Multi-Robot Manipulation without Communication

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Motivation

➢ *Multi-Robot Manipulation*

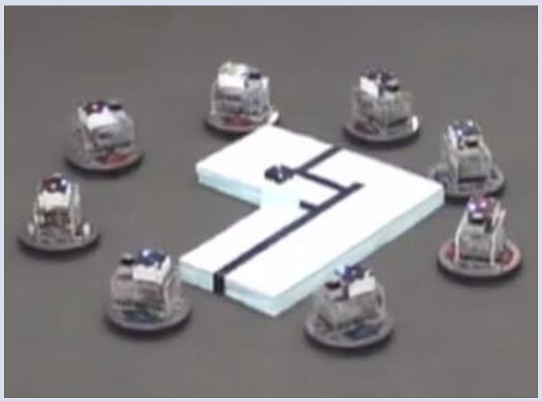
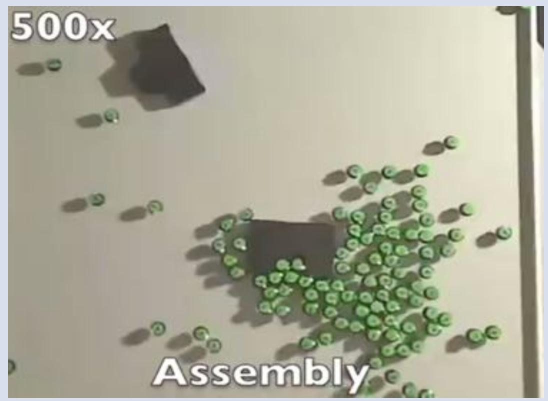
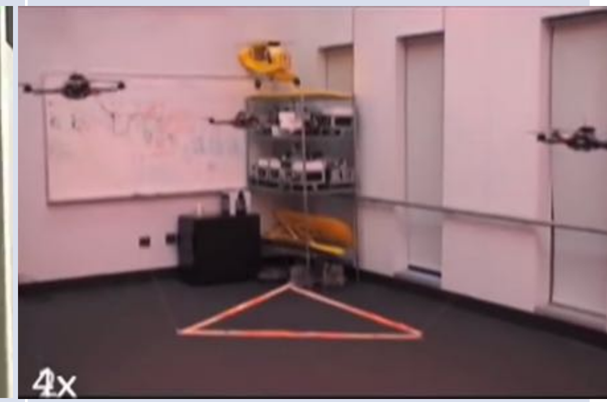
- Transport large objects
- Scalable, high fault tolerance
- Construction, manufacturing, disaster relief

➢ *Minimalist Approach*

- **No** explicit communication
- **No** global localization information
- Inexpensive individual robot

Related Works 1

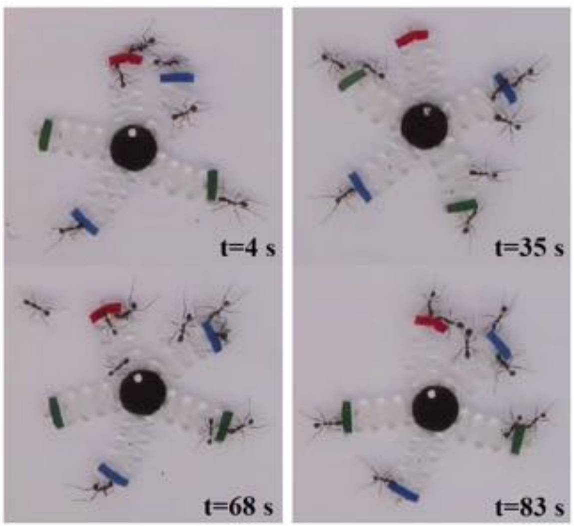
➢ *Featured solutions for multi-robot manipulation*

