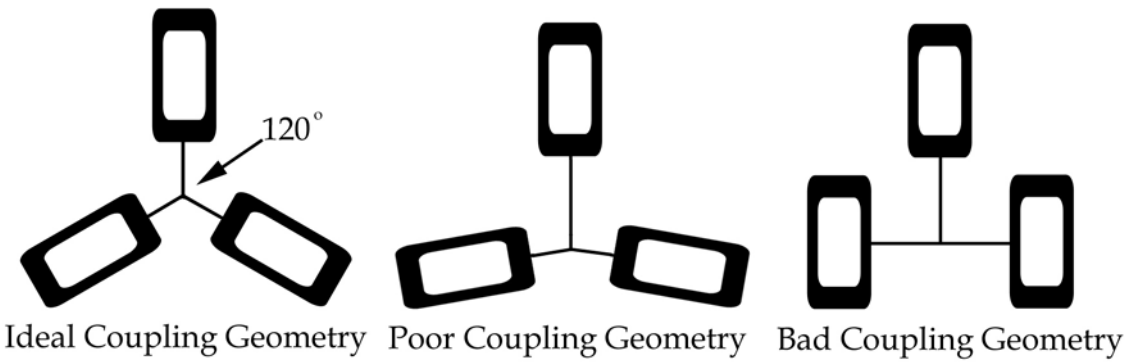


Coupling Stability

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

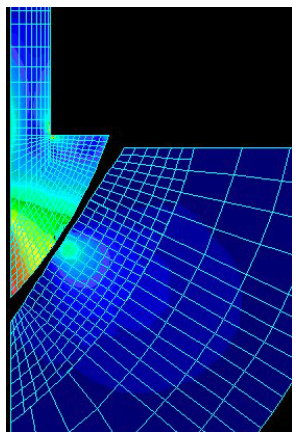


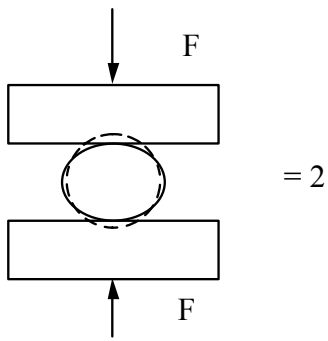




Hertz Contact Stress Design

- 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





= 2

Contact Mechanics Equations:

Equivalent radius and modulus

$$R_e = \frac{1}{\frac{1}{R_{1\,major}} + \frac{1}{R_{1\,minor}} + \frac{1}{R_{2\,major}} + \frac{1}{R_{2\,minor}}}$$

