Kinematic Multi-Robot Manipulation with No Communication Using Force Feedback

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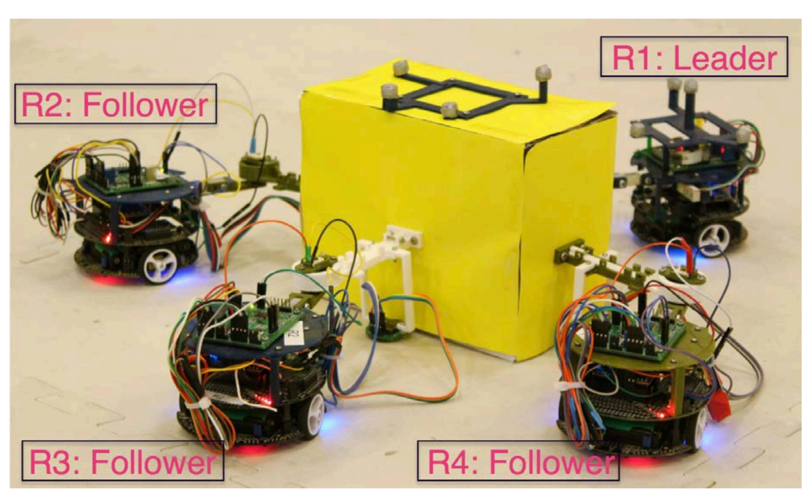
Summary

- Cooperative manipulation with **no** communication
- Follower robots **measure object's motion** as an implicit way for force coordination.
- Leader steers the group, can be a human.
- Proof of force alignment of all robots.
- Custom-built robot prototype with 2D force sensor and laser velocity sensor.

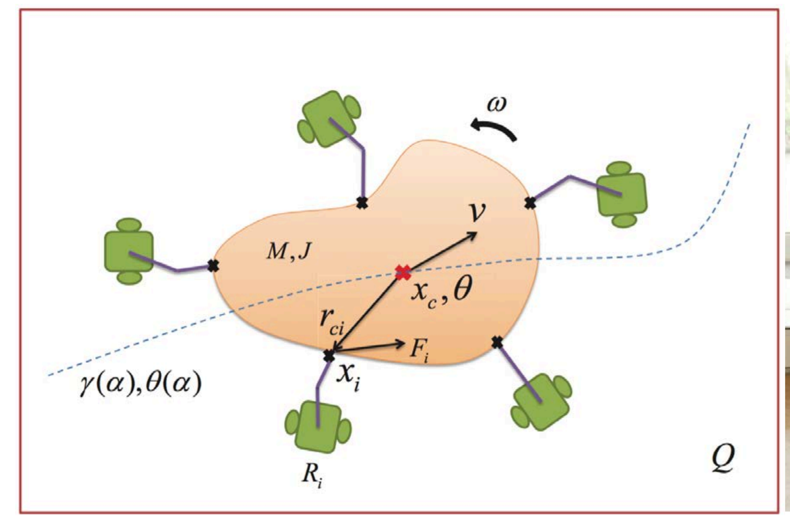


Experiment Video

Application Highlights

- Scalable, fault tolerance
- No communication, no global localization, inexpensive individual robot
- Construction, manufacturing, disaster relief

Dynamics and Force Controllers



- Object Dynamics

$$M\dot{\mathbf{v}} = \sum_{i=1}^{N} \mathbf{F}_i - \mu M g \frac{\mathbf{v}}{\|\mathbf{v}\|}$$