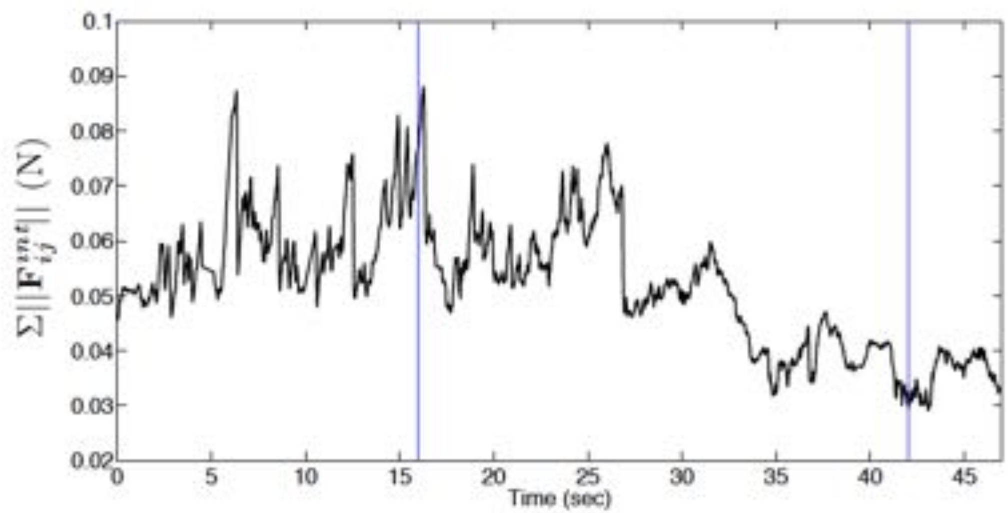
Caging / Force closure	Ensemble Control	Quadrotors
		
Fink et al. ICRA 08	Becker et al. IROS 13	Fink et al. IJRR 11
External localization info. Collision with objects	Centralized. Operated by human. Not automatic.	External localization info. Planning is centralized and offline.

Related Works 2

➢ *How ants manipulate objects*

- [Berman et al. RSS2010] Ants align their forces better and better as they move the object





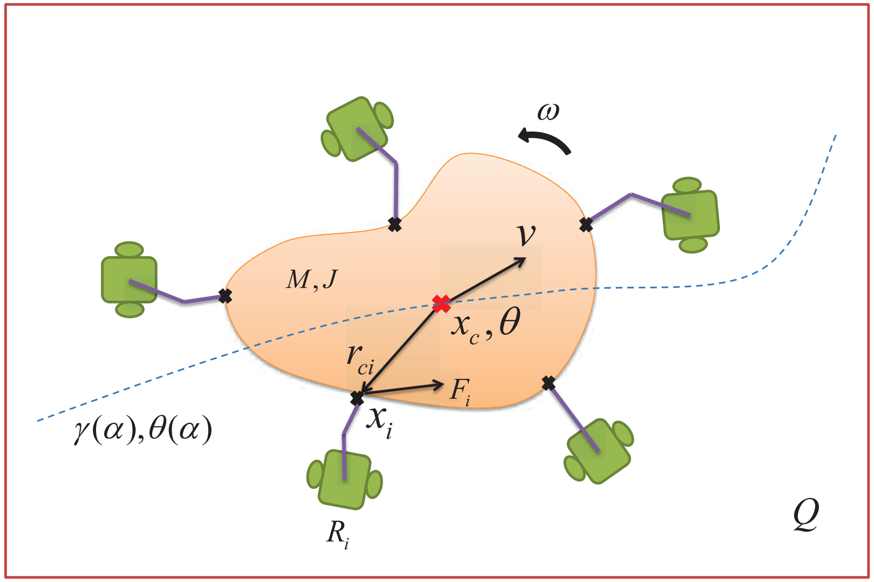
- [McCreery et al. **Insectes Sociaux**] Ants detect small-scale vibration or deformation of the object in order to coordinate their forces

