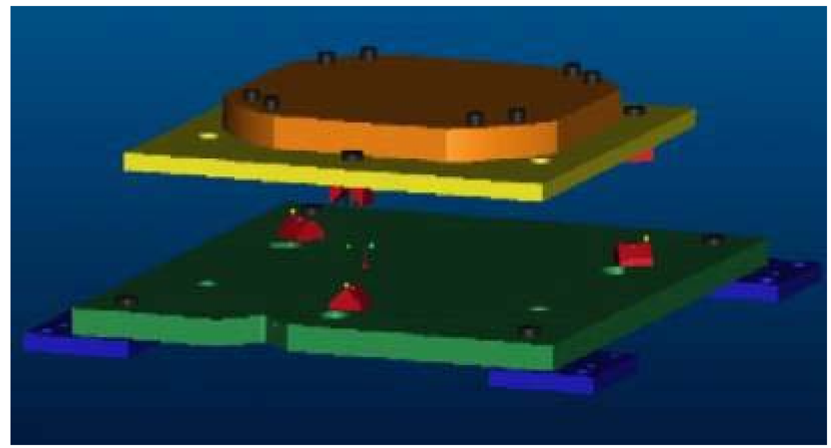
High-Accuracy, Quick-Change, Robot Factory Interface



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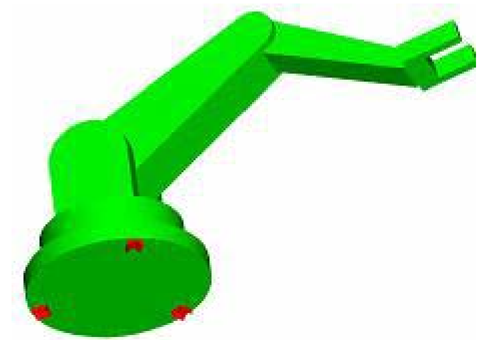
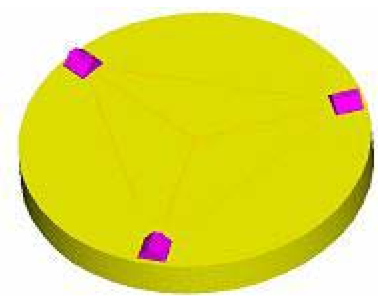
PERG ABB

Project Goals

Design, test, and demonstrate production feasibility of a modular robot baseplate with kinematic couplings as locators:

- A repeatable, rapidly exchangeable interface between the foot (three balls/contactors) and floor plate (three grooves/targets)
- Calibrate robots at ABB to a master baseplate
- Install production baseplates at the customer site and calibrated the kinematic couplings directly to in-cell tooling
- Install robot according to refined mounting process with gradual, patterned preload to mounting bolts
- TCP-to-tooling relationship is a deterministic frame transformation
- Base calibration data handling is merged with ABB software, enabling **0.1 mm TCP error contribution** from repeatability and exchangeability error of kinematic couplings





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Prototype Coupling Designs

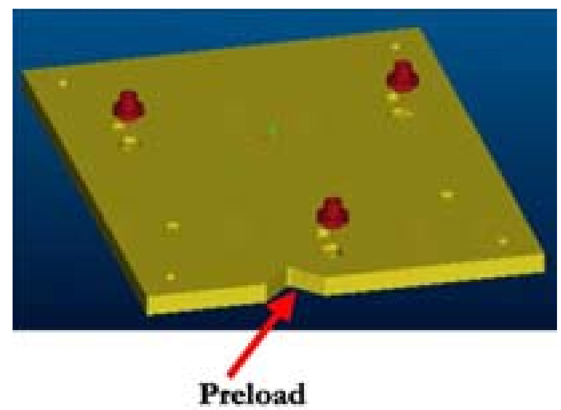
Design 3-point kinematic coupling mounts for the 6400R foot:

Canoe Ball

- Six "point" contacts
- 0.5m radius ball surface
- 20 mm diameter elastic Hertzian contact