- Followers' Force Controller

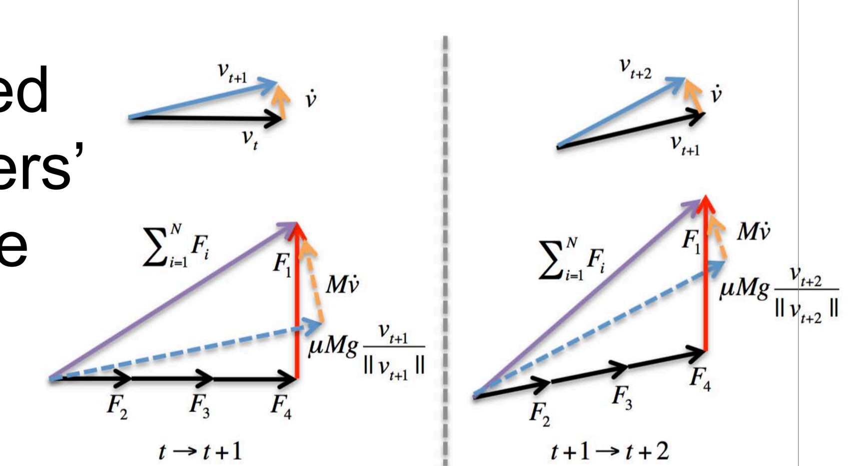
$$\mathbf{F}_i^i = \frac{\mu M g}{N} \frac{\mathbf{v}^i}{\|\mathbf{v}^i\|},\ i = \{2, 3, \cdots, N\}$$

- Leader's Force Controller

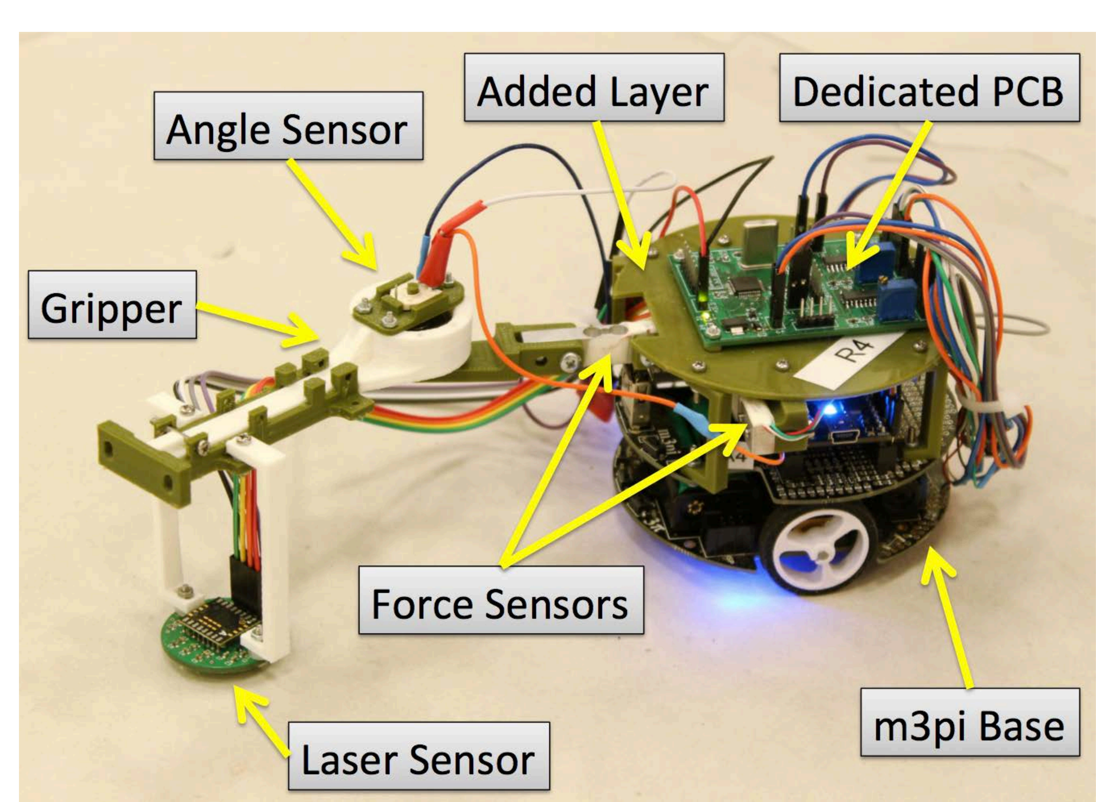
$$\mathbf{F}_1^1 = f_d \frac{\mathbf{v}_d^1}{\|\mathbf{v}_d^1\|} \qquad f_d = K_p \max\{\|\mathbf{v}_d^1\| - \|\mathbf{v}^1\|, 0\}.$$

