Design and integration of a multi-axis force sensor for the Roombots

Student: Joel Rey
Type: Semester project
Supervisors: Alex Sproewitz, Rico Moeckel
Roombots

• Modular robot
• Designed for two main tasks:
  – Self assembly and reconfiguration of static structures
  – Building block for locomotion with modular robots

Picture taken from [1]
Purpose of Load-Cells in Roombots

- Detect collision, direction of a contact
- Closed-loop control for locomotion
- Other collision detections techniques available (optical proximity sensors, bumpers), but not omnidirectional and no information about force intensity
Load-cells

• Convert forces and torques into electric signals
• Are places in series with the structure of interest
• Composed of:
  – Mechanical structure
  – Strain gauges
  – Electronics

6 axis load-cell in the arm of the iCub. Pictures taken from iCub.org
Load-cells

• Can be seen as linear systems
• Can be characterized by a matrix and inverted to find the system matrix.
Load cells: Strain gauges

• Resistors which resistance changes as a function of strain: $\Delta R/R = K\varepsilon$ (K: gauge factor)

• Two different types:
  – Foil strain gauges ($K = 2$)
  – Semiconductor strain gauges ($K = 100$)
    • As small as 1mm long
    • 10 to 20 $ each
Load cells: mechanics

• Stress $\sigma = \text{force} / \text{surface}$ (pressure)
• Strain $\varepsilon = \text{elongation}/\text{initial length}$
• $\varepsilon = \frac{\sigma}{E}$ ($E$: elasticity)
• Stress in bending beams: 2 ways of measuring
  – Bending: $\sigma = \gamma \frac{M}{I}$
  – Shear: $\sigma = \frac{P \cdot S'}{(I \cdot B)}$

Picture taken from [2]
Load cells: electronics

- Wheatstone bridges convert resistance change into voltage signal.
- Half-bridge: two anti-symmetrical strain gauges in one arm of the bridge. Compensates for non-linearity and thermal sensitivity.
- \[ V_{\text{out}} = \Delta R \cdot V_{\text{in}} / 2 \]
Design: initial considerations

• A 4-axis load cell is enough for our purpose.
  -> Unmeasured components must be negligible

• Integration of the load cell should not require important parts of the Roombots to be redesigned.

• The load cell should not mechanically weaken the Roombots
Good locations

Cross-section of half a Roombot module, picture taken from [1]
Design: Initial considerations (3)

• Semiconductor strain gauges from Micro-Instrument.
  – High gauge factor (150)
  – Matching pairs available for thermal compensation

• Material for structure: aluminum alloy 7022 (Certal)
  – High maximal elastic deformation
Design: Initial considerations (4)

- Load cell must fit to the symmetry of the Roombots.
Design: method

• Finite element analysis on SolidWorks using the simulation toolkit.
• Different models where investigated.
• Optimization is a problem with high dimensionality -> lots of parameters to test and lots of data to collect.
• Sometimes graphs where sufficient.
Design: model 1

- Two parts
- Measures bending strain
- Mx, My, Mz and Fz
Design: model 2

- Adding cuts to release the constraints
Design: model 2

Discarded because
-No space for strain gauges under the beams
-Two parts -> too heavy
Design: model 3

- Measures bending strain
- Fx, Fy, Fz, Mz
Design: model 3

Discarded because:
- No good location for strain gauges
- Too big influence of unmeasured components (Mx, My)
Design: model 4

- Measures shear strain
- Thicker beams
- Mx, My, Mz, Fz

- Strain gauges pairs on the side of the beams
- One extra pair on top of one beam
Design: model 4

Problem:
Large influence of $F_y$ on the top pair
Design: model 5

Cutting niches to measure the strain closer to the center of the beam.

Larger beams $\rightarrow$ Reduces effect of $F_y$
Design: final model

- Removable beams to facilitate the bonding of the strain gauges.
- Reduced mass.
- Extended floor surface.
Design: backup model

- Fixed beams.
- We were not sure if removable beams were a good idea.
Gluing the strain gauges

- Gluing the strain gauges was tedious. They are so small! (Less than 1 mm long)
- Connecting pads
Electronics: initial plan

• Initially we were planning to have a PCB circuit to handle the small signals.
Electronics: Backup solution

- We did not get the PCB on time so we built Wheatstone bridges out of simple resistors.
Electronics: strain gauge resistance

• Strain gauge nominal resistance decreased during the bonding process from 540Ω to around 340Ω.
• Supposedly matching pairs have up to 15Ω difference.
• Could be due to residual stress or damage by heat during the curing process.
Experiment: setup

• Characterization of the load cell (find its matrix)

• LabView acquisition device for collecting data.
Experiment: tour plot
Experiment: procedure

• Measurement of the voltage output of the 4 strain-gauge pair in half-bridge circuit. (offset corrected)

• Measurement for Mx, My, Mz and Fz at different intensities

• Load cell powered at 5V (draws 60 mA)
Results: Mx
Results: Mz
Results: Fz
Results
## Results: Linearized

### Simulation prediction

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<thead>
<tr>
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<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>Fz</th>
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<td>-0.0008</td>
<td>0.0006</td>
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<td>-0.0004</td>
<td>0.0006</td>
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<tr>
<td>P4</td>
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<td>-0.0123</td>
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### Experiment measurements

<table>
<thead>
<tr>
<th></th>
<th>Mx</th>
<th>My</th>
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<th>Fz</th>
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<tbody>
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</tbody>
</table>
Results: system matrix

Measurements for each pair

Inverted result matrix = system matrix

Force/moment components
Results

• Coherent but large difference for the coefficients
• Not really linear
• Where does it come from?
  – Mechanical model
  – Strain gauges orientation, resistance variation
  – Disturbance from unmeasured components (Fx, Fy)
Conclusion

• Experimental results do not fit the expected values closely.
  – Investigation should be done to find why.

• However, the load cell can still be fully characterized and used in the Roombots
  – But optimization on SolidWorks is not precise, and each load cell should be characterized by measurements.
Future work

• Further testing of the load cell
• Improve electronics and integrate to the Roombots electronics.
• Use the data provided by the sensor for control.
References


• iCub project: iCub.org

• Gab_soon Kim: *Development of a small 6-axis force/moment sensor for robot’s fingers*. Measurement Science and Technology 15, 2004