Localization for Robotic Assemblies with Position Uncertainty

Ph.D. Dissertation Defense

Siddharth R. Chhatpar
Advisor: Michael S. Branicky
November 4, 2005
[Here, and on pages 14 and 19 of this presentation, clips from http://dora.case.edu/msb/pubs/icra06submit.mp4 were shown.]

Localization for Robotic Assemblies with Position Uncertainty

Siddharth R. Chhatpar and Michael S. Branicky

Case Western Reserve University
Cleveland, OH

Research funded by NIST ATP (70NANB7H3024) and NSF Grant CNS-0208919
Class of Robotic Assemblies with Position Uncertainty

Forward Clutch

Planetary Gear
ParaDex Robot

- High accuracy and repeatability
- High payload
- Hybrid control: Selected axes can be put under position-control or compliant-control (natural admittance control)
Outline

• Blind Search Strategies
• Intelligent Localization
  – Problem Formulation
  – Precession and Sweep Strategies
• General Localization Strategy
  – Localization with Analytical and Sampled Maps
  – Implementing Localization Using the Cell Approach
  – Implementing Localization Using Particle Filtering
• Summary of Contributions
Simplified Problem: Circular Peg-in-Hole
Assembly Characterization

In terms of exhaustive coverage of search space, a finite set of points is equivalent to the continuous search area.
Set of \textit{Valid} Search Paths

Requirements:
\begin{itemize}
  \item Continuous path
  \item For every point in the search area, there is at least one point on the path within assembly clearance radius, $c$, of it
\end{itemize}

Conversely, any path through the area which when dilated by $c$, covers the entire search area, is valid
Example Search Paths

1. Joining discrete points in exhaustive coverage set
   - Travelling Salesman problem

2. Hand-crafted search paths
   - Concentric circles
Example Search Path

- A spiral search path has smooth curvature throughout
- Spiral search path was used extensively for successful assemblies of example transmission components
Localization Problem Set-up
Peg-Hole Contact Surface

With a tilted peg the contact surface is more informative
Peg-Hole Contact Hyper-Surface

- Six-dimensional *hyper-volume* of relative peg-hole configurations
  - Poses (positions and orientations) of the peg w.r.t. the hole
- Bounded by a five-dimensional hyper-surface for peg-hole contact

(x,y,z) slice of contact hyper-surface for peg contacting hole with fixed relative orientations
Precession and Sweep Strategies
Precession Strategy

![Diagram of Precession Strategy]

- Peg tilt axis
- Tilted peg
- Hole
- Original tilt axis
- Current tilt axis
- Rotation of tilt axis
- $h_1$
- $h_2$
Precession Strategy

**Example peg trajectory**

Tilt axis angle = 2.68 rad

**TABLE:** Relative peg-hole position $(x-y) \rightarrow$ height $(z)$
Sweep Strategy
Sweep Strategy

Peg height recorded during sweep

Database of (x,y,z) slices
General Localization Strategy
General Localization Strategy

• **Strategy**
  – Acquire and store a map of the contact hyper-surface
  – Use map to run localization algorithm:
    Match individual peg-hole contact measurements to the map to localize relative peg-hole configuration

• **Outline:**
  – Localization with analytical and sampled maps
  – Implementing localization strategy using **cell approach**
  – Implementing localization strategy using **particle filtering**
Analytical and Sampled Maps
Two-Dimensional Example

Probe moves on surface

Candidate moves matching actual move (some shown)

All but one of the shown candidate moves are pruned out
Circular Peg-in-Hole Localization Using Analytical Maps

Contact hyper-surface is represented by a set of functions:

\[ f_i(X) = \chi_i, \quad \text{where } f_i : \mathbb{R}^5 \rightarrow \mathbb{R}; \quad X \in \mathbb{R}^5; \quad \chi_i \text{ is a constant} \]

A 3-dimensional slice of the 5-dimensional contact hyper-surface for fixed relative orientations of the peg and hole; peg tilt = 30°
Localization Using Analytical Map
A Slice of the Contact Surface
Localization Using Analytical Map

Peg moves to new position: $T_{p_1}^w$ to $T_{p_2}^w$
Second Slice of the Contact Surface
Localization Using Analytical Map
Localization Using Analytical Map
Third Slice of the Contact Surface
Localization Using Analytical Map
General Solution: Outline

Step 0: Initialize: Set $k = 0$
- Set $B_0$ to include all transformations corresponding to uncertainty region

Step 1: Update: $k = k + 1$
- Compute peg move: $T_{p_k}^{p_{k-1}}$
- Compute new belief set, $\bar{B}_k$
- Update: $(B_{k-1})^{upd} = T_{p_k}^{p_{k-1}}B_{k-1}$
- Compute: $B_k = \bar{B}_k - (B_{k-1})^{upd}$

Step 2: Check:
- if $B_k$ is satisfactory → goto Step 3
- elseif iterations > $N$ → goto Step 4
- else → goto Step 1

