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# Decentralized task allocation for surveillance systems with critical tasks

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## HIGHLIGHTS

- A task allocation problem with peculiar constraints, such as critical tasks, is modeled.
- Heterogeneous robotic agents with limited capacity are considered.
- The proposed decentralized algorithm relies on auction and consensus algorithms.
- The proposed decentralized algorithm is a polynomial time algorithm.

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## ABSTRACT

This paper considers the problem of assigning a set of tasks to a set of heterogeneous agents under the additional assumptions that some tasks must be necessarily allocated and therefore are critical for the assignment problem, and that each agent can execute a limited number of tasks. In order to solve this problem in a decentralized way (i.e., without any form of central supervision), we develop an extension of an algorithm proposed in the recent literature. After analyzing convergence and communication requirement of the algorithm, a set of numerical simulations is provided to confirm the effectiveness of the proposed approach.



## 1. Introduction

Driven by the evolution of computing and communication technologies, many researchers have focused on algorithms suitable for decentralized environments, where each resource is governed by an autonomous decisional entity, called *agent*, which defines the actions performed by the controlled resource basing on local interactions with other agents. In the context of multi-agent systems, the problem of Task Allocation (or equivalently Task Assignment, TA) plays a central role in many different domains, ranging from operation research [1] to transportation [2,3] and vehicle routing [4], from pickup and delivery [5–7] to environmental surveillance and monitoring [8,9].

The area of multi-robot systems [10,11] is certainly one of the fields in which significant advances on decentralized TA algorithms have been recently achieved. In particular, in the context of robotics, tasks are often associated to destinations that agents have to reach [12,13]. For this reason, a considerable part of the literature focuses on specific aspects such as vehicle routing [14], trajectory planning [15], heterogeneous robot [16], energy efficiency [17], uncertainty and robustness [18], temporal deadline [19] or precedence constraints among tasks [20]. Moreover, the recent related literature also focuses on TA algorithms suitable for large-scale systems [21,22] and coalition formation with constrained resources [23,24]. In the general context of TA algorithms, many authors have identified auction algorithms [25,26] as a powerful decision tool to deal with this type of problems [27–30].

This paper aims at extending the range of application of a class of auction-based TA algorithms by considering some important aspects that emerge in application domains such as transportation, surveillance and environmental monitoring, which are often disregarded in target-tracking formulations. The first aspect is that the maximum number of tasks that can be assigned to a single agent (the agent *capacity*) is fixed a priori due to physical limitations (e.g., fuel or battery capacity, space for resources, etc.). Moreover, it is also important to consider approaches suitable to deal with *heterogeneous* agents that can perform different tasks due to differences in their storage, sensory or actuating equipment. Another peculiar requirement is the need of guaranteeing the assignment of some *critical* tasks which must be considered mandatory (e.g., pickup or delivery of highly dangerous or perishable materials, surveillance of critical targets).

The proposed TA algorithm, called *Decentralized Critical Task Allocation Algorithm* (DCTAA), is based on the Consensus-Based

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**Main Nomenclature**

| | |
|---|---|
| $N_a$ | Number of agents |
| $N_t$ | Number of tasks |
| $\boldsymbol{\Delta}$ | Matrix of admissible assignments |
| $\mathcal{I}$ | Index set for agents |
| $\mathcal{J}_1$ | Index set for critical tasks |
| $\mathcal{J}_2$ | Index set for non-critical tasks |
| $\mathbf{b}_i$ | Bundle of agent $a_i$ |
| $\mathbf{p}_i$ | Path of agent $a_i$ |
| $L_t$ | Bundle dimension |
| $K$ | Overload parameter |
| $c_{ij}$ | Score increment for agent $a_i$ adding task $t_j$ to its bundle $\mathbf{b}_i$ |
| $n_{ij}$ | Inserting position for agent $a_i$ adding task $t_j$ to its path $\mathbf{p}_i$ |
| $S_i^{\mathbf{p}_i}$ | Score for agent $a_i$ performing tasks along path $\mathbf{p}_i$ |
| $\mathbf{f}_i$ | Feasible assignment (FA) for agent $a_i$ |
| $\boldsymbol{\alpha}_i$ | Dynamic assignability vector for agent $a_i$ |
| $\mathbf{z}_i$ | Winning agent vector |
| $\mathbf{y}_i$ | Winning bid vector |
| $\mathbf{w}_i$ | Second winning agent vector |
| $\mathbf{v}_i$ | Second winning bid vector |
| $\mathbf{s}_i$ | Timestamp vector |
| $\mathbf{m}_i$ | Marked task vector |

