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Coordination of Multiple Teams of Robots for an Optimal Global Plan

Zeynep G. Saribatur and **Esra Erdem** and **Volkan Patoglu** *
Sabancı University, İstanbul, Turkey
{zgsaribatur, esraerdem, vpatoglu}@sabanciuniv.edu

Abstract

We consider multiple teams of heterogeneous robots, where each team is given a feasible task to complete in its workspace on its own, and where teams are allowed to transfer robots between each other. We study the problem of finding a coordination of robot transfers between teams to ensure an optimal global plan (with minimum makespan) so that all tasks can be completed as soon as possible by helping each other. We propose to solve this problem using answer set programming.

Introduction

Multiple teams of robots with heterogeneous capabilities are commonly employed to complete a task collaboratively in many application domains, ranging from search and rescue operations to exploration missions, service robotics to cognitive factories. In these domains, the goal is for all teams to complete their tasks as soon as possible, and should the need arise, teams help each other by lending robots.

We propose a semi-distributed method to find an optimal global plan (with minimum makespan) for all teams, via a neutral mediator who does not know anything about the workspaces of teams, and where limited amount of information is exchanged between the mediator and the teams. First, the mediator gathers information from the teams about when they can lend or need to borrow how many robots and of which sort. Then the mediator computes a coordination of robot transfers among the teams to ensure an optimal global plan. Next, the mediator informs each team about when they are expected to lend/borrow what kind of robots, as well as the makespan of the optimal global plan. After each team utilizes this information for their local planning, combination of the local plans form an optimal global plan.

In this note, we focus on the coordination problem only, i.e., finding a coordination of robot transfers among the teams to ensure an optimal global plan. We propose to solve this problem using answer set programming (ASP) (Brewka, Eiter, and Truszczynski 2011).

Related Work Our work is similar to works on decoupling plans of multiple agents to coordinate their actions (de Weerdt and Clement 2009) in that local plans are computed by agents and then combined in order to compute a global plan. In these related works, a conflict-free coordination is ensured by specifying social laws before local planning (Shoham and Tennenholtz 1995; ter Mors, Valk, and Witteveen 2004) or putting restrictions on local plans to be able to merge them into a global plan (Yang, Nau, and Hendler 1992; Stuart 1985; Georgeff 1988), or by exchanging information between teams about their partial plans or goals (ter Mors, Valk, and Witteveen 2004; Decker and Lesser 1994; Alami, Ingrand, and Qutub 1998).

Our method is different from these works in that no restrictions are put on the order of actions for local planning of each team, and that teams do not exchange information about their plans or goals with each other. Also, we do not assume that all teams are in the same workspace, or all robots are of the same sort. Moreover, our goal is not to find any coordination of teams that would allow decoupling of their local plans, but to find a coordination of teams for an optimal global plan (with minimum makespan); therefore, we also consider transfer of robots between teams.

Problem Description

Consider multiple teams of n types of robots, where each team is given a feasible task to complete in its workspace on its own, and where teams are allowed to transfer robots between each other. The goal is to find a coordination of robot transfers between teams to ensure an optimal global plan (with minimum makespan) for all teams so that all tasks are completed as soon as possible within at most k steps, where at most $\overline{m}_x$ robots of type x are transferred between any two teams. Due to cost of transfers, we assume that robot transfers between workspaces back and forth is not desired, and robots can be transferred between two teams in a single batch.

According to our semi-distributed approach to find an optimal global plan described in the introduction, which extends our earlier method (Erdem et al. 2013) to heterogeneous robots, a neutral mediator asks yes/no questions of the following three forms to every team (in any order), for every $\bar{l} \leq k$, $l \leq \bar{l}$ and $m \leq \overline{m}_x$, $x \leq n$:

- Can you complete your task in $\bar{l}$ steps?
- Can you complete your task in $\bar{l}$ steps, if you lend (resp. borrow) m robots of type x before (resp. after) step l?

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To restrict the number of questions, we assume that teams borrow/lend robots of the same sort.

Teams' answers to these questions can be used to identify lenders and borrowers, and decide whether teams can collaborate with each other so that every team completes its task in $\bar{l}$ steps as follows. First, we identify the earliest lend times and latest borrow times by a collection of partial functions and the transportation delay time between workspaces by a function.

Next, we define when a set of lender teams can collaborate with a set of borrower teams.