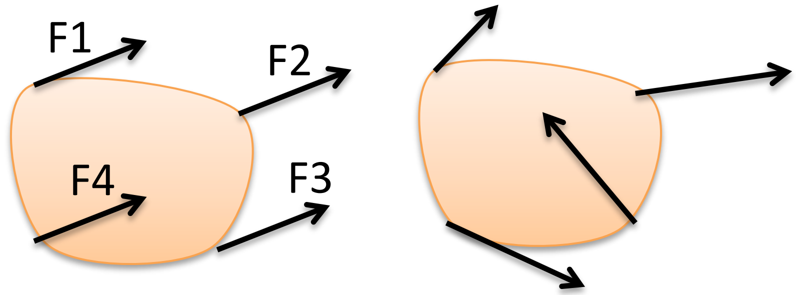
Our Approach: Overview

1. Surround and Grasp
2. Apply forces

3. Measure Obj's movement
4. Force Consensus

5. Leader robot steers all forces
6. Leader can be a human



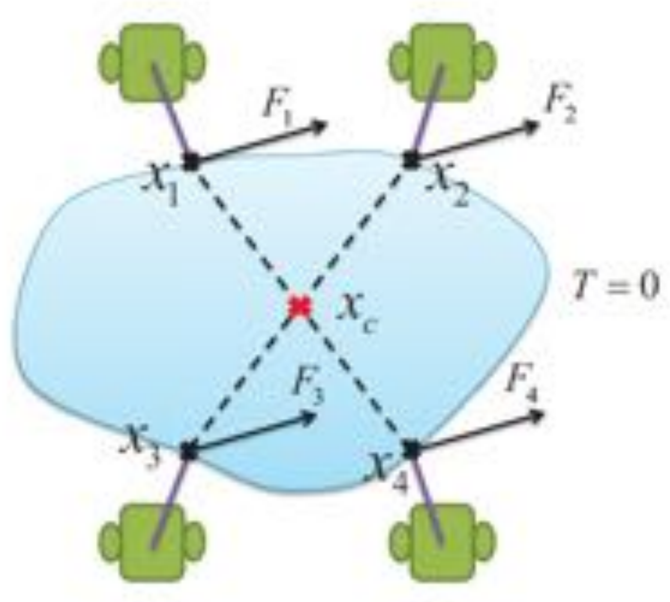


Force Consensus Force not Consensus

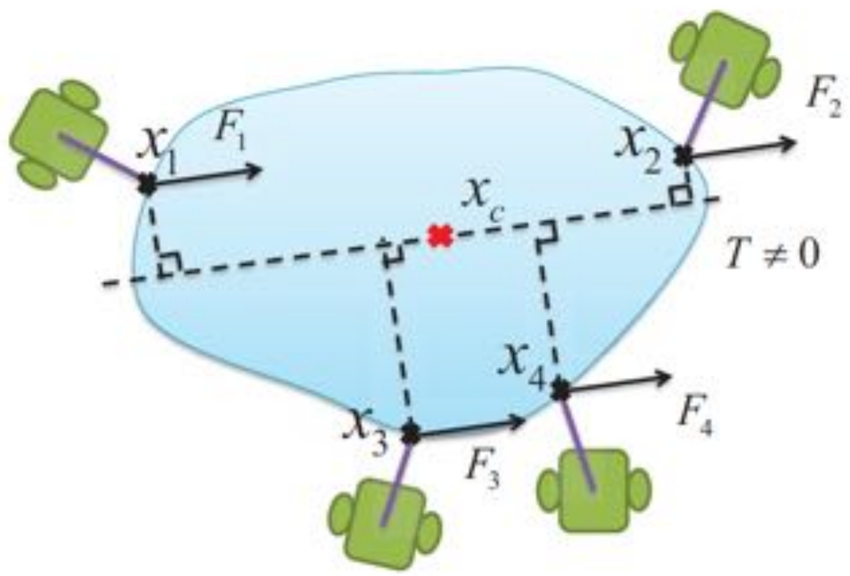
Assumptions

1. Robots have proper mechanism to grasp the object, and apply a **force** to the object with desired magnitude and direction.
2. Robots can **follow the object** and have their desired force maintained.
3. Robots are equipped with necessary sensors to **measure** the movement of the object.
4. One **leader robot** knows the desired trajectory of the object, can measure the angle and and angular velocity of the object, and can also apply a torque to the object.
5. Other **follower robots** have no information about their positions, the object's position and the desired trajectory of the object.
6. Robots are **centrosymmetrically** distributed around the object.

Centrosymmetric Assumption



Centrosymmetric



Non-Centrosymmetric

Problem Formulation

➢ *Known Parameters:*

Mass of the object	Moment of Inertia	Coeff. of static friction	Coeff. of viscous friction	Number of robots	Acceleration of gravity
