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Innovative Applications of O.R.

The block-information-sharing strategy for task allocation: A case study for structure assembly with aerial robots☆

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ABSTRACT

A new paradigm for task allocation in cooperative multi-robot systems is proposed in this paper. The block-information-sharing (BIS) strategy is a fully distributed approach, where robots dynamically allocate their tasks following the principle of *share* & *divide* to maintain an optimal allocation according to their capabilities. Prior studies on multi-robot information sharing strategies do not formally address the proof of convergence to the optimal allocation, nor its robustness to dynamic changes in the execution of the global task. The BIS strategy is introduced in a general framework and the convergence to the optimal allocation is theoretically proved. As an illustration of the approach, the strategy is applied to the automatic construction of truss structures with aerial robots. In order to demonstrate the benefits of the strategy, algorithms and simulations are presented for a team of heterogeneous robots that can dynamically reallocate tasks during the execution of a mission.

1. Introduction

Multi-robot task allocation in dynamic environments is one of the fundamental problems in cooperative robotics and a challenging area in operational research (Dias, Zlot, Kalra, & Stentz, 2006; Gerkey & Matarić, 2004; Korsah, Stentz, & Dias, 2013; Shima, Rasmussen, Sparks, & Passino, 2006; Tsalatsanis, Yalcin, & Valavanis, 2012): given a group of cooperative robots, a global task to be performed in a dynamic environment and a cost function, how should subtasks be allocated to the robots in order to complete the task while minimizing costs?

Let us consider a task such as the cooperative manipulation of structures addressed in the ARCAS European Project (http://www.arcas-project.eu/) funded by the European Commission. One of the goals of this project is to assemble a structure using a team of aerial robots equipped with on-board manipulators. The practical interest of this system can be found in situations where it is required to build a structure in places with difficult access through conventional means (see Fig. 1). The use of aerial robots allows to perform assembly operations in any point in space, which in areas of difficult access represents a relevant advantage over ground robots.

Assembly planning (Ghandi & Masehian, 2015) is the process of creating a detailed plan to craft a whole product from separate parts by taking into account the geometry of the final structure, available resources to manufacture the product, fixture design, feeder and tool descriptions, etc. Efficient assembly plans can significantly reduce time and costs. The assembly planning problem has been shown to be NP-complete (Kavraki, Latombe, & Wilson, 1993) and covers three main assembly subproblems: sequence planning, line balancing, and path planning.

Jimenez (2011) presents a classification of structures according to different features: number of hands, monotonicity (whether operations of intermediate placement of subassemblies are required), linearity (whether all assembly operations involve the insertion of a single part or multiple parts which have to be inserted simultaneously), and coherence (whether each part that is inserted will touch some other previously placed part). The structures considered in this paper are sequential (for two robots), monotone, linear and contact-coherent.

This paper focuses on the line balancing stage and introduces a novel paradigm for coordinating multiple robots in the execution of cooperative tasks in dynamic scenarios. The basic idea is to share information within a group or *block* of robots before assigning subtasks to all the members of the block. In this way, the method simulates a centralized system using a decentralized approach in which the robots share information in order to guarantee

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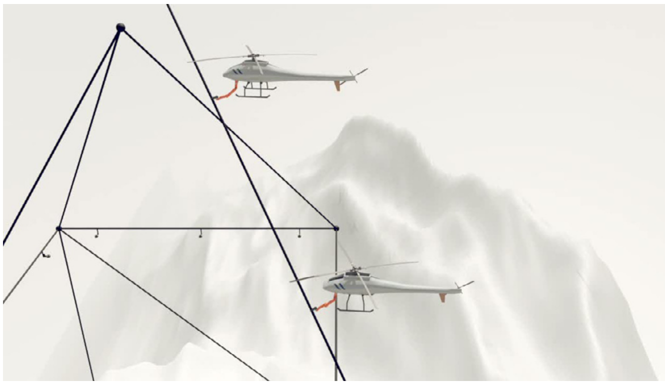

Fig. 1. Two aerial robots equipped with LWR KUKA robotic arms manipulating a bar to build a structure in places with difficult access by conventional means.

a local optimal solution in each stage of the algorithm. Our strategy fits the *locally centralized paradigm* mentioned in Cao, Fukunaga, and Kahng (1997) and allows the team to perform task allocation periodically in an entirely decentralized manner. Moreover, by allocating tasks to robots repeatedly, a team can adapt as circumstances change achieving fluid coordination.

The block-information-sharing (BIS) strategy was introduced in Caraballo et al. (2014) by the authors for area monitoring missions as a generalization of the one-to-one paradigm presented in Acevedo et al. (2013a, 2014). In these papers, the authors have experimentally demonstrated that this strategy converges to an optimal situation in which a particular objective function, the idle time function, is minimized. However, neither theoretical proofs on the convergence nor approach formalization have been published so far.