$$E_e = \frac{1}{\frac{1 - {}^2_1}{E_1} + \frac{1 - {}^2_2}{E_2}}$$

Deflection of Contact Point

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

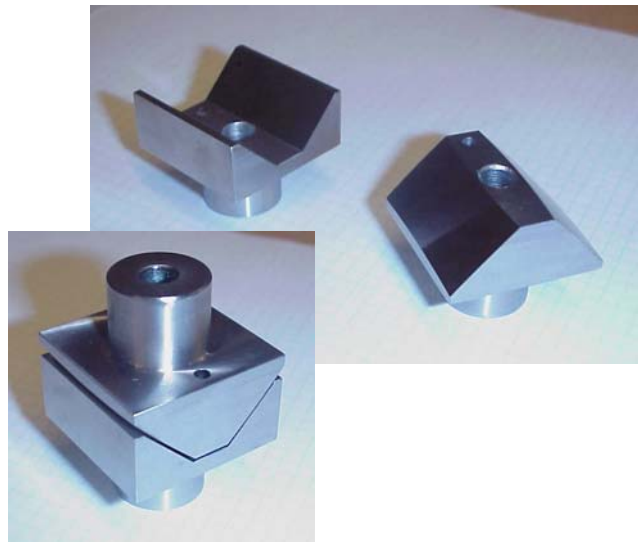
Contact Pressure of Contact Ellipse

$$q = \frac{3F}{2\ cd}$$

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

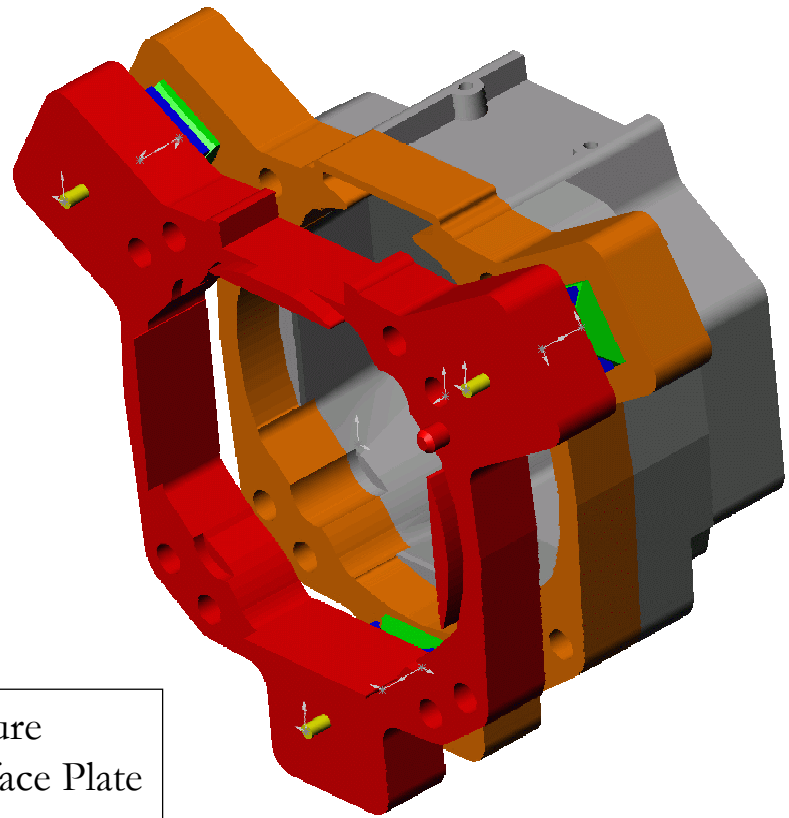


	Fx	Fy	Fz	Mx	My	Mz
Normal Operation	7588	8755	7542	3843	5567	7362
Emergency Stop	9020	23712	2321	5687	8192	29320

Units in N or N-m

CAD Model for Ball and Groove Coupling

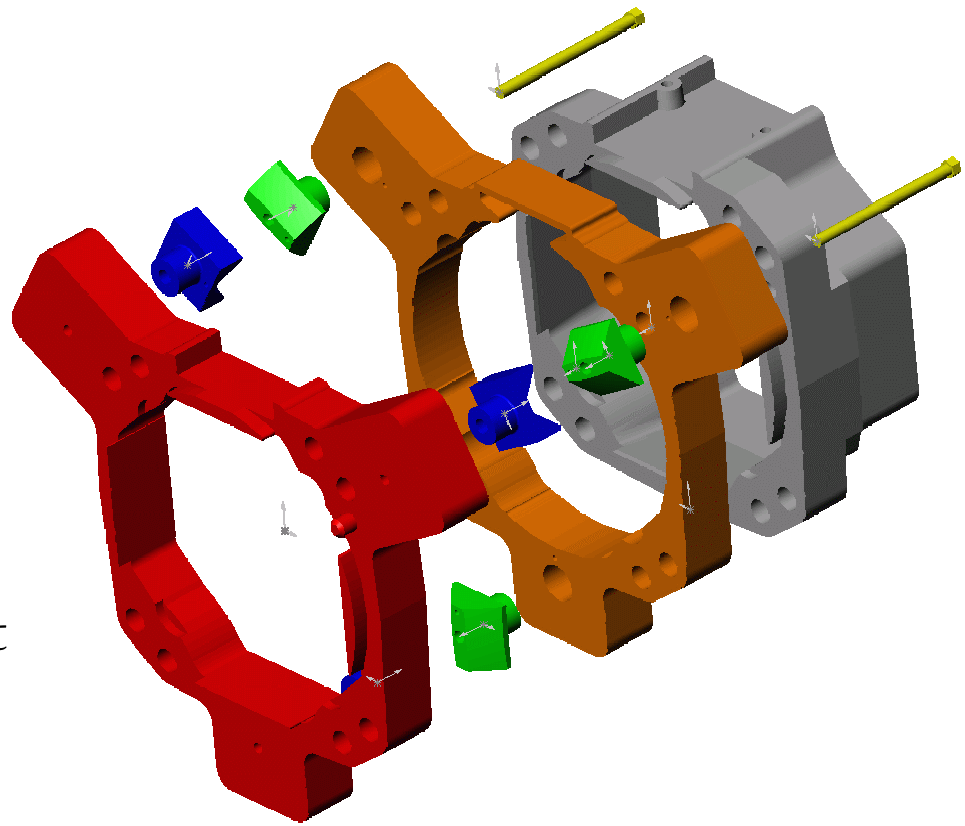
- Plates are 30mm thick
- Interface plates have negative features to couple with existing interface
- Interface plates installed between wrist and arm
- Tabs added to outside to hold large balls and grooves, coupling features in future can be integrated into wrist