M	J	μ_s	μ_v	N	g

➢ *Quantities Measurable by Robots*

Object's velocity	Object's acceleration
v	$\dot{v}$

- Note: v and $\dot{v}$ are at the center of the mass of the object.

Problem Formulation

Dynamics of the object

- Translational Dynamics

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

- Rotational Dynamics

$$J\dot{\omega} = T_1 - \frac{\mu_v}{M} J\omega$$

Goal

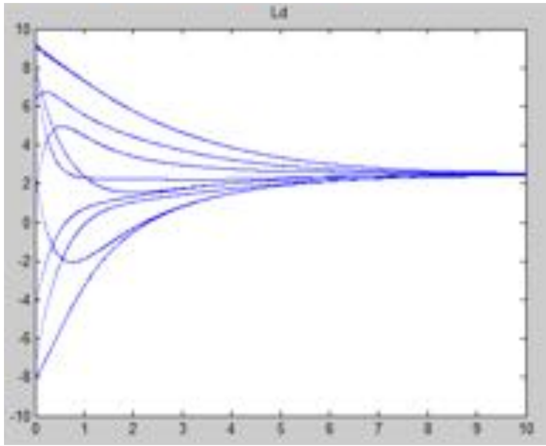
- A decentralized force updating law for F_i such that v and ω can be controlled in order to follow a desired trajectory.

Force Coordination via Consensus

MSL

➢ *Background*

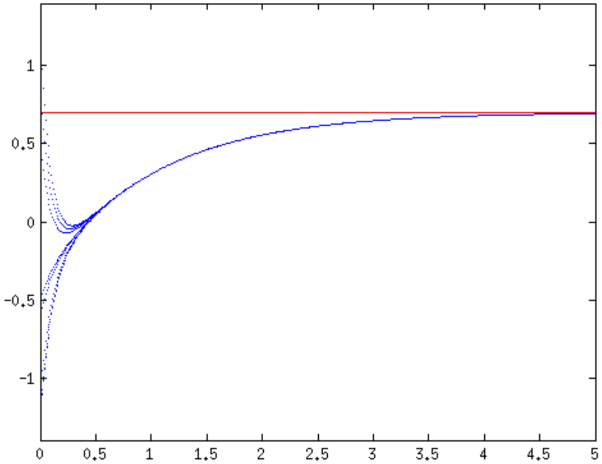
- Linear consensus algorithm



$$\dot{x}_i(t) = \sum_{v_j \in N_i} a_{ij}(x_j - x_i)$$

- Leader-following (steering)

  For example, fix $x_1(t) = x_1(0)$



[Olfati-Saber et al. TAC 2004]

[Jadbabaie et al. TAC 2003]

Force Coordination via Consensus

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➢ *Force Consensus without Communication*

Force updating law for each robot *i*

Linear consensus law, normally needs communication since *Fj* unknown

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

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

However, we know the sum… through translational dynamics!

