Cooperative Mobile Manipulation without Explicit Communication [Wang, 2016]

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Outline

Motivation

Communication networks of robots confronts various problems

1. Very noisy
2. Demands high computational power
3. Deals with uncertainty
4. Might get vanished

Instead, we employ affordable sensing information

- Motion planning imposed by the leader
- Utilize force feedback
- Information attained locally

Applications

Both large and small number of robots can be used depending on the object's size

- Automated construction site
- Manufacturing facilities
- Structured environment

Translational Object Dynamics

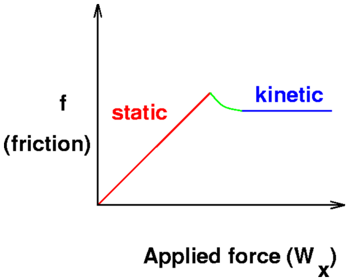
Translational motion subject to Newton's second law

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

- μ_k coefficient of kinetic friction
- μ_v coefficient of rolling friction
- $\frac{v}{||v||}$ unity tangent vector

Friction

- Friction of rigid bodies discriminates in 2 regions
- Static proportional to force
- Kinetic friction assumed constant
- Spinning wheels can replace kinetic w/ viscous friction - velocity related



Source: http://deutsch.physics.ucsc.edu/6A/book/forces/node21.html

Translational Dynamics Cases

1. For lightweight objects after Euler's discretization

$$M\frac{v_{t+1} - v_t}{\Delta t} = \sum_{i=1}^{N} F_i(t) - \mu_k M g \frac{v_t}{||v_t||} \tag{2}$$

2. For heavyweight objects

$$M\dot{v} = \sum_{i=1}^{N} F_i - \mu_v v \tag{3}$$

Assumption 1: M, μ_k, μ_v, g, N given

Object's Rotational Dynamics

$$J\dot{\omega} = T_1 + \sum_{i=2}^{N} r_i \times F_i - T_f = T_1 + \sum_{i=2}^{N} r_i \times F_i - \frac{\mu_\nu}{M} J\omega \qquad (4)$$

- T_f, static friction related torque, obect's motion $Q \in \mathbb{R}^2$
- $\sum_{i=2}^{N} r_i \times F_i$, follower robots torque
- r_i, vector from object's CoM to the contact point
- T_l, leader's applied torque

Assumption 2: Leader know object's ω and applies T_1

CB-ANTS Case

Constant Boost force (CB-ANTS) case deals with dragging the object

- Lightweight objects
- Dominant friction is kinetic
- Both global and local information studies

CB-ANTS Follower's Controller

Follower's force feedback controller

$$F_i^c = \frac{\mu_k M g}{N} \frac{v^c}{||v^c||}, \quad i = \{2, 3, \ldots, N\} \tag{5}$$

- v^c, object's velocity at CoM
- Includes information for the leader's motion intention
- Restricts the follower's forces so the leader's force dominates

CB-ANTS Leader's Controller

Leader's force feedback controller

$$F_l^l = f_d \frac{v_d^l}{||v_d^l||} = K_p max\{||v_d^l|| - ||v^l||, 0\} \frac{v_d^l}{||v_d^l||} \tag{6}$$

- v_d^l, v^l, desired and current velocity of the leader
- K_p, proportional gain
- Utilized max function to track the leader's velocity

Overall goal: Steer the object through a specific trajectory to the goal position

CB-ANTS Consensus

Theorem 1: In CB-ANTS case by employing equations 2, 5, 6 all follower robots align to the leader's direction and converge at

$$\phi = (N-1)\frac{\mu_k Mg}{N} \tag{7}$$

- Time step needs to be bounded $0 < \Delta t < N\frac{||v_t||}{\mu_k g}$
- Object's velocity converge to leader's velocity

Theorem 2: Follower forces converge to the leader's force exponential fast

Object's Dynamics

Object's discrete dynamics

$$v_{t+1} = \left(1 - \frac{\mu_k g \Delta t}{N||v_t||}\right) v_t + \frac{\Delta t K_p max\{||v_d^l|| - ||v^l||, 0\}}{M||v_d||} v_d \quad (8)$$

- Leader robot has to have specific force abilities to steer the object
- Leader's force needs to be at least above $\mu_k Mg/N$.

