Teams of Collaborating Robots for Flexible Manufacturing
From Distributed Algorithms to Big Control

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Flexible Manufacturing

Credit: Martin Sehr, Siemens

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Credit: ECM
How to coordinate, control, and plan for large teams of manufacturing robots in dynamic, stochastic environments?

Fully distributed
Local information
Limited communication
Reactive control and sensing

Fully centralized
Global information
Communication intensive
Optimal planning and scheduling

Credit: Farelli.info
Credit: Business-opportunities.biz
Our Approach

- Local sensor information
- Local-Global Map
- Global state

- Individual robots
- Global-Local Online replanning
- Centralized planner
• Low-level reactive control primitives
• High level global planning and scheduling
• Local-global map
• Low-level reactive control primitives

• High level global planning and scheduling

• Local-global map
Distributed Multi-Robot Manipulation

Leader:
Knows desired trajectory

Followers:
No explicit communication
No global localization
No knowledge of trajectory

Credit: Farelli.info
Main Idea: Force Consensus

Object itself “communicates” necessary information

Wang, Schwager IJRR 2016
ICRA 2016, DARS 2016, CDC 2015, DARS 2014
Distributed Consensus

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

Olfati-Saber et al. TAC 2004
Jadbabaie et al. TAC 2003
Force Consensus through Physics

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

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

Unknown sum of forces

Can determine from object motion
Convergence

Theorem (Leader Following)

• The forces of all followers converge to the leader’s force exponentially fast, with convergence rate $N$

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

More robots -> faster convergence!
Experimental Studies

Custom-built Robot Platform
Experiments
Cooperative Manipulation with Quadrotors

Wang et al, ICRA 2018

Cooperative Object Transport in 3D with Multiple Quadrotors using No Peer Communication

Zijian Wang, Sumeet Singh, Marco Pavone, Mac Schwager
Department of Aeronautics and Astronautics, Stanford University
Cooperative Manipulation with Online Learning

Culbertson et al, ICRA 2018
Best Manipulation Paper
• Low-level reactive control primitives
• High level global planning and scheduling
• Local-global map
Package Swap Planning

Naive, no swapping
Package Swap Planning

Better to swap midway!
MILP Formulation

Minimize: \( \sum_{t=1}^{T} \sum_{k=1}^{P} J'_k z_k[s, t] \)
subject to: \( x_i[s, t] = \{0, 1\} \)
\( z_k[s, t] = \{0, 1\} \)
\( \sum_{s=1}^{S} x_i[s, t] = 1 \)
\( \sum_{s=1}^{S} z_k[s, t] = 1 \)
\( x_i[s, t + 1] \leq T_s x_i[s, t] \)
\( z_k[s, t + 1] \leq T_s z_k[s, t] \)
\( T_s \) is the adjacency vector (\( T_{s=a}[b] = 1 \) iff \( a \) is adjacent to \( b \))

\[
\begin{cases}
  z_k[s, t] \leq \sum_{i=1}^{n} x_i[s, t] + z_k[s, t - 1] & s_k = z_f[k] \\
  z_k[s, t] \leq \sum_{i=1}^{n} x_i[s, t] & \text{otherwise}
\end{cases}
\]

- Efficient for < 10 robots and packages, 12x12 grid
- Efficient receding horizon version for larger problems
In this work we present a novel MILP formulation to the package delivery problem with exchanges in a discrete grid world. Furthermore we apply an MPC wrapper to the solver in order to reduce the amount of memory needed to solve the problem in a reasonable amount of time. This algorithm has the potential to be used as a high level planner for more complicated distribution delivery scheduling.

A. Extensions

In our solution we formulated the optimization problem in CONVEX.jl and passed it off to the commercial solver Gurobi. While Gurobi is very fast as a solver, the entire pipeline might benefit from a more direct formulation as CONVEX.jl creates quite the bottleneck. Currently, the algorithm only takes one scenario at initialization, and all package locations are held in memory. An additional feature could be to allow for packages to be added at random or removed from the system when delivered to more closely mimic a real life scenario. Lastly, some level of congestion aware routing could be applied to make the system more robust in real life conditions where agents share the physical roadways.

REFERENCES


Problem Specification

Planning Results

10 robots, 18 packages, 15x15 grid
Looking Forward

- Fuse distributed low-level and centralized high-level
- Local-Global map
- Analysis
  - Safety guarantees
  - Suboptimality bounds
- Case studies
Thanks!

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