Will result in a force consensus without communication

Force Coordination via Consensus

MSL

➢ *Leader following*

- Choose robot 1 as the leader
- If we **fix** the leader's force, then followers' forces will converge to the leader's

$$\lim_{t \to \infty} F(t) = F_1(0)\mathbf{1}$$

- If we **actively change** the leader's force, we can steer the group force dynamically

Force Coordination via Consensus

➢ *Leader following (Theorem 1)*

- Treat the **leader's force** (may be changing) as the **input**, the **group force** as the **output**, then their relationship can be characterized by the following first-order state space equations:

$$\begin{aligned} \dot{\eta}(t) &= -\eta(t) + F_1(t) \\ F_s(t) &= (N-1)\eta(t) + F_1(t) \end{aligned} \tag{12}$$

where $F_s(t) = \sum_{i=1}^{N} F_i(t)$ is the group force, and $\eta(t) = (\sum_{i=2}^{N} F_i(t))/(N-1)$ denotes the average force of all followers.

Force Coordination via Consensus

➢ *Convergence rate (Theorem 2)*

- Difference among follower robots

Theorem 2. *The difference among all followers in (9) will converge exponentially to zero regardless of the leader's input. The rate of this exponential convergence increases linearly with the number of robots.*

$$F_i(t) - F_k(t) = Ce^{-Nt}$$

- Convergence rate of the group force

$$\dot{F}_s = (N-1)\dot{\eta} + \dot{F}_1 = (N-1)(F_1 - \eta) + \dot{F}_1$$

- More robots -> faster convergence!

Controller Design and Trajectory Following

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➢ *Overall state-space dynamics*

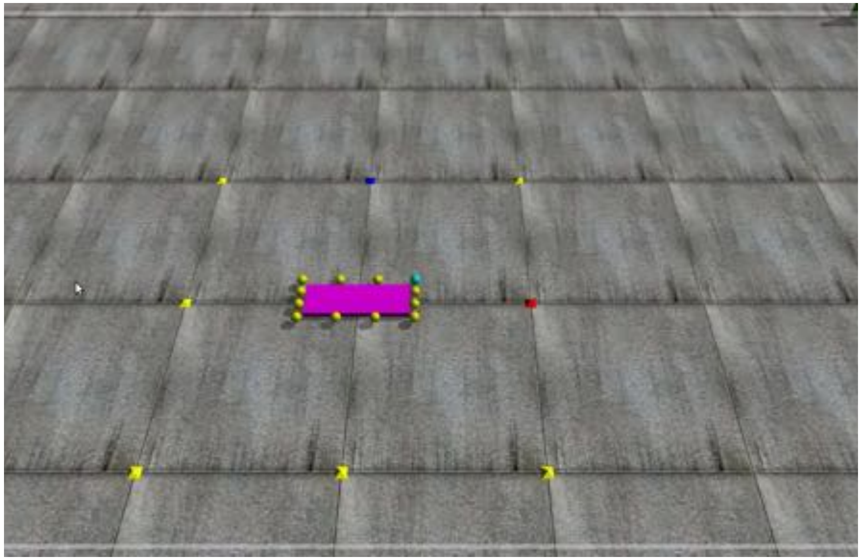
- Put everything together:

