Evaluation of a 4-Degree of Freedom Parallel Manipulator Stiffness

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11th World Congress in Mechanism and Machine Science
April 1-4, 2004
Tianjin, China
Introducing H4 parallel robot

- H4, a robot built at LIRMM/CNRS
- Parallel architecture with four legs
- 4 DDF : 3 translations, 1 rotation
- Advantages :
  - Accelerations up to 10 g
  - Ideal for « pick and place » operations
- H4 prototype must be optimized
- Re-design for stiffness
  - Long arms
  - Stiffness for improving accuracy
- Partnership with LaRAMA / IFMA
- In ROBEA Max CNRS program
H4 kinematics

- 6R and 16S joints
- 4 DDF: 3 translations, 1 rotation
- Architecture with 4 legs R-(S-S)$_2$ = actuator + forearm + 2 bars
- Spatial parallelograms (S-S)$_2$ plane in normal conditions
- 4 rotative actuators
Articulated Travelling Plate

- An articulated Travelling Plate (TP)
- H-shaped
- End effector:
  - Connected to central bar: maximum rotation of +/- 45° around Z
  - Through a geared rotation amplifier (4:1 ratio) for 180° capability
Measuring Displacements

- External force on TP
- From 10 to 50 N
- 3 displacements on TP
- 3 dial indicators
- No rotation measurements for the moment
- Only translational stiffness
- Actuators are powered
- TP position controlled
- Pose at 45°
Experimenting
Measuring Material Properties

- Bars from 3rd party provider, no specifications
- Need to evaluate stiffness for FEM study

Specific fixtures

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Elasticity modulus</th>
<th>Cross section (dimensions in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm</td>
<td>Aluminium 2024 series</td>
<td>74 000 MPa</td>
<td>Square tube with round corners (Side 25, Thickness 2.5, Ext radius 3, Int. Radius 1)</td>
</tr>
<tr>
<td>Bar</td>
<td>Carbon Epoxy</td>
<td>57 700 MPa</td>
<td>Round tube (External diameter 10.4, Thickness 2)</td>
</tr>
</tbody>
</table>
FEM Beam Model

- Simple beam model with constant cross section
- 1 element per beam
- 2 nodes per beam
- 3 displacements and 3 forces per node
- FEM = material strength theory in that case
Fast articulated model

Displacement relaxations:
- S joint: translations are the same on each beam but not rotations
- R joint: all the movements are the same but not rotation around joint axis

S – S links:
- Beam becomes bar element with no self rotation around longitudinal axis for matrix inversion
Force along Y

- Presentation
- Experimenting
- FEM Analysis
- Results
  - Force on XYZ
  - Curves
  - Coupling
  - Stiffness
- Conclusion

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Force along Z

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Comments on curves: shape

Results are rather linear

- FEM simulated results are perfectly linear
- Measured results are rather linear (except experimental errors)
- Curves start at origin
Comments on curves: relative positions

- FEM results are under experimental results but very close
  - Dotted lines are generally under plain lines
  - Justification: measurements include geometrical defaults, clearance, joint stiffness
  - An exception: \( D_Y \) simulated = 2 \( D_Y \) experiment
  - Justification: experimental error
Comments on curves: coupling

- **Coupling**: a force along one direction may generate a displacement along another direction

- A force along $X$ generates displacement along $X$ and a bit on $Z$
- A force along $Y$ generates only displacement along $Y$ -> No coupling on $Y$
- A force along $Z$ generates displacement mostly along $X$, then $Z$
Understanding coupling

- With $F_x$, **coupling** between $X$ and $Z$

- With $F_y$, **no coupling**
Compliance matrices

- One pose at 45°

- Experimental compliance matrix

- FEM compliance matrix

- Experimental -FEM : quite correct except one big difference
Conclusion

• One pose at 45°, two methods for getting stiffness
  • Experimental + FEM
  • Results are in close agreement
• H4 has different stiffnesses on X Y Z
  • Strong coupling between X and Z
  • No coupling along Y

To be done...

• Stiffness maps
• Re-design for stiffness

Videos