RF-Compass: Robot Object Manipulation Using RFIDs

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Limitation of Today’s Robotic Automation

Fixed-position, single-task robot

• Limited to large-volume production line
• Inability to change manufacturing process
Toyota has been slowly backing away from heavy automation. The labor saved by robots was *wasted most of all by reprogramming robots.*

The potential for much broader industrial acceptance is tied to the development of robots that can *absorb data, recognize objects, and respond to information and objects in their environment with greater accuracy.*

This is the *future.* A new wave of robots, far *more adept* than those now commonly used by automakers and other heavy manufacturers.
Mobile Manipulation

Fetching, grasping, and manipulating objects

- Extend automation to small/medium factories
- Easy to reconfigure manufacturing process
Requirements for Mobile Manipulation

• Centimeter-scale localization, e.g., 2cm
• Minimal instrumentation → portable
Current Approaches

• Motion capture system, e.g., VICON
  – Sub-centimeter accuracy
  – Heavy instrumentation & Expensive
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• Imaging (e.g., optical camera, Kinect, LIDAR)
  – Needs prior training

or ?
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• Motion capture system, e.g., VICON
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  – Needs prior training
  – Does not work in NLOS/occlusion

or ?
Can RF localization help?
Current RF localization schemes are too coarse

- State-of-the-art WiFi localization: 23cm [ArrayTrack]
- State-of-the-art RFID localization: 11cm [PinIt]
  BUT requires a dense grid of reference tags

How to get a few cm accuracy without environment instrumentation?
RF-Compass

• Place RFID tags on both robot and objects
• No reference tags in the environment
Identifying the Object

- RFID: a passive sticker – no battery, low cost
- Reader shines RF signal on tags
  - Each tag replies with its unique ID
  - Works for up to 10 meters
How to get centimeter-scale accuracy?
Building block: RF pairwise comparison

- Compare distances between RFIDs

Distance ordering based on signal similarity [SIGCOMM’13]
Basic building block 2cm accuracy
Basic Idea: Localization by Partitioning

Is the red tag closer to Tag 1 or Tag 2?
Basic Idea: Localization by Partitioning

Tag 1 is closer than Tag 2
Basic Idea: Localization by Partitioning

Tag 3 is closer than Tag 4
Basic Idea: Localization by Partitioning

Tag 4 is closer than Tag 1

Tag 4 is closer than Tag 1
Basic Idea: Localization by Partitioning

But not yet centimeter accuracy
Basic Idea: Localization by Partitioning

- Partitions can be iteratively refined
Iterative Refining via Robot Navigation

• Leveraging robot’s consecutive moves
Iterative Refining via Robot Navigation

• Every robot move gives a new set of partitions
Iterative Refining via Robot Navigation

• Lay new partitions over old partitions to refine
Iterative Refining via Robot Navigation

- Keep refining until reaching centimeter accuracy
Iterative Refining via Robot Navigation

- Keep refining until reaching centimeter accuracy
Formulation as an Optimization

\[
2(x_2 - x_1) 2(y_2 - y_1) \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \leq x_2^2 + y_2^2 - x_1^2 - y_1^2
\]
Formulation as an Optimization

\[
\begin{bmatrix}
2(x_2 - x_1) & 2(y_2 - y_1) \\
\vdots & \vdots \\
2(x_0 - x_1) & 2(y_0 - y_1)
\end{bmatrix}
\begin{bmatrix}
x_0 \\
y_0
\end{bmatrix}
\leq
\begin{bmatrix}
x_2^2 + y_2^2 - x_1^2 - y_1^2 \\
\vdots
\end{bmatrix}
\]
Formulation as an Optimization

\[ A \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \leq b \]

- A feasibility problem with linear constraints
- Efficiently solved via convex optimization
- Over-constrained system
  \[ \Downarrow \]
  Robustness to errors & outliers

Works correctly even if randomly flipping 10% of pairwise comparisons, shown in paper
Orientation

Problem: also need orientation for grasping

Solution:

• Multiple RFIDs on object
• Naïve approach: localize each RFID independently and find orientation
• Our approach: joint optimization using knowledge of their relative location
**Evaluation**

- Used a robot to fetch IKEA furniture parts
- 9 tags on robot, 1 – 4 tags on object
Baseline

• VICON motion capture system
• Sub-centimeter accuracy
• Infrared cameras + infrared-reflective markers
Navigation Performance

Direct line-of-sight

RF-Compass
VICON

CDF

Ratio to Optimal Path in LOS

Only 6% longer than optimal on average

Occlusion and NLOS

RF-Compass

VICON does NOT work in NLOS

CDF

Ratio to Optimal Path in NLOS

RF-Compass enables effective navigation in NLOS
Center Position Accuracy

Error in Position Estimate (cm)

<table>
<thead>
<tr>
<th>Number of Tags on Furniture Part</th>
<th>Error in Position Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Tag</td>
<td>4 cm</td>
</tr>
<tr>
<td>2 Tags</td>
<td>2.8 cm</td>
</tr>
<tr>
<td>3 Tags</td>
<td>1.9 cm</td>
</tr>
<tr>
<td>4 Tags</td>
<td>1.3 cm</td>
</tr>
</tbody>
</table>
Orientation Accuracy

<table>
<thead>
<tr>
<th>Number of Tags on Furniture Part</th>
<th>Error in Orientation (degree)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Tags</td>
<td>5.8°</td>
<td></td>
</tr>
<tr>
<td>3 Tags</td>
<td>3.6°</td>
<td></td>
</tr>
<tr>
<td>4 Tags</td>
<td>3.3°</td>
<td></td>
</tr>
</tbody>
</table>

Number of Tags on Furniture Part
Conclusion

• RF-Compass: accuracy of a few cm and degrees

• Iterative refining by leveraging robot’s navigation

• Opens up opportunities for bridging robot object manipulation with RF localization