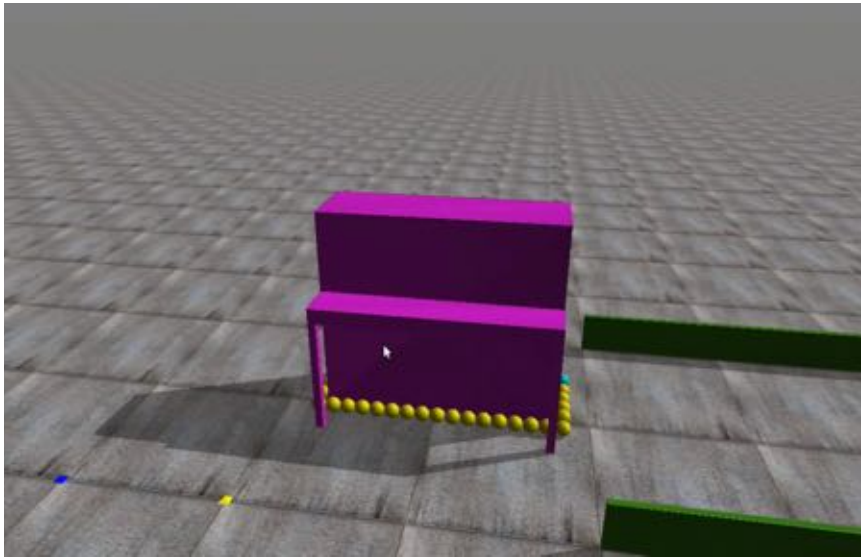
$$\begin{pmatrix} \dot{\eta} \\ \dot{v} \\ \dot{\omega} \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ \frac{N-1}{M} & -\frac{\mu_v}{M} & 0 \\ 0 & 0 & -\frac{\mu_v}{M} \end{pmatrix} \begin{pmatrix} \eta \\ v \\ \omega \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ \frac{1}{M} & 0 \\ 0 & \frac{1}{J} \end{pmatrix} \begin{pmatrix} F_1 \\ T_1 \end{pmatrix} + \begin{pmatrix} 0 \\ -\mu_s g \frac{v}{\|v\|} \\ 0 \end{pmatrix}$$

➢ *Controller design*

- Feedback control can be used to get desired performance on v and ω
- Use other trajectory following algorithms to choose desired v and ω

Simulations in Open Dynamic Engine (ODE)





12 Robots, 1 Leader
1kg Rectangular Plank
0.6m*0.2m*0.1m

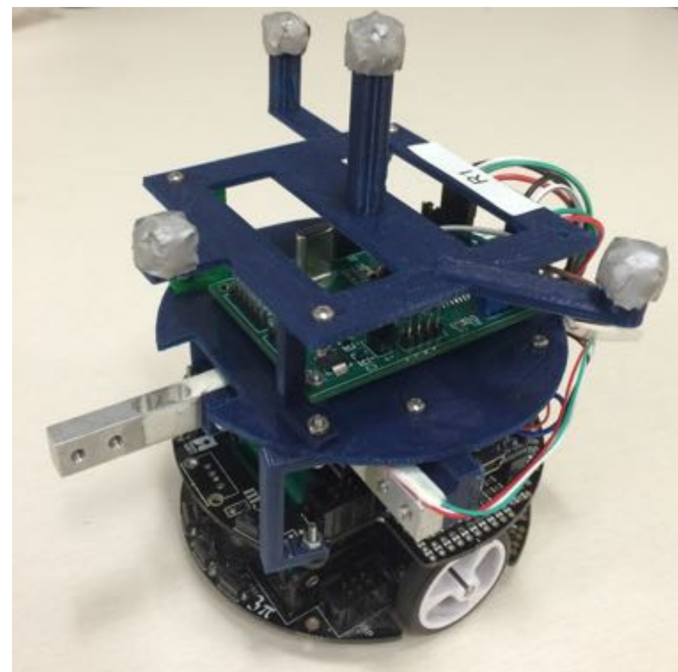
1000 Robots, 1 Leader
273kg Steinway Piano
1.54m*0.67m*1.32m

Conclusion

- A scalable multi-robot manipulation approach
- Completely decentralized
- Guarantee the efficiency of cooperation by reaching a force consensus
- A dynamic model
- No explicit communication
- No global localization information

Future Work

- Consensus using velocity and acceleration at attachment points rather than at the center of mass. (New paper submitted to ICRA 2015)
- Validation on physical robots
- Adaptive control
- Human-swarm interaction



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Thanks for you attention!

More info on our website:
http://sites.bu.edu/msl/

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