CB-ANTS Local Follower's Controller

Follower's force feedback controller using local measurements

$$F_i = \frac{\mu_k M g}{N} \frac{v_t + \omega_t \times r_i}{||v_t + \omega_t \times r_i||} \tag{9}$$

- v_t, object's velocity at CoM
- $\omega_t \times r_i$, angular velocity at contact point
- Includes information for the leader's motion intention
- Restricts the follower's forces so the leader's force dominates

Leader's force feedback remains the same as in equation 6

Local Object's Dynamics

Object's discrete dynamics using local measurements

$$v_{t+1} = \frac{\Delta t}{M} f_d \frac{v_d}{||v_d||} + \sum_{i=2}^{N} \left(\frac{\mu_k g \Delta t}{N||v_t + \omega_t \times r_i||} \right) \omega_t \times r_i + \\ + \left(1 + \sum_{i=2}^{N} \frac{\mu_k g \Delta t}{N||v_t + \omega_t \times r_i||} - \frac{\mu_k g \Delta t}{||v_t||} \right) v_t \qquad (10)$$

- 1^{st} term: Control input of the leader v_d
- 2^{nd} term: Disturbing term, we want to eliminate
- 3^{rd} term: Internal dynamics of the studied object, $|a| < 1$

Angular velocity boundary

Theorem 3: Sufficient condition to maintain theorem 1 is to bound ω

$$||\omega_t|| < \frac{||v_t||}{N||r_m||} \tag{11}$$

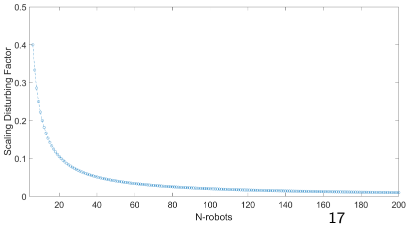
- m maximum radius value of CoM to contact point
- $m = \max_i ||r_i||,\ i = \{2, \ldots, N\}$

Elimination of Disturbing Factor

Theorem 4: Under centrosymmetric contact points assumption, follow theorem 3, and utilize N-robots $N > 3$, then we can restrict the disturbing factor

$$\left\| \sum_{i=2}^{N} \left(\frac{\mu_k g \Delta t}{n \| v_t + \omega_t \times r_i \|} \right) \omega_t \times r_i \right\| < \frac{\mu_k g \Delta t}{N} \left(\frac{2N - 1}{N^2 - N} \right) \qquad (12)$$

- Inequality is direct related to a scaling factor $(2N - 1)/(N^2 - N)$
- Disturbing term scales down exponentially



P-ANTS Case

Proportional force (P-ANTS) case deals with lifting and pulling the object on rolling devices

- Heavyweight objects
- Dominant friction is the rolling friction of the wheel
- Both global and local information studies

P-ANTS Follower's Controller

The consensus protocol commonly used for flocking

$$\dot{F}_i = \sum_{j \in N_i} (F_j - F_i) = \sum_{j \in N_i} F_j - NF_i \tag{13}$$

- N-complete graph

Employing equation 3

$$\dot{F}_i = M\dot{v} + \mu_v v - NF_i \tag{14}$$

- Reach consensus while the leader does not change its force
- $\dot{v}$, v object's velocity and acceleration at the CoM

P-ANTS State Equations

The state equations of P-ANTS

$$\dot{\eta} = -\eta + F_l \tag{15}$$

$$F_s = (N-1)\eta + F_l \tag{16}$$

- F_l, leader's force and the input
- $\eta = (\sum_{i=2}^{N} F_i)/(N-1)$, avg force of the followers and state
- $F_s = \sum_{i=1}^{N} F_i$, total force and the output of our system

P-ANTS Local Follower's Controller

Follower's force feedback controller using local measurements

$$\dot{F}_i = (\sum_{j \in N} F_j - NF_i) - \frac{M}{J} r_i \times (\sum_{j \in N} r_j \times F_j) \tag{17}$$

- 1^{st} term: Similar to equation 13
- 2^{nd} term: Disturbing term, we want to eliminate
- Leader's torque assumed to be negligible for many robots
- Under assumption 3 the centrifugal terms eliminated

P-ANTS Local Follower's Controller Matrix Form

The matrix form of follower's force feedback controller using local measurements

$$\dot{F} = \left(- L_a - \frac{M}{J} R_a(t) \right) F = -LF \tag{18}$$

- $F \in \mathbb{R}^{2N}$, vector of followers and leader forces
- $R_a(t) \in \mathbb{R}^{2N \times 2N}$, product of skew matrices
- The matrix form only focus on 2D-space