Proof of Force Convergence

- **Theorem 1**: the proposed controllers cause followers' forces synchronize to the leader's
- Proof: Vector-based



Robot Design



- 2D force sensors
- Optical velocity sensor
- 1-DOF gripper

Force Feedback Control

- Reference frame conversion

$$\mathbf{v}^i = R(\theta_i)\mathbf{v}$$

- Linear force generation model

$$\mathbf{v}_c^i - \mathbf{v}^i = K_f(\mathbf{F}_i - \mathbf{f}_i)$$

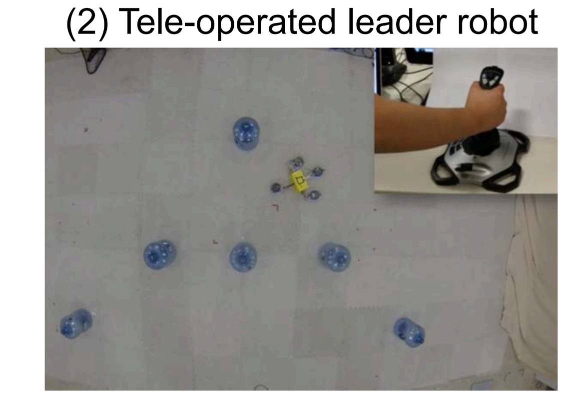
- Point offset control (overcome non-holonomic)

$$\mathbf{v}_p^i = \left[\frac{(\omega_l - \omega_r) r_w l}{d_w}, \frac{(\omega_l + \omega_r) r_w}{2}\right]$$

