High-Accuracy, Quick-Change, Robot Factory Interface

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**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
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
Prototype Coupling Designs

**Groove/Cylinder**
- Twelve line contacts
- Aluminum cylinders
- Apply bolt preload (elastic deflection of cylinders) for dynamic stability
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
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 = $\delta_{R_{sph}}$
- Contact point to bottom plane = $\delta_{hR}$
- Measurement feature height = $\delta_{hmeas}$
- Protrusion height = $\delta_{hprot}$

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

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

$$
x_{h_b} = x_{h_b,\text{nom}} + \delta_{R, h_b} \delta_{pos} \text{RandN}() \cos(\theta_{\text{rand}})
$$

$$
y_{h_b} = y_{h_b,\text{nom}} + \delta_{R, h_b} \delta_{pos} \text{RandN}() \sin(\theta_{\text{rand}})
$$

$\theta_{\text{rand}} = 2\pi \text{Rand}()$
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.:

\[
\frac{(q_1 - b_1) \cdot N}{\|N\|} = R_1
\]

\(q_1, b_1 = \) initial, final center positions;
\(N = \) groove normal; \(R = \) 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.:

\[
x_{s,1} = \delta_x + u_{s,1} + v_{s,1} \left[ -\theta_z \right] + w_{s,1} \left[ \theta_y \right] \\
y_{s,1} = \delta_y + u_{s,1} \left[ \theta_z \right] + v_{s,1} + w_{s,1} \left[ -\theta_x \right] \\
z_{s,1} = \delta_z + u_{s,1} \left[ -\theta_y \right] + v_{s,1} \left[ \theta_x \right] + w_{s,1}
\]

\(q_{s,1}, q_{s,1}, q_{s,1}) = \) 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:

\[
T_{\text{interface}} = \begin{bmatrix}
1 & -\theta_z & \theta_y & \delta_x \\
\theta_z & 1 & -\theta_c & \delta_y \\
-\theta_y & \theta_x & 1 & \delta_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
Interchangeability Results

Simulate interchangeability 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
Total Mechanical Accuracy

“Quick-Change” Accuracy = Repeatability + Exchangeability

(measured) (simulated)

<table>
<thead>
<tr>
<th></th>
<th>Canoe balls</th>
<th>0.22 mm</th>
<th>=</th>
<th>0.06</th>
<th>+</th>
<th>0.16*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-pin</td>
<td>0.12 mm</td>
<td>=</td>
<td>0.07</td>
<td>+</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Groove/cylinder</td>
<td>-</td>
<td>=</td>
<td>0.06**</td>
<td>+</td>
<td>(Incomplete)</td>
<td></td>
</tr>
</tbody>
</table>

- 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
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 $f(\text{accuracy requirement})$