Finding Optimal Plans for Multiple Teams of Robots through a Mediator: A Logic-Based Approach

Esra Erdem, Volkan Patoglu, Zeynep G. Saribatur, Peter Schüller, Tansel Uras
Motivation

- Conventional manufacturing systems fall short of responding to demands.
- New approaches for automated fabrication become crucial.
- Cognitive factories are aimed towards manufacturing plants. They rapidly respond to changing customer needs and customization requests.
Cognitive Factories

Advantages:
- High-level reasoning
- Sophisticated planning and decision-making algorithms
Cognitive Factories

Challenges:

- Coordination between multiple teams of robots
- Achieve overall shortest delivery time
The Problem and Our Goal

We have multiple teams of robots:

- Each team is given a feasible task to complete.
- Teams can transfer robots between each other.

Constraints:

C1 Teams do not know each other’s information

C2 Lending/borrowing robots between workspaces back and forth is not desired.
   Robots can be transferred between two teams in a single batch.

Our goal:

- To find an optimal global plan for all teams.
Finding an optimal global plan for all teams, with at most $k$ steps, subject to constraints [C1] and [C2], through a mediator.
Our Method
First Phase

- For every $\bar{l} \leq k$:
  1. The mediator asks yes/no questions to every team.
  2. The mediator tries to find a *coordination* of the teams.

- A coordination for the optimal value of $\bar{l}$ is found.
For the optimal value of $\bar{\gamma}$:

1. The mediator informs each team.
2. Each team computes an optimal local plan.

An optimal global plan for all teams is the union of all optimal local plans.
For every $l \leq \bar{l}$ and $m \leq \bar{m}$:

**Q1** Can you complete your task in $\bar{l}$ steps?

**Q2** Can you complete your task in $\bar{l}$ steps, if you lend $m$ robots before step $l$?

**Q3** Can you complete your task in $\bar{l}$ steps, if you borrow $m$ robots after step $l$?
First Phase
Coordination of Teams

We introduce:

- \( Lend\_earliest_m : Lenders \rightarrow \{0, ..., \bar{l}\} \)
- \( Borrow\_latest_m : Borrowers \rightarrow \{0, ..., \bar{l}\} \)
- Delay time:
  - \( Delay : Lenders \times Borrowers \rightarrow \mathbb{N} \)

We define:

- Collaboration between \( Lenders \) and \( Borrowers \)
A collaboration is a function:

$$f : Lenders \times Borrowers \rightarrow \{0, ..., \bar{I}\} \times \{0, ..., \bar{m}\}$$

such that the followings hold:

- A borrower does not borrow fewer robots than it needs.
- A lender does not lend more robots than it can.
Example Scenario

- $\text{Lend}_{\text{earliest}}_m$ and $\text{Borrow}_{\text{latest}}_m$
- $\text{Delay}(i, j) = |i - j|$
Example Scenario

- **Collaboration function:**
  \[ f(1, 3) = (3, 1), \ f(1, 4) = (3, 1), \ f(2, 4) = (2, 1) \]
First Phase
Find-Collaboration

**Input**  For a set *Lenders*, a set *Borrowers*, positive integers \( \bar{l} \) and \( \bar{m} \), a delay function *Delay* and a collection of *Lend\_earliest\_m* and *Borrow\_latest\_m* for every positive integer \( m (m \leq \bar{m}) \).

**Output**  A collaboration between *Lenders* and *Borrowers* with at most \( \bar{m} \) robot transfers and within at most \( \bar{l} \) steps, relative to *Delay*.
First Phase
Find-Collaboration

Input For a set Lenders, a set Borrowers, positive integers $\bar{l}$ and $\bar{m}$, a delay function Delay and a collection of Lend_earliest$_m$ and Borrow_latest$_m$ for every positive integer $m$ ($m \leq \bar{m}$).

Output A collaboration between Lenders and Borrowers with at most $\bar{m}$ robot transfers and within at most $\bar{l}$ steps, relative to Delay.

