Cyber-Physical Manipulation (CPM): Locating, Manipulating, and Retrieving Large Objects with Large Populations of Robots

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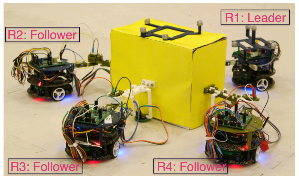
Summary

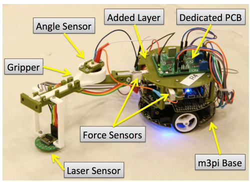
- Ant-style manipulation for locating and transporting large objects with many small robots
- Full system including exploration, object discovery, object manipulation, object transport
- Studying information asymmetry and spectrum of robot capabilities



Project Thrusts

- **Structured exploration:** Deploy robots to form mesh network covering environment of environment
- **Object Grasping:** Surround and grasp object
- **Distributed State Estimation & Path Planning:** Plan path through mesh network and avoid collision by considering the object's geometry
- **Force Consensus:** Initiate object motion by force consensus
- **Distributed Trajectory Tracking:** Follow planned path
- **Human-Robot Cooperation:** Human leader can guide the robotic group

Robotic Hardware

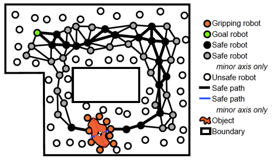


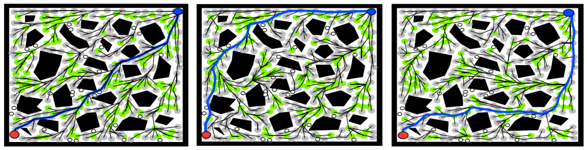
Custom-built m3pi Robot

- 2D force sensors
- Optical velocity sensor
- 1-DOF gripper
- ZigBee communication
- No localization

Distributed Path Planning

- Distributed Bellman-Ford
- Computed over network
- Nearest nodes along path beckon gripping robots
- Cost corresponding to collision likelihood

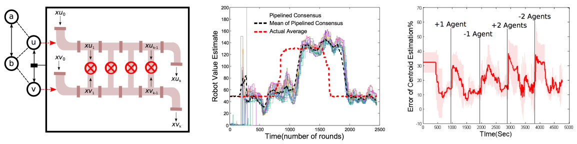




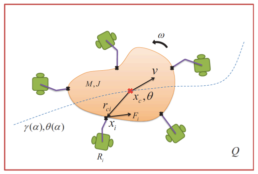
Simulation results with various network topologies.

Pipelined Consensus & State Estimation

- Track changing global state in a decentralized way
- Robust to message loss, changes in topology and agent population, sensor noises.



Coordination without Communication



$$M\dot{v} = \sum_{i=1}^{N} F_i - \mu_s M g \frac{v}{\|v\|} - \mu_v v$$

- Robots achieve force consensus to move object
- No communication
- **No** global localization and reference frame
- Object itself acts as communication medium
- Use local measurements

Approach 1: Large inertial and viscous force, many robots

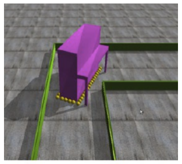
Follower force feedback law:

$$\dot{F}_i(t) = \sum_{j=1, j\neq i}^{N} \left(F_j(t) - F_i(t)\right)$$

← Standard linear consensus

Newton's 2nd law:

$$= \sum_{j=1}^{N} F_j(t) - NF_i(t) = M\dot{v} + \mu_s M g \frac{v}{\|v\|} + \mu_v v - NF_i(t)$$



Closed-loop system is 1st order:

Leader input →

$$\dot{\eta}(t) = -\eta(t) + F_1(t)$$

Sum of forces →

$$F_s(t) = (N-1)\eta(t) + F_1(t)$$

1000 robots transport a scale piano through maze

Approach 2: Large kinetic friction, comparable number of robots

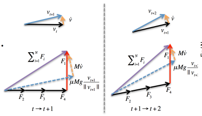
Follower force feedback law:

$$\mathbf{F}_i^i = \frac{\mu M g}{N} \frac{\mathbf{v}^i}{\|\mathbf{v}^i\|}, \quad i = \{2, 3, \cdots, N\}.$$

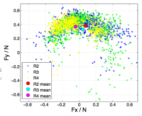
Leader force feedback law:

$$\mathbf{F}_1^1 = f_d \frac{\mathbf{v}_d^1}{\|\mathbf{v}_d^1\|}$$

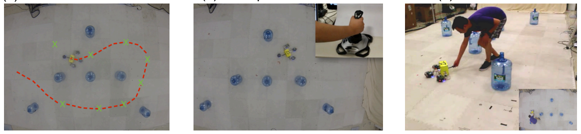
$$f_d = K_p \max\{\|\mathbf{v}_d^1\| - \|\mathbf{v}^1\|, 0\}$$



Evolution of force convergence



Experiment result of force convergence



Experiments with different leaders, same follower robots.

Publications

[5] Z. Wang and M. Schwager, "Kinematic Multi-Robot Manipulation with No Communication Using Force Feedback," IEEE Intl. Conf. on Robotics and Automation (ICRA), 2016, **Submitted.**

[4] Z. Wang and M. Schwager, "Multi-Robot Manipulation with No Communication Using Only Local Measurements," IEEE Conf. on Decision and Control (CDC), 2015, **Accepted.**

[3] G. Habibi, Z. Kingston, Z. Wang, J. McLurkin and M. Schwager, "Pipelined Consensus for Global State Estimation in Multi-Agent Systems," Intl. Conf. on Autonomous Agents and Multi-Agent Systems (AAMAS), pp. 1315-1323, May 2015.

[2] Z. Wang and M. Schwager, "Multi-robot Manipulation without Communication," Intl. Symp. on Distributed Autonomous Robotic Systems (DARS), pp. 43-56, Nov 2014.

[1] G. Habibi, W. Xie, M. Jellins, J. McLurkin, "Distributed Path Planning for Collective Transport Using Homogeneous Multi-Robot Systems," Intl. Symp. on Distributed Autonomous Robotic Systems (DARS), pp. 57-70, Nov 2014.