Definition 1. *An* $n\overline{m}\bar{l}$-collaboration *between Lenders and Borrowers with at most* $\overline{m} = \max\{\overline{m}_x\}$ *robot transfers, with* n *types of robots, and within at most* $\bar{l}$ *steps, relative to Delay, is a partial function*

$$f : Lenders \times Borrowers \times \{1, \ldots, n\} \mapsto \{0, \ldots, \bar{l}\} \times \{0, \ldots, \overline{m}\}$$

(where $f(i,j,x) = (l,u)$ *denotes that team* i *lends* u *robots of type* x *to team* j *at step* l*) such that the following hold:*

(a) For every borrower team $j \in Borrowers_x$*, there are some lender teams* $i_1, \ldots, i_s \in Lenders_x$*,* $x \leq n$*, where the following two conditions hold:*
- $f(i_1, j, x) = (l_1, u_1), \ldots, f(i_s, j, x) = (l_s, u_s)$ *for some time steps* $l_1, \ldots, l_s \leq \bar{l}$*, some positive integers* $u_1, \ldots, u_s \leq \overline{m}_x$*, and some type* x*,*
- $Delay(i_1, j, x) = t_1, \ldots, Delay(i_s, j, x) = t_s$ *for some time steps* $t_1, \ldots, t_s \leq \bar{l}$*;*

and there is a positive integer $m \leq \overline{m}_x$ *such that*

$$\max\{l_1 + t_1, \ldots, l_s + t_s\} \leq Borrow\_latest_{m,x}(j)$$
$$m \leq \sum_{k=1}^{s} u_k.$$

(b) For every lender team $i \in Lenders_x$*, for all borrower teams* $j_1, \ldots, j_s \in Borrowers_x$*,* $x \leq n$*, such that* $f(i, j_1, x) = (l_1, u_1), \ldots, f(i, j_s, x) = (l_s, u_s)$ *for some time steps* $l_1, \ldots, l_s \leq \bar{l}$*, some positive integers* $u_1, \ldots, u_s \leq \overline{m}_x$*, and some type* x*, and there is a positive integer* $m \leq \overline{m}_x$ *such that*

$$Lend\_earliest_{m,x}(i) \leq \min\{l_1, \ldots, l_s\}$$
$$m \geq \sum_{k=1}^{s} u_k.$$

Now we are ready to define the computational problem of finding a coordination of multiple teams of heterogeneous robots, to complete all the tasks as soon as possible in at most $\bar{l}$ steps where at most $\overline{m}$ robots can be relocated:

FINDCOLLABORATION_n

INPUT: For a set *Lenders* of lender teams, a set *Borrowers* of borrower teams, positive integers n, $\bar{l}$ and $\overline{m}_x$, $x \leq n$: a delay function *Delay* and a collection of functions $Lend\_earliest_{m,x}$ and $Borrow\_latest_{m,x}$ for every positive integer $m \leq \overline{m}_x$, $x \leq n$.

OUTPUT: A $n\overline{m}\bar{l}$*-collaboration* between *Lenders* and *Borrowers* with at most $\overline{m} = \max\{\overline{m}_x\}$ robot transfers, with at most n types of robots, and within at most $\bar{l}$ steps, relative to *Delay*.

Proposition 1. *The decision version of* FINDCOLLABORATION_n *(i.e., existence of a* $n\overline{m}\bar{l}$*-collaboration) is NP-complete.*

Our Method

We solve this problem using ASP. For that we model FINDCOLLABORATION_n in ASP. The input is represented by a set of facts, using atoms of the forms $delay(i,j,l)$, $lend\_earliest(i,m,l,x)$, and $borrow\_latest(j,m,l,x)$ where $1 \leq x \leq n$, $i \in Lenders_x$, $j \in Borrowers_x$, $m \leq \overline{m}$, $l \leq \bar{l}$.

An $n\overline{m}\bar{l}$-collaboration f is defined by atoms of the form $f(i,j,l,u,x)$ (describing $f(i,j,x) = (l,u)$), by first "generating" partial functions f:

$$\{f(i,j,l,u,x) : l \leq \bar{l}, u \leq \overline{m}\}1 \leftarrow (1 \leq x \leq n, i \in Lenders_x, j \in Borrowers_x)$$

and then ensuring that the borrowers can borrow exactly one type of robot and that the lenders can lend at most one type of robots. Then the partial functions that do not satisfy conditions (a) and (b) of Def. 1 are "eliminated":

$$\leftarrow not\ condition\_borrower(j,x), fB(j,x) \quad (j \in Borrowers_x, 1 \leq x \leq n)$$
$$\leftarrow not\ condition\_lender(i,x) \quad (i \in Lenders_x, 1 \leq x \leq n).$$

With the ASP formulation whose some parts are described above, an ASP solver can find an $n\overline{m}\bar{l}$-collaboration.

Discussion

We have introduced a method for finding a coordination of multiple teams of heterogeneous robots to help each other, to be able to complete all their tasks as early as possible. We have applied this method to a cognitive toy factory with real robots. Videos of the demonstrations are available at http://cogrobo.sabanciuniv.edu/?p=748.

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