Theorem
The decision version of Find-Collaboration is NP-complete.
Our Method
First Phase

For every $\bar{l} \leq k$:

1. The mediator asks yes/no questions to every team.
2. The mediator tries to find a *coordination* of the teams.

A coordination for the optimal value of $\bar{l}$ is found.
Our Method
First Phase - Automated Reasoners

- For every $\bar{l} \leq k$:
  1. The mediator asks yes/no questions to every team.
     - Method: The domain is represented in C+ (Erdem et al. 2012).
       Each query is a planning problem with temporal constraints.
       The formulation is transformed into ASP using the tool Cplus2ASP
       (Casolary and Lee 2011).
     - Automated reasoner: ASP solver
  2. The mediator tries to find a *coordination* of the teams.
    - Method: The problem is represented in ASP.
    - Automated reasoner: ASP solver

- A coordination for the optimal value of $\bar{l}$ is found.
  - Linear search, as suggested in (Trejo et al. 2001).
% lender I lends U robots to borrower J at step L  
\{ f(I,J,L,U) : step(L): num(U) \} 1 :- borrower(J), lender(I).

% a borrower team does not borrow fewer robots than it needs  
condition_borrower(J) :-
  % borrower J needs at least M robots until step L  
borrow_latest(J,M,L), borrower(J), step(L), num(M),  
% the latest step that J borrows robots should be at most L  
#max[f(I,J,L1,U)=L1+T:lender(I):num(U):delay(I,J,T)] L,  
% the total number of robots J borrows should be at least M  
M [f(I,J,L1,U)=U:lender(I):step(L1)].

:- not condition_borrower(J), borrower(J).
Our Method

Representation of the Coordination Problem in ASP

% lender I lends U robots to borrower J at step L
\{f(I,J,L,U) : step(L): num(U) \} 1 :- borrower(J), lender(I).

...

% a lender team does not lend more robots than it can
condition_lender(I) :-
  % lender I can lend at most M robots after step L
  lend_earliest(I,M,L),lender(I), step(L), num(M),
  % the earliest step that I lends robots should be at least L
  L #min[f(I,J,L1,U)=L1:borrower(J):num(U)],
  % the total number of robots I lends should be at most M
  [f(I,J,L1,U)=U:borrower(J):step(L1)] M.

:- not condition_lender(I), lender(I).
Our Method
Second Phase

- For the optimal value of $\bar{\bar{a}}$:
  1. The mediator informs each team.
  2. Each team computes an optimal local plan.

- An optimal global plan for all teams is the union of all optimal local plans.
Our Method
Second Phase - Automated Reasoners

- For the optimal value of $\bar{l}$:
  1. The mediator informs each team.
  2. Each team computes an optimal local plan.
     - Automated reasoner: ASP solvers

- An optimal global plan for all teams is the union of all optimal local plans.
We performed some experiments in a Painting Factory domain.
Experiments

- We performed some experiments in a Painting Factory domain.

Solvers

- Clasp version 2.1.3 (with Gringo version 3.0.4)
## Experimental results for six scenarios

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<th>Workspace (grid cells)</th>
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<th>Optimal Global Plan (with collaboration) length</th>
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Simulation
Related Work

Decoupling plans of multiple agents to coordinate their actions: (M. M. de Weerdt 2009)

- Coordination before planning: Social laws (Shoham and Tennenholtz 1995; ter Mors et al. 2004).
- Coordination during planning:
  - Partial Global Planning (PGP) framework (Durfee and Lesser 1987).
  - The Plan Merging Paradigm (Alami et al. 1998).
- Coordination after planning:
  - Plan-synchronization process starting with individual plans (Georgeff 1988).
  - Introducing restrictions on individual plans (Yang et al. 1992; Foulser et al. 1992).
  - Using A* search with a smart cost-based heuristic (Ephrati and Rosenschein 1993).
Conclusion

- We introduced a method to find an optimal global plan.
- We defined the problem of determining a coordination, and proved its intractability.
- We evaluated the usefulness of our approach in a cognitive factory setting using the state-of-the-art ASP solvers, and observed a promising decrease in the total process time.
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