Three-Pin

- Three line + three surface contacts
- In-plane preload overcomes friction to deterministically seat pins
- Vertical bolt preload engages horizontal contact surfaces



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Prototype Coupling Designs

Groove/Cylinder

- Twelve line contacts
- Aluminum cylinders
- Apply bolt preload (elastic deflection of cylinders) for dynamic stability

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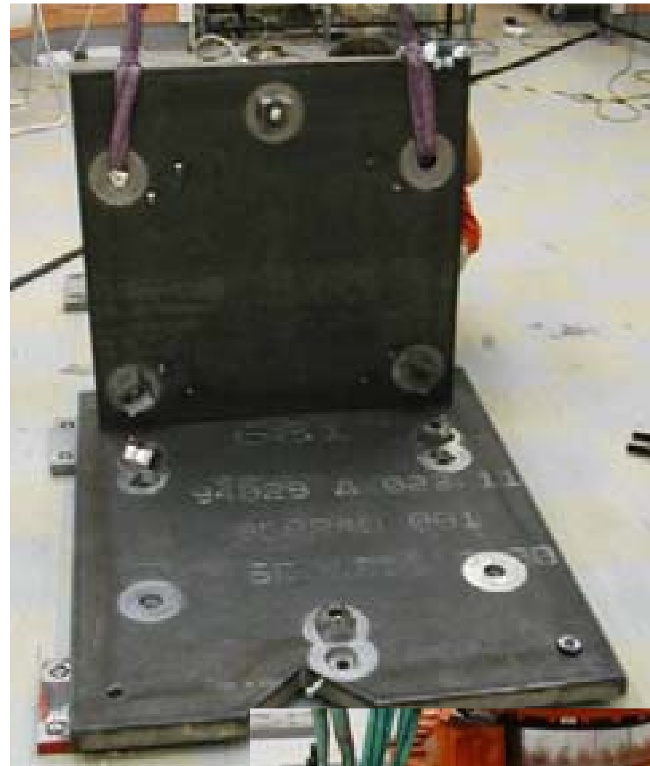
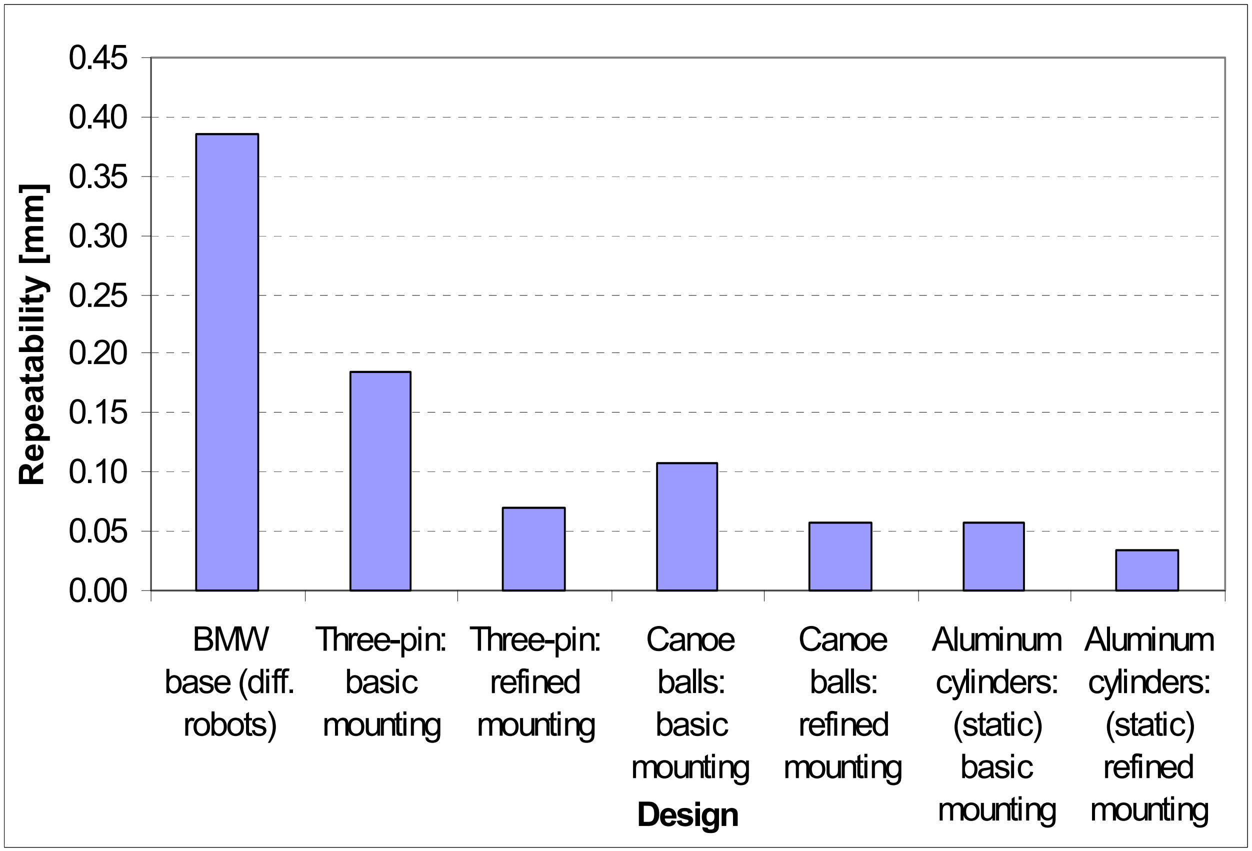
Prototype Base Mounting