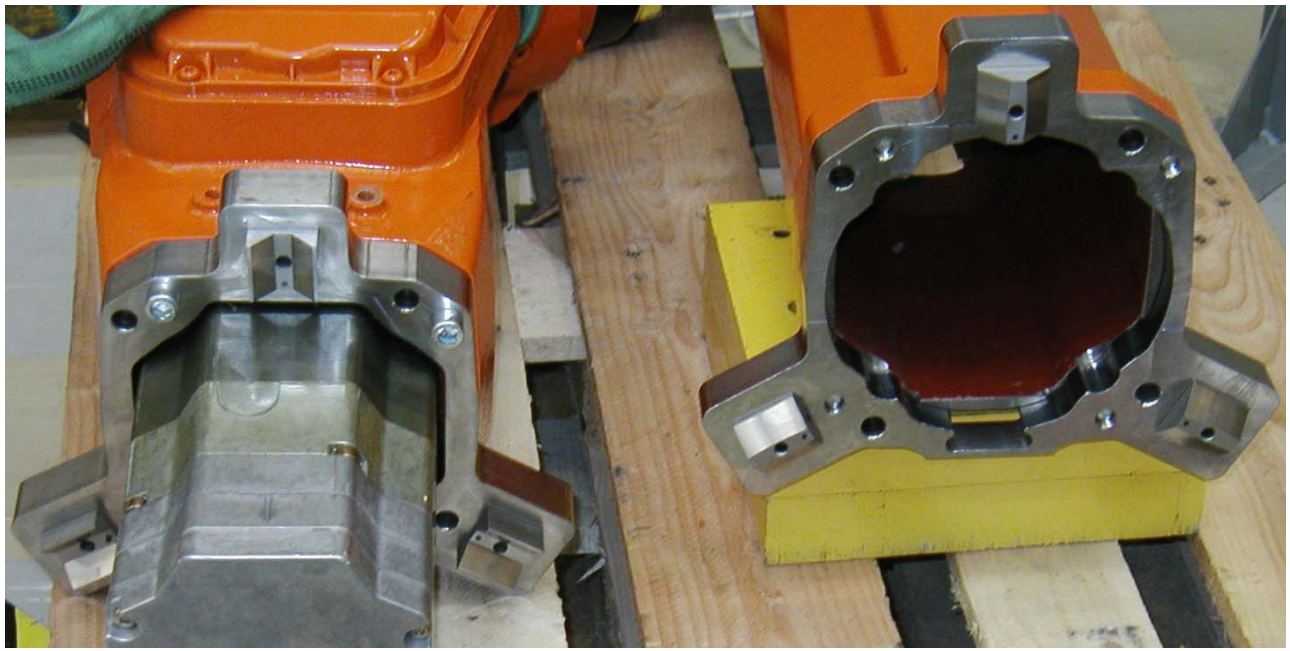
Grey – Robot Structure
Orange – Arm Interface Plate
Green – Canoe Balls
Blue – Grooves
Red – Wrist Interface Plate
Yellow – Preload Bolts
Not Shown – Wrist Unit