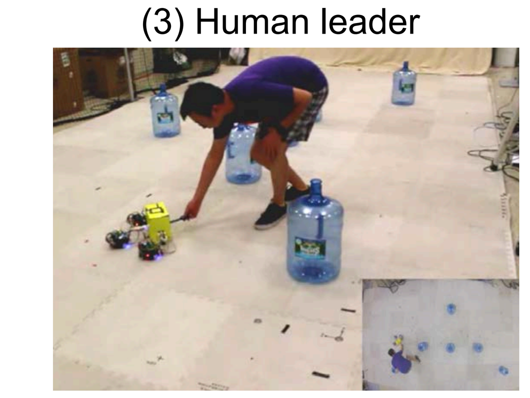
Results

(1) Autonomous leader robot

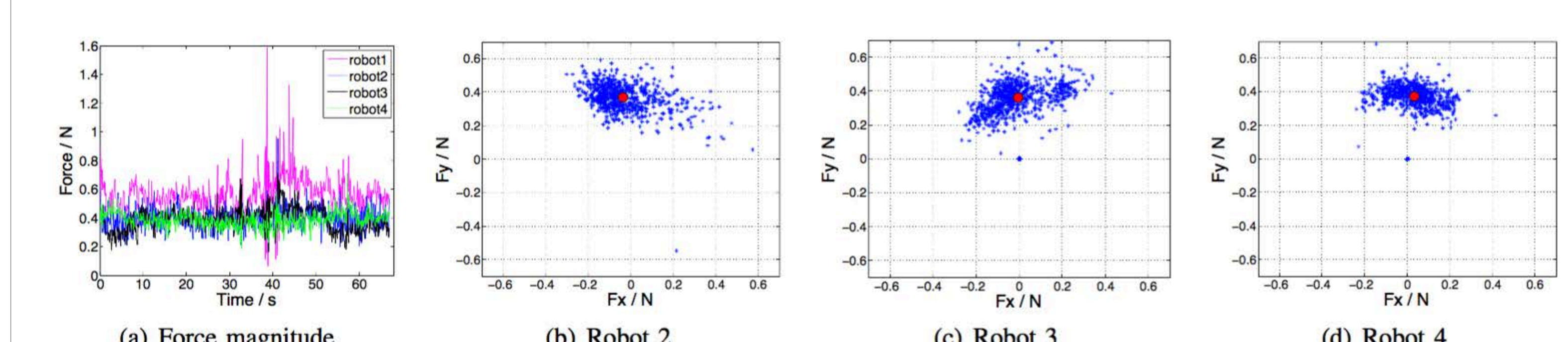
(2) Tele-operated leader robot



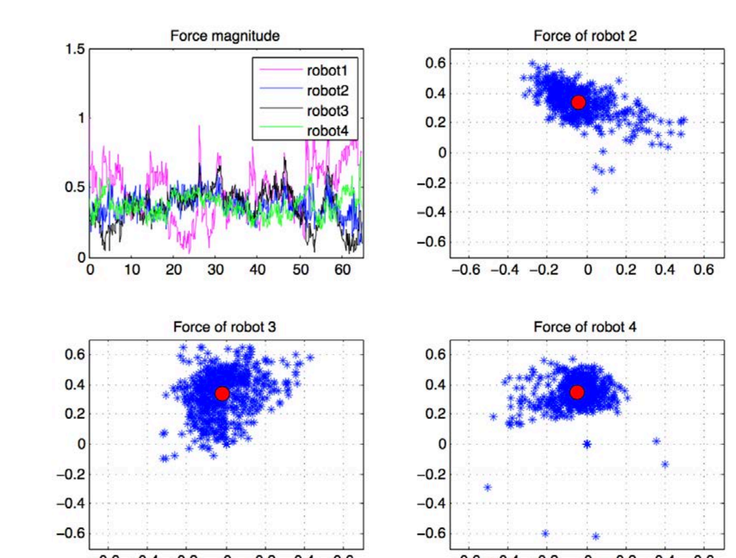
(3) Human leader



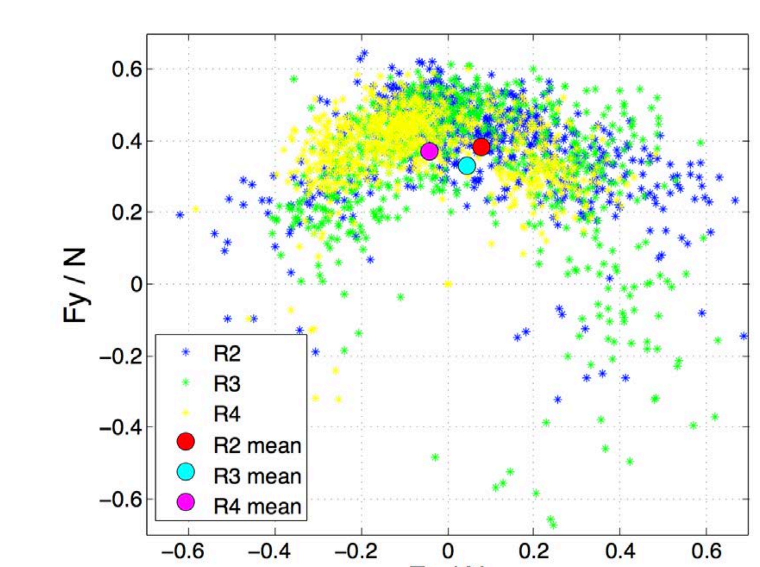
Experiments with different leaders, same follower robots.



Force histories in Exp. (1)



Force histories in Exp. (2)



Force histories in Exp. (3)

Paper QR Code (Scan)

Paper (PDF)

Video (YouTube)