P-ANTS Local Follower's Controller Boundary Condition

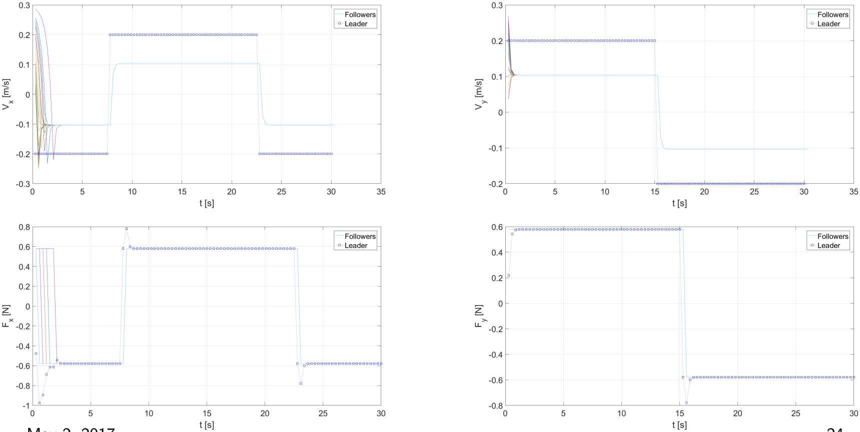
Eigenvalues o Laplacian matrix are less or equal to zero only if

$$\frac{M}{J}\sum_{i=1}^{N}||r_i||^2 < N \tag{19}$$

- Restricts the number of robots
  1. Object's mass M
  2. Inertia matrix J
  3. Radius from contact point to CoM of object r_i

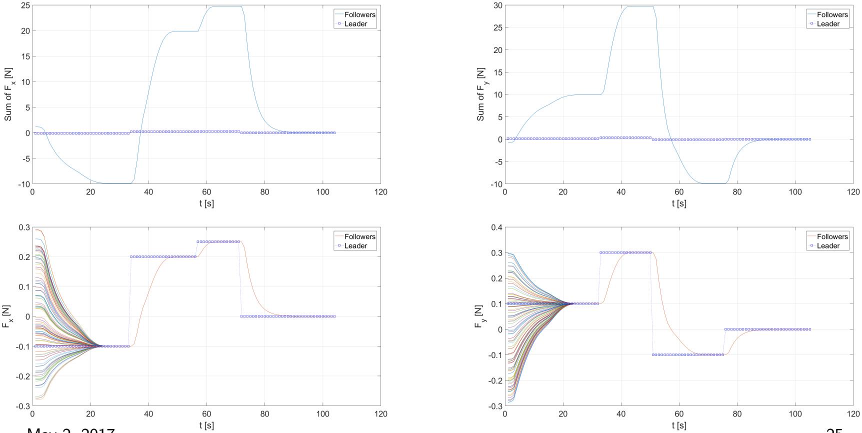
CB-ANTS Global

Velocity direction alignment and force consensus in x and y axes



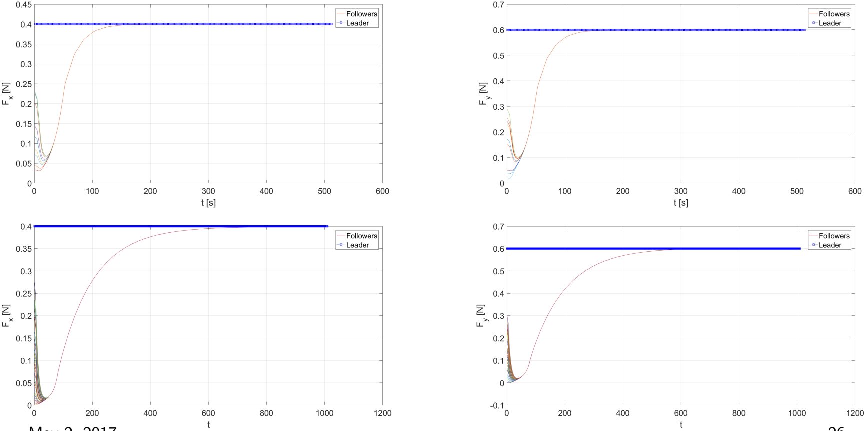
P-ANTS Global

Sum of forces and force consensus in x and y axes



P-ANTS Local

Force consensus w/ 10 and 100 robots in x and y axes



Conclusions

- Cooperative manipulation framework w/o explicit communication presented
- Force feedback information utilized
- Leader robot impose its force intention to the followers
- Two different cases studied depending on the object weight
  - CB-ANTS for lightweight objects by dragging
  - P-ANTS for heavyweight objects by lifting and pulling on rolling devices
- Two solutions presented for each case
  - Using global measurements
  - Using local measurements

Random Thoughts

- Discretization of object's dynamics
- Assumption 1, 2, 3 make the methodology compatible only in structured environments
- Assumption 3 for CB-ANTS and small number of robots is not feasible
- State equations for P-ANTS should not be used, because they are based on N-Complete graph
- P-ANTS w/ local measurements should extend in $3D$-space, because the inertia matrix is affected

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Thank You!