Bundle Algorithm (CBBA) which combines auction mechanisms with consensus algorithms [31] to solve spatially distributed task assignment problems. The CBBA is based on a score function that condenses in a unique scalar figure the degree of effectiveness of each possible task-to-agent assignment. In principle, by ad hoc definition of its score function, the CBBA could cope with agent heterogeneity, capacity constraints and mandatory assignments for critical tasks. However, the design of a score function combining in a satisfactory way the various objectives and constraints may turn out to be another challenging optimization problem. Moreover, incorporating hard constraints as penalty terms in the score function does not give deterministic guarantees about their actual satisfaction (e.g., a task can remain unassigned for an indefinite time). The risk of leaving some of the critical tasks unassigned using CBBA could be overcome by extending the bundle size, but this option is not admissible when the bundle size is bounded by physical constraints. For these reasons, this paper considers an approach in which assignment constraints (due to agent heterogeneity and limited capacity) as well as the requirements of assigning critical tasks are modeled as hard constraints, separated from the score function which only considers "soft" (in opposition to hard) evaluation criteria related, e.g., to distance, energy efficiency or similar performance measures.

Other interesting extensions of the CBBA have been already developed to deal with issues such as time windows of task validity [32], asynchronous communication [33], handling obstacle regions in path planning [34], cooperation and coupled constraints between robots [35,36]. In [37] an extension is proposed to increase the exploration of the solution space, together with the algorithm complexity. In all the mentioned literature, as well as in this paper, it is assumed that all the agents know the task set. The case in which some tasks are only known by a subset of agents is considered in [38]. A hierarchical architecture to handle in a coordinate way (small) teams of agents is proposed in [39]. It must be remarked that the mentioned CBBA extensions cannot guarantee the assignment of critical tasks, since the allocation is exclusively driven by the score function.

The approach presented in this paper focuses on the use of teams of robots in surveillance problems [40,41], such as monitoring of public and private sites. Surveillance systems encompass spatially distributed mobile and static sensors to provide effective complete monitoring of the area of interest. These systems are typically heterogeneous, distributed, and characterized by mandatory activities, and therefore motivate the decentralized algorithm developed here.

The main contributions of this work, which includes some preliminary results presented in [42], are as follows: (I) the description of the TA problem with functional heterogeneity, resource constraints, and guarantees of allocation of critical tasks; (II) the development of the DCTAA that solves the considered TA problem; (III) the analysis of theoretical issues concerning algorithm convergence and complexity; (IV) the algorithm validation in simulation under different conditions and a comparison with a centralized optimization algorithm.

The organization of the paper is as follows. Section 2 formulates the problem statement while Section 3 describes the proposed TA algorithm. Section 4 discusses some theoretical issues, and Section 5 summarizes the numerical results. Finally, Section 6 concludes the paper with final remarks.

## 2. Problem statement

This section provides the formal statement of the considered problem and describes the scoring mechanism.

### 2.1. Task allocation

Given a list of $N_t$ tasks and $N_a$ agents, the allocation problem is to find a conflict-free and constraint-fulfilling assignment that maximizes a predefined score function. The score function is the sum of local rewards determined as a function of the tasks assigned to each agent. An assignment is free of conflicts if each task is assigned to no more than one agent. Various types of constraints may arise depending on the specific application. In many application domains, each agent can only perform a limited number of tasks denoted by $L_t$. In heterogeneous scenario, a task can be assigned only to a subset of agents able to perform it. This further constraint can be handled introducing the *matrix of admissible assignments*, $\boldsymbol{\Delta}$, where $\Delta_{ij}$ is 1 if task $t_j$ can be performed by agent $a_i$ and 0 otherwise. A valid $\boldsymbol{\Delta}$ must have at least one non-zero element in each row (i.e., each agent can perform at least one task) and in each column (i.e., each task can be performed by at least one agent). In some contexts, it is also necessary to guarantee that a number of critical tasks whose assignment is mandatory are assigned to agents independently from all the other problem constraints, while the non-critical tasks are all the tasks whose assignment is desirable but not strictly mandatory.

The described task allocation problem can be modeled with the following integer program:

$$\max \sum_{i=1}^{N_a} \left( \sum_{j=1}^{N_t} c_{ij}\,(\mathbf{b}_i)\, x_{ij} \right) \tag{1}$$

subject to:

$$\sum_{j=1}^{N_t} x_{ij} \le L_t \quad \forall i \in \mathcal{I} \tag{2}$$

$$\sum_{i=1}^{N_a} x_{ij} = 1 \quad \forall j \in \mathcal{J}_1 \tag{3}$$

$$\sum_{i=1}^{N_a} x_{ij} \le 1 \quad \forall j \in \mathcal{J}_2 \tag{4}$$

$$x_{ij} \le \Delta_{ij} \quad \forall\,(i,j) \in \mathcal{I} \times \mathcal{J} \tag{5}$$

$$x_{ij} \in \{0,1\} \quad \forall\,(i,j) \in \mathcal{I} \times \mathcal{J} \tag{6}$$