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

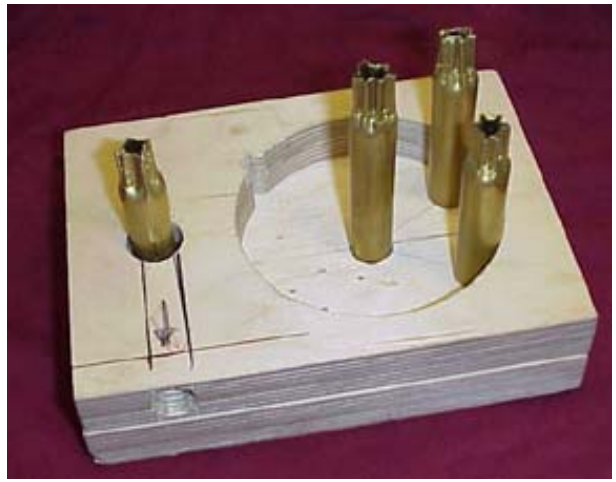


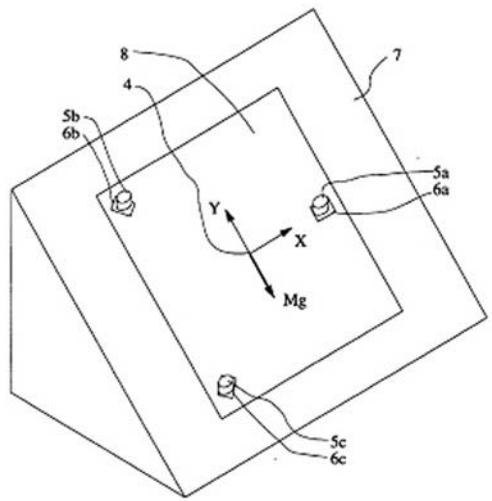




Planar Kinematic Coupling Design

- 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

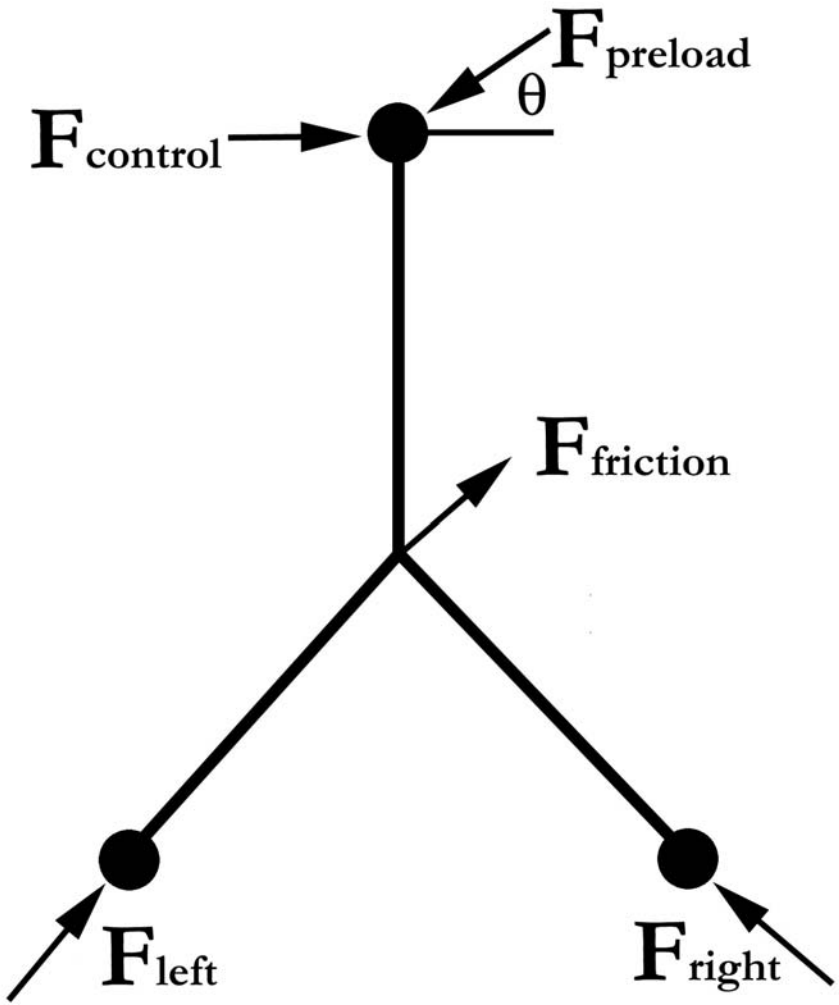




Planar Kinematic Coupling Design

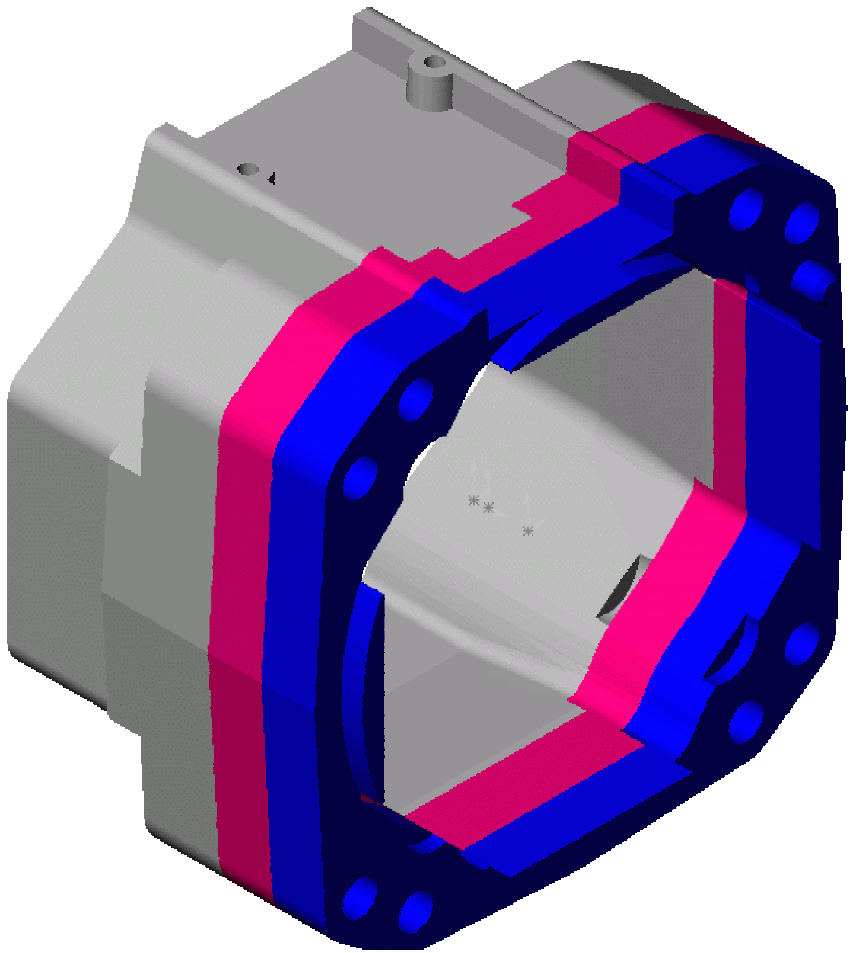
Four step design process:

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

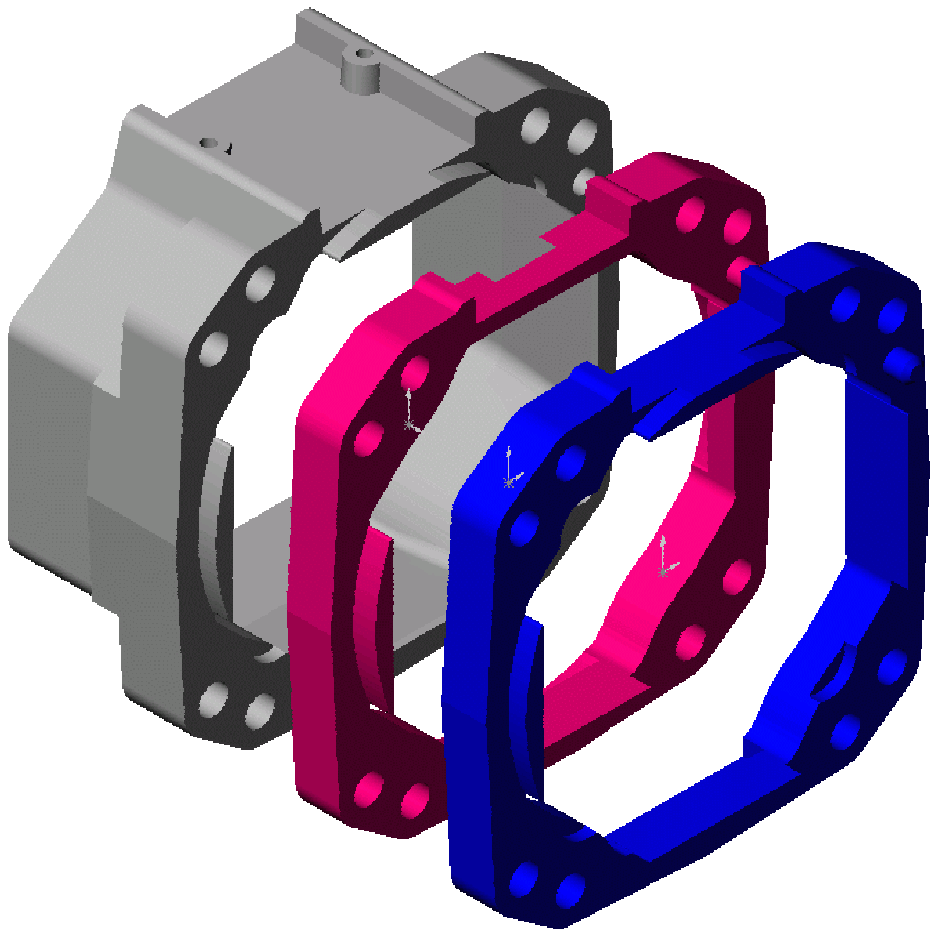
- Plates are ~20mm thick
- Interface plates have negative features to couple with existing interface
- Interface plates installed between wrist and arm