Tests at ABB Robotics Vasteras, July/August 2001:

- Static (bolted) and dynamic (5-point path) repeatability of canoe ball and three-pin interfaces
- Static (manipulator rest only) repeatability of groove/cylinder interface
- Test both basic (air wrench) and refined (torque wrench, greased bolts) mounting processes
- Measure tool point motion using Leica LTD500 Laser Tracker
- Repeatability of robot path + measurement system approximately 20 microns



Repeatability Performance



- Canoe balls vs. BMW base = **83% reduction**
- Three-pin vs. BMW base = **85% reduction**
- Cylinders vs. BMW base = **92% reduction**
- Refined mounting vs. basic mounting = 50-70% reduction
- 8-bolt blue pallet repeatability (not shown) = 1.63 mm

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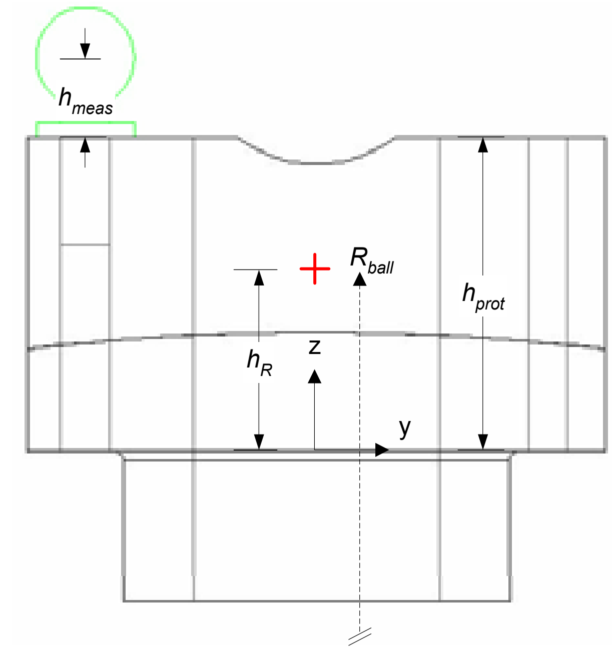
Interchangeability Error Model

Consider stackup of errors in coupling manufacturing, mounting plate manufacturing, and coupling-to-plate assembly:

For example in z-direction of a ball mount, tolerances:

- Sphere radius = δ_{Rsph}
- Contact point to bottom plane = δ_{hR}
- Measurement feature height = δ_{hmeas}
- Protrusion height = δ_{hprot}

$$\varepsilon_z = \frac{1}{2}\left(\left(2\left(\frac{\delta_{Rsph}}{\sqrt{2}}\right) + \delta_{hR} + \delta_{hprot} + \delta_{hmeas} + \sqrt{2\left(\frac{\delta_{Rsph}}{\sqrt{2}}\right)^2 + \delta_{hR}^{\ 2} + \delta_{hprot}^{\ 2} + \delta_{hmeas}^{\ 2}}\right)\right)$$



Each dimension is perturbed by generating a random variate, e.g. for mounting hole placement:

$$x_{h_{b_1}} = x_{h_{b_1 nom}} + \delta_{R,h_{b_1}} \delta_{pos} \mathrm{RandN}() \cos(\theta_{rand})$$

$$y_{h_{b_1}} = y_{h_{b_1 nom}} + \delta_{R,h_{b_1}} \delta_{pos} \mathrm{RandN}() \sin(\theta_{rand})$$

$$\theta_{rand} = 2\pi \mathrm{Rand}()$$

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Interchangeability Solution Method

Linear system of 24 constraint equations between the balls and grooves – accounts for both positional and angular misalignment:

1. Contact sphere centers must be at minimum (normal) distance between the groove flats, e.g.:

$$\frac{(q_1 - b_1) \cdot N_1}{\|N_1\|} = R_1$$

q_1, b_1 = initial, final center positions;
N_1 = groove normal; R_1 = sphere radius.

2. By geometry, the combined error motion of contact spheres is known with respect to the error motion of their mounting plate. For small angles, e.g.:

$$\mathrm{x}_{\mathrm{s},1} = \delta_{x_c} + \mathrm{u}_{\mathrm{s},1} + \mathrm{v}_{\mathrm{s},1}\left[-\theta_{z_c}\right] + \mathrm{w}_{\mathrm{s},1}\left[\theta_{y_c}\right]$$
$$\mathrm{y}_{\mathrm{s},1} = \delta_{y_c} + \mathrm{u}_{\mathrm{s},1}\left[\theta_{z_c}\right] + \mathrm{v}_{\mathrm{s},1} + \mathrm{w}_{\mathrm{s},1}\left[-\theta_{x_c}\right]$$
$$\mathrm{z}_{\mathrm{s},1} = \delta_{z_c} + \mathrm{u}_{\mathrm{s},1}\left[-\theta_{y_c}\right] + \mathrm{v}_{\mathrm{s},1}\left[\theta_{x_c}\right] + \mathrm{w}_{\mathrm{s},1}$$

$(q_{S,1}, q_{S,1}, q_{S,1})$ = initial center positions;
$(x_{S,1}, y_{S,1}, z_{S,1})$ = final center positions.