Step 3: Localization successful → Assemble
Step 4: Localization failed → Stop
Localization Using Sampled Maps

- Analytical maps: difficult to generate
- Sampled maps: use a CAD-model or a robot
- Issue: Sampled maps are incomplete
- Need methods for approximate localization
Localizing with Sampled Maps
Localizing with Sampled Maps

Example circular and square peg-in-hole assemblies:

Assembly clearance $\leq 0.5\text{mm}$; Initial uncertainty $\geq 20\text{mm}$

Hence, number of configurations in map $\geq 10^8$
Problems in Localizing with Sampled Maps

- Large and intractable maps
- Heavy computational load with the first few map-matches
- Two ways to get around this:
  - Cell Approach (Worst-Case, Bounds)
  - Particle Filtering (Probabilistic, Errors)
Localization Using Cell Approach

Localizing in stages of increasing resolution
Localization Trial
Localization Trial
Localization Trial
Localization Trial
Localization Trial
Localization Trial
Localization Using Particle Filtering

• Probabilistic scheme that can handle errors arising from actuation, measurement, and incorrect maps

• Belief set contains a fixed number of weighted particles

• Each particle represents an estimate of the current relative peg-hole configuration

• The particles are updated after each peg move, and the best particles are more likely to be propagated
Particle Filtering Implementation: Simple Two-Dimensional Example
Two-Dimensional Example Continued
Peg move selected at random $T_{P_1}^{P_2}$

Updated particles

Peg move selected actively $T_{P_1}^{P_2}$

Updated particles
Circular Peg-in-Hole Assembly Results

• Initial uncertainty region: \((x,y)\) circle of radius 25 mm

• Localization goal: within \((x,y)\) circle of radius 4 mm

• All 30 assembly trials were successful (100%)

• Uncertainty resolution of more than 97% achieved
Square Peg-in-Hole Assembly Results

- Initial uncertainty region:
  \((x,y)\): circle of radius 20 mm,
  Orientation \((\theta_z)\): 90°

- Localization goal:
  \((x,y)\): within circle of radius 4 mm,
  Orientation \((\theta_z)\): within 10° of the actual

- 27 out of 30 assembly trials successful (90%)
Key-Lock Assembly

Sampled map of the key-lock contact surface
Lock-Key Assembly Results

• Three-dimensional uncertainty in \((x,y,z)\)

• Initial uncertainty region: \((x,y)\) circle of radius 10 mm

• Localization goal: within \((x,y)\) circle of radius 2 mm

• 45 out of 50 assembly trials successful

• Uncertainty resolution of 96% in the \((x,y)\) search region for each successful assembly
Active Localization

Uncertainty volume \((x \times y \times \theta_z)\) after each iteration (averaged over 10 trials) using random and active localization for the square peg-in-hole assembly.
Summary of Contributions

1. Formulated conditions for a search path to provide exhaustive coverage in terms of assembly clearance

2. Introduced novel idea to transform problem of searching for peg-hole alignment into that of localizing a point on a hyper-surface

3. Developed intelligent localization strategies: precession strategy, sweep strategy, and general localization strategy

4. Described implementation of localization strategy using analytical and sampled maps

5. Introduced ideas of assembly sufficiency and goal region to guarantee localization sufficient for assembly with sampled maps
Summary of Contributions (Continued)

6. Presented the cell approach algorithm to localize in stages of increasing resolution for computational efficiency

7. Implemented localization strategy using particle filtering with coarsely-sampled maps

8. Active localization was implemented successfully in conjunction with particle filtering

9. Our localization strategy was validated with mathematical analysis, computer simulations, and actual robotic assemblies
Acknowledgments

• Advisor: Prof. Michael Branicky

• Support: NIST ATP, NSF

• My Committee:
  Prof. Wyatt Newman
  Prof. Roger Quinn
  Prof. Cenk Cavusoglu
Related Work

- **Mobile robot localization**
  - Determining the pose (position and orientation) of a mobile robot by matching observations to a map of the environment
  - Thrun, Burgard, Fox, etc.

- **Fixtured-workpiece localization**
  - Find the transformation between the unknown workpiece coordinate frame and some reference coordinate frame
  - Zexiang Li, Chu, Gou, etc.

- **Geometric pattern-matching**
  - For two point sets $A$ and $B$, in $d$ dimensions, determine the rigid transformation that brings set $A$ closest to set $B$
  - Chew, Goodrich, Gavrilov, Indyk, etc.

- **Sensing by probing and point sampling**
  - Identify part pose by probing efficiently with a minimum number of probe points
  - Erdmann, Jia, etc.
Future Work

• Cell approach:
  – Develop a procedure to easily compute the transformations between the probe and surface coordinate frames corresponding to each cell of possible current occupation
  – Pre-compute what observations are profitable, and only carry out matching when a profitable observation is made

• Particle Filtering:
  – Extend the implementation to more dimensions, e.g., six-dimensional square peg-in-hole assembly, while maintaining (approximately) the same map-size (coarser sampling)