Workshop on Uncertainty in Automation, ICRA 2011

Aerial Robots for Construction

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Acknowledgements
ONR N00014-08-1-0696 (HUNT)
ONR Grant N00014-09-1-1051 (SMARTS)
ARL W911NF-08-2-0004 (MAST)
ONR N00014-09-1-1051 (ANTIDOTE)
Q. Lindsey, D. Mellinger, V. Kumar, Construction of Cubic Structure with Teams of Aerial Robots, RSS, LA, June 2011
Cooperating Robots and Assembly
Unmanned Air Vehicles

- **Aerovironment Black Widow** – 2.12 oz.
- **BAE Systems Microstar** – 3.0 oz.
- **Astec Pelican**
- **Astec Hummingbird**
- **U. Penn Piper cub 6 lb**
- **Stanford DFly**
- **Aerovironment Pointer** – 9.6 lb
- **UCB Smart bird**
- **Boeing/Insitu Scaneagle** – 33 lb
- **AAI Shadow 200** – 328 lb
- **Bell Eagle Eye** – 2,250 lb
- **Gen. Atomics – Predator B** – 7,000 lb
- **Boeing X-45A UCAV** – 12,195 lb (est)
- **Northrop-Grumman Global Hawk** 25,600 lb
- **D. Pines, 2005**
Assembly

- Structured
- Mass/Batch
- Indoor

- Human intervention usually always possible

- Process tolerance < 0.1 mm

Construction

- Unstructured
- Customized
- Outdoor

- Potentially remote, hostile environments

- Process tolerance > 5 mm
Goal

Assembly and Construction of 3-D Structures
Goal
Assembly and Construction of 3-D Structures

This talk …

Special Cubic Structures
Assembly Primitives

P1

P2

P3

P4
Tolerances and Variation

Product Design
*Part, assembly*

Tolerances

Assembly
*Process Model*

Admissible variation

Manufacturing
*Assembly plan*

Successful!

Process tolerance

Process variation

Unsuccessful!

Robotic
*Assembly Model*

Automation, Robotics

Penn Engineering
Assembly Primitives

P1

P2

P3

P4
Special Cubic Structures

Structures consisting of layers/strata

- No holes in any 2D stratum
- No cantilevered sections
Wavefront Raster (WFR) Algorithm

1: Build any square in the 2-D region
2: while not finished do
3: mark squares immediately connected to already built region
4: for (leftmost column) to (rightmost column)
5: build marked squares in column from bottom to top
Quad Rotors

[Mellinger, Michael and Kumar, ISER 2010; Mellinger and Kumar, ICRA 2011]
Cooperative Grasping and Lifting

\[ u^* = \arg \min_u \{ J | Au = w \}, \quad J = \sum_i f_i^T Q f_i \]
Part Bins
Gripper
Force Feedback

- Can estimate mass, moments of inertia
- Confirm stable prehension

Feel/respond to forces

Estimated Mass (kg) vs. Time (s) graph
Assembly Modes

M1

M2

M3

M4

M5
Assembly

- Hover at $P_1$
- Execute trajectory from $P_1$ to $P_2$
- Hover at $P_2$
- Yaw Left
- Yaw Right
- Release and Ascend

Failed assembly, repeat attempt

- $|\psi_{error}| > \psi_{max}$
- $|\psi_{error}| > \psi_{max}$
Assembly Errors
## Assembly Results with Three Robots

<table>
<thead>
<tr>
<th>Number of Parts</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>32</td>
<td>34</td>
<td>40</td>
<td>192</td>
</tr>
<tr>
<td>Successful</td>
<td>32</td>
<td>33</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Attempts</td>
<td>32</td>
<td>34</td>
<td>39</td>
<td></td>
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<tr>
<td>Actual Time</td>
<td>449.6</td>
<td>486.6</td>
<td>588.2</td>
<td>587.3</td>
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<tr>
<td></td>
<td>450.7</td>
<td>486.2</td>
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<tr>
<td>Column retries</td>
<td>5</td>
<td>3</td>
<td>8</td>
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</tr>
<tr>
<td></td>
<td>5</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Beam retries</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Time (in simulation)</td>
<td>443.6</td>
<td>480.4</td>
<td>581.9</td>
<td>2642.0</td>
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</tbody>
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Challenges

- Distributed assembly
Challenges

- Distributed assembly
- Unstructured environments
Challenges

- Distributed assembly
- Unstructured environments
- Part design and payloads
Robotic Assembly/Construction

Product Design
*Part, assembly*

**Tolerances**

Assembly Process Model

**Admissible variation**

Manufacturing
*Assembly plan*

Robotic Assembly Model

Successful!

Process tolerance

Automation, Robotics

Process variation
Conclusion

- Agile, small, aerial robots create new opportunities for robotics
- SWAP constraints
- Force feedback enables adaptation
- Networks enable functionality beyond what can be achieved by individual robots