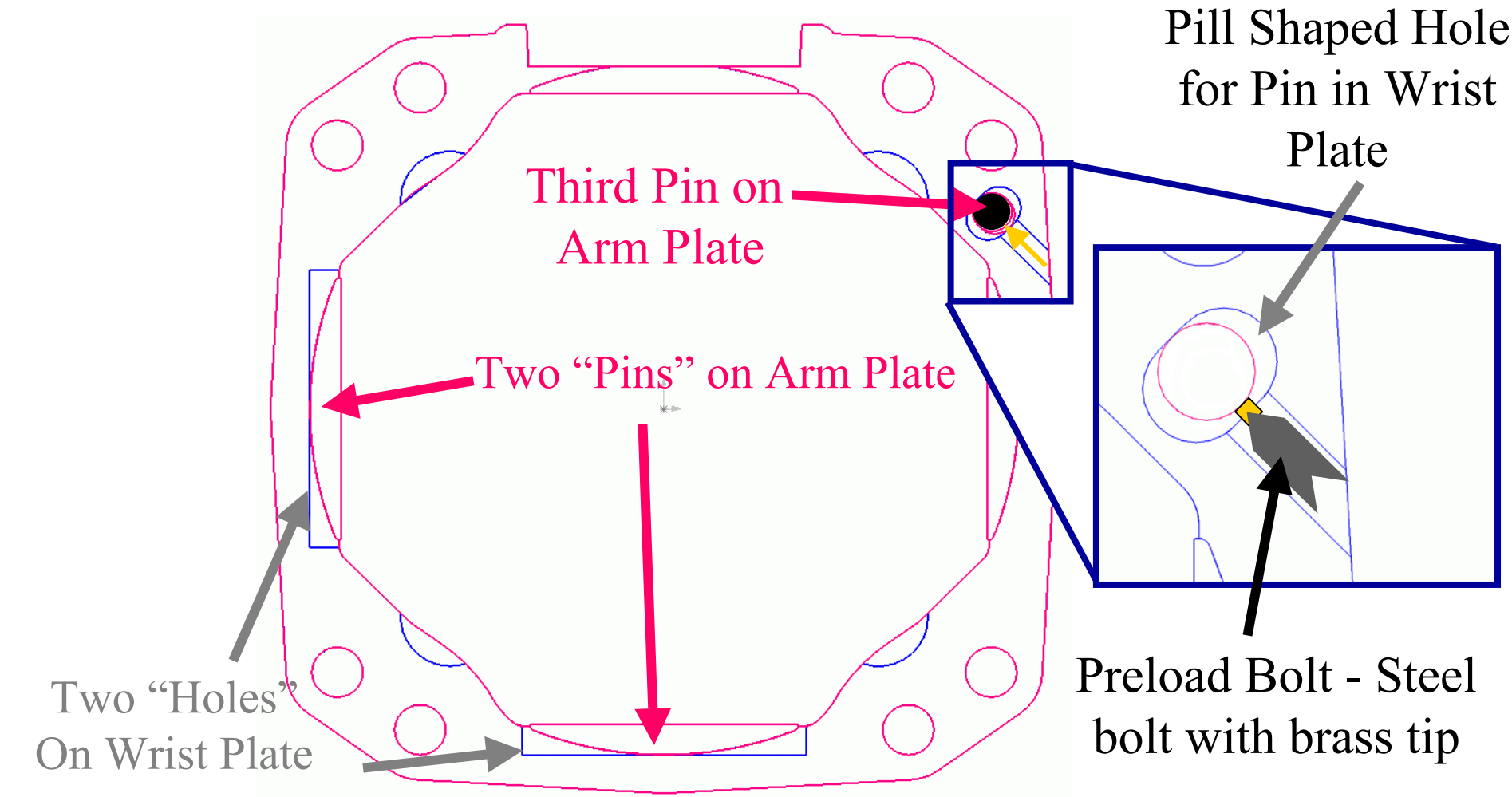
Grey – Upper Arm
Red – Arm Interface Plate with Pins for Coupling
Blue – Wrist Interface Plate with Receptacles
Wrist – Not Shown

CAD Model of Planar Kinematic Coupling

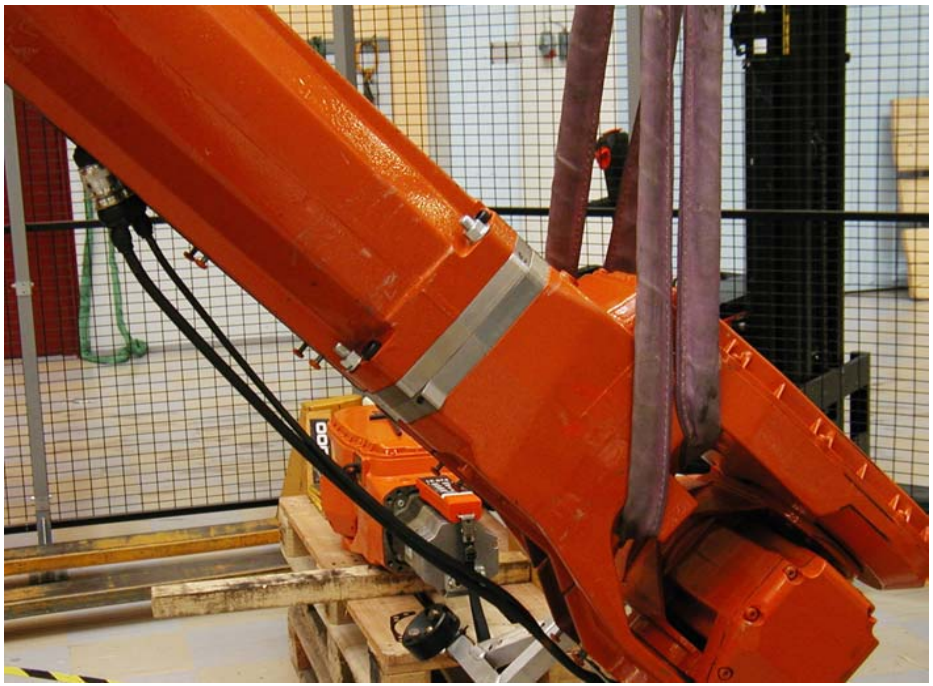
- All features are integral to the interface plates
- Bolting Pattern
  - Four bolts used to secure each plate to robot structure
  - Four bolts to connect coupling
  - One in-plane preload bolt
- Changes to existing robot are minimal, replace control pin and add preload pin



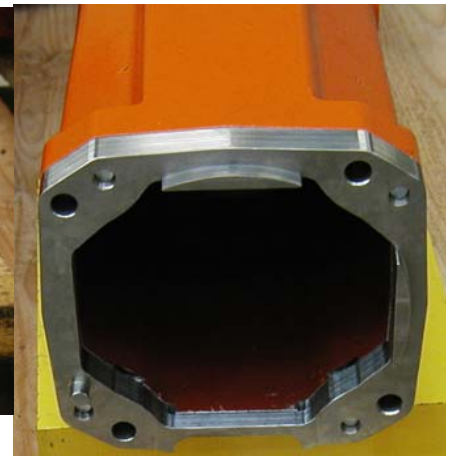
Operation of Planar Kinematic Coupling

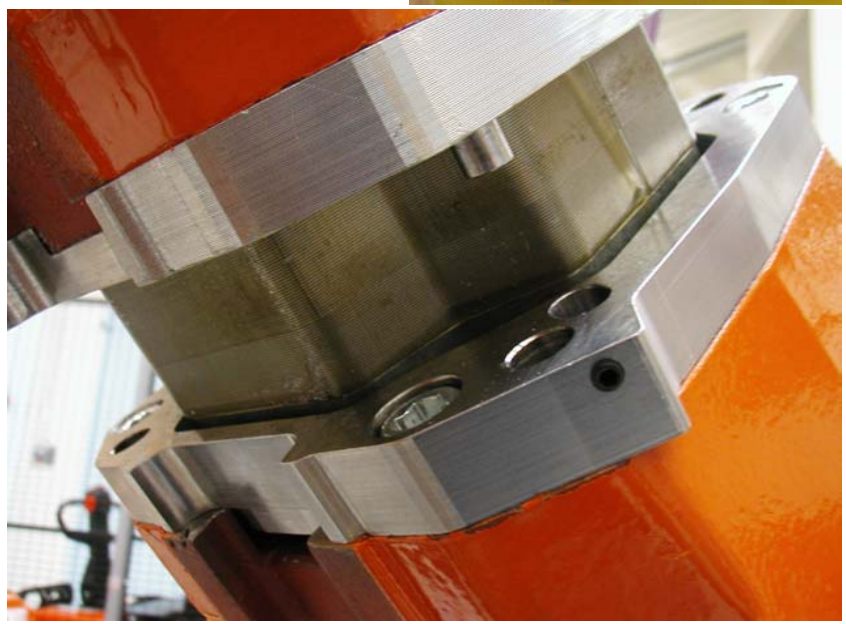


Prototypes for Planar Kinematic Coupling









Prototype Wrist Plate Mounting

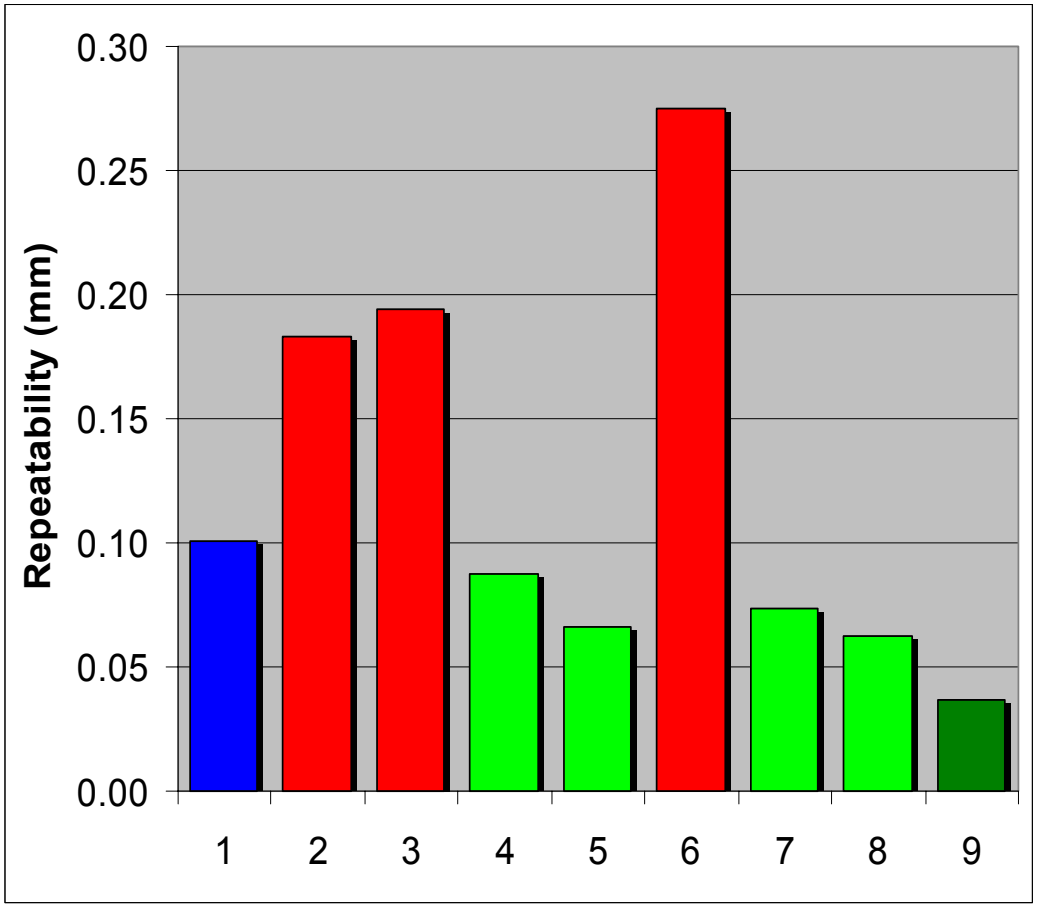
Tests at ABB Robotics Västerås, Sweden July 2001:

- 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



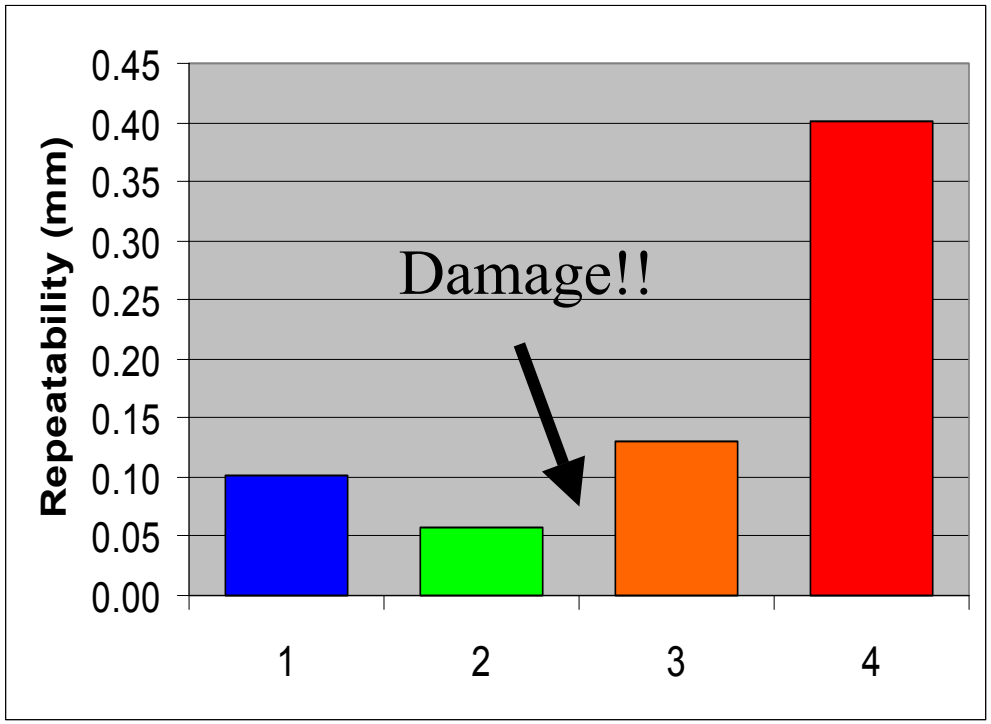


Repeatability Performance of KC



	Installation Angle	Additional Preload	Measurement Type	Bolting
1	Original Interface			
2	45°	0 Nm	5 pt	Plain
3	45°	15 Nm	5 pt	Plain
4	45°	50 Nm	5 pt	Plain
5	45°	75 Nm	5 pt	Plain
6	45°	120 Nm	5 pt	Plain
7	90°	0 Nm	5 pt	Refined
8	90°	Clamps	5 pt	Refined
9	90°	Clamps	Static	Refined

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

Positions of Robot for 5pt Measurement











Repeatability Results and Conclusions

- Performance of Different Coupling Designs
  - Canoe balls vs. Normal Wrist @ 45 º = **35% reduction**
  - Canoe balls vs. Normal Wrist @ 90 º = **64% reduction**
  - Potential Three-pin vs. Normal Wrist @ 45 º = **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 90º improved repeatability from 0.180 mm to 0.074 mm
  - Refined bolting procedure and mounting process at 90º improved repeatability from 0.180 mm to 0.062 mm



ABB

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



ABB

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