In this paper, the convergence of the BIS strategy is formally proved in a general task allocation scenario. Moreover, it is shown how to use this strategy to design a fault-tolerant approach for structure construction using a cooperative team of aerial robots. The robots work in parallel and the dynamic assignments of the tasks are performed using blocks in order to maintain a balanced allocation where each aerial robot approximately spends the same time to construct the assigned section. Thus, the maximum time a robot spends to complete the assigned section of the construction is minimized. Consequently, the benefit obtained is twofold: the total time for the construction is optimized and the robustness of the approach is guaranteed since the system is periodically re-balanced to cope with certain events, such as battery failure or the loss of some aerial robots, during the construction process.

The paper is organized as follows. The optimization problem is formulated in Section 3. In Section 4 the block-information-sharing paradigm for a general scenario is formally introduced, proving the convergence to the optimal allocation. In a case study presented in Section 5, the paradigm is employed in a structure assembly task, where the proposed approach is implemented and validated in a simulation of the construction of a structure using a team of aerial robots equipped with on-board manipulators. The obtained results of these simulations are shown at the end of Section 5. Finally, Section 6 closes the paper with some conclusions.

2. Related work

The task allocation problem has been widely studied in different areas. Centralized mechanisms have advantages including a guaranteed optimal solution. However, their limitations are well known, i.e. their slow response to dynamic events and vulnerability to failures. In dynamic and uncertain environments, decentralized mechanisms are preferred. Decentralized task allocation approaches for autonomous agents have been well studied in robotics (Dias et al., 2006; Gerkey & Matarić, 2004; Khamis, Hussein, & Elmogy, 2015; Korsah et al., 2013; Lemaire, Alami, & Lacroix, 2004). Gerkey and Matarić (2002) presents a dynamic task allocation scheme using an auction process for a heterogeneous robot team. Dias (2004) introduces a market-based multi-robot task allocation architecture in which robots are modeled as self-interested agents with the goal of maximizing individual profits. In practice, robots have a limited communication capability which may influence development and performance of the task allocation algorithm significantly.

In addition, our problem is also related to the well-known assembly line balancing (ALB) optimization problem in operational research (Boysen, Fliedner, & Scholl, 2007; Scholl & Becker, 2006). The ALB problem deals with partitioning the total assembly operations into a set of m elementary tasks $o_i (i = 1, \dots, m)$ with times t_i, and assigning them to a team of n assembly robots $r_k (k = 1, \dots, n)$ such that all robots approximately spend equal assembly times and the so-called "precedence constraints" between operations are satisfied. Assuming that the set S_k of tasks is assigned to the kth robot, its assembly time is $t(S_k) = \sum_{j \in S_k} t_j$. The ALB problem is NP-hard (Scholl & Becker, 2006) and soft computing approaches have been proposed in Rashid, Hutabarat, and Tiwari (2012). The main goal in an ALB model is the allocation of the tasks among stations so that the precedence relations are not violated and a given objective function is optimized. Besides balancing a newly designed assembly line, an existing assembly line has to be re-balanced periodically or after certain changes in the production process or the production plan. In our case, the team of cooperative robots must satisfy the precedence constrains between the construction operations and therefore the performance of the system is related to the time a robot is waiting for other neighbors to continue the construction. Because of the long-term effect of balancing decisions, the objective functions have to be carefully chosen while considering strategic goals. In structure construction using aerial robots, the total time for the construction is improved when the timeouts are minimized.

3. Problem statement

Consider a cooperative team of autonomous and heterogeneous robotic agents and a task which has to be accomplished by the team. In a cooperative framework, it is assumed that the task is *divisible* and *parallelizable* in such a way that it can be partitioned so that each subtask is assigned to a robot in the team. Individual agents execute their subtasks independently except in the common parts where neighbors need to coordinate their cooperation.

The time to perform the overall task is determined by the maximum time spent by the individual robots on their subtasks while a balanced allocation needs to be maintained in order to prevent overload and ensure efficiency. Considering the parallel nature of this scenario, performing the task in the shortest possible time requires minimizing the maximum time spent by the individual robots.

As in the ALB problems, the task to perform can be modeled as a set of operations where subtasks correspond to a disjoint partition of the task. The formalization of the problem is illustrated with two examples:

(i) building a structure using assembly parts (we assume equal complexity of placing the parts) in which the task is the set of assembly operations;
(ii) monitoring a region, where the task is the set of all points in the region.

Let T be the set representing the general task to be performed, where each subtask is a subset of T. Let $U_1, U_2, \dots, U_n$ be a team

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