3. Solve linear system and place six error parameters in HTM:

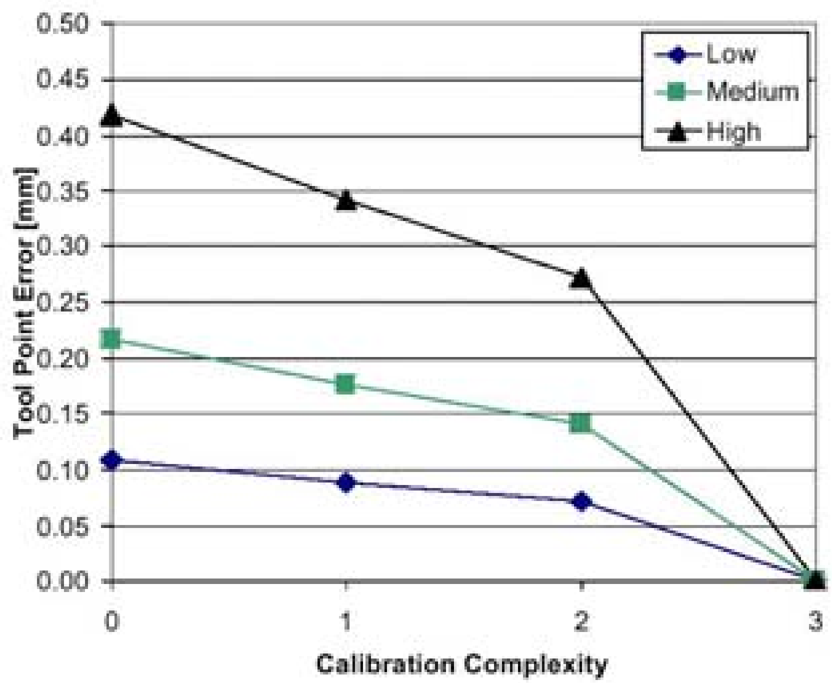
$$T_{interface} = \begin{bmatrix} 1 & -\theta_{z_c} & \theta_{y_c} & \delta_{x_c} \\ \theta_{z_c} & 1 & -\theta_{x_c} & \delta_{y_c} \\ -\theta_{y_c} & \theta_{x_c} & 1 & \delta_{z_c} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Interchangeability Results

Simulate interchangeablity error from manufacturing variation:

- Calibrate interfaces by measuring contacts and calculating interface error transformation
- Model direct measurement of pins + contacts, and offset measurement of canoe balls
- Exchangeability is error between calculated and true interface transformation, given chosen level of calibration and manufacturing tolerances (low, med, high)
- 250-trial Monte Carlo simulation in MATLAB at each calibration level

Three-pin interchangeability:



0 = no interface calibration

3 = full (x,y,z) of pins and contact surfaces

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Total Mechanical Accuracy

"Quick-Change" Accuracy = Repeatability + Exchangeability

			Repeatability (measured)		Exchangeability (simulated)
Canoe balls	0.22 mm	=	0.06	+	0.16*
Three-pin	0.12 mm	=	0.07	+	0.05
Groove/cylinder	-	=	0.06**	+	(Incomplete)

- Interface calibration decouples accuracy from manufacturing tolerances of mounting plates and couplings (if direct measurement of contacts)

- Results show repeatability is highly f(mounting process) – this may present a performance limit for factory mountings; interface should be micron-repeatable under perfect conditions

Totally, a near-deterministic prediction of robot interface accuracy

*driven by error of offset position measurement

**static only

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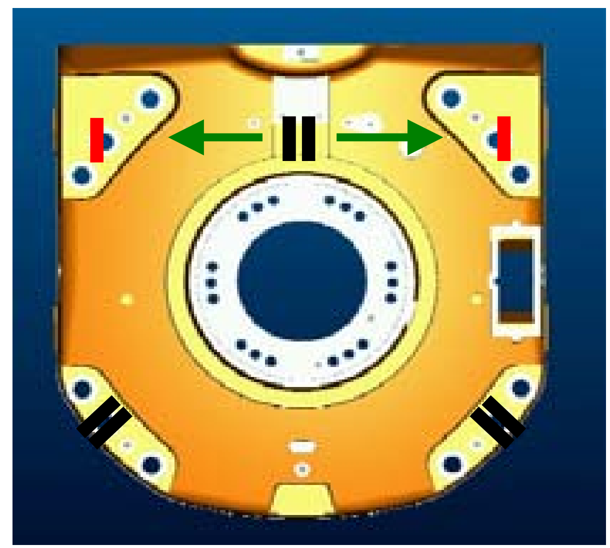
Recommended Next Steps

- Test groove/cylinder interface with preload + motion
- Test traditional quasi-kinematic couplings
- Evaluate long-term dynamic performance
- Production three-pin adaptation to BMW base
- Canoe ball 4-point mounting for Voyager?
- Build kinematic coupling "Expert System" – combine test results, simulation results, etc. into design tool that gives minimum cost recommendation as f(accuracy requirement)



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