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Harnessing coherence of area decomposition and semantic shared spaces for task allocation in a robotic fleet

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ABSTRACT

Task allocation is a fundamental problem in multi-robot systems where heterogeneous robots cooperate to perform a complex mission. A general requirement in a task allocation algorithm is to find an optimal set of robots to execute a certain task. This paper presents the work that harnesses an area decomposition algorithm, and a space-based middleware to facilitate task allocation process in unstructured and dynamic environments. To reduce spatial interference between robots, area decomposition algorithm divides a working area into cells which are then dynamically assigned to robots. In addition, coordination and collaboration among distributed robots are realized through a space-based middleware. For this purpose, the space-based middleware is extended with a semantic model of robot capabilities to improve task selection in terms of flexibility, scalability, and reduced communication overhead during task allocation. In this way a framework which exploits the synergy of area decomposition and semantically enriched space-based approach is created. We conducted performance tests in a specific precision agriculture use case focusing on the utilization of a robotic fleet for weed control introduced in the European Project RHEA – Robot Fleets for Highly Effective Agriculture and Forestry Management.

1. Introduction

Today, cooperating robots are commonly used in controlled and structured environments, such as factories, where they are managed from a central place that supervises mission execution. Due to the advances in the perception and locomotion technology, there is a great potential to use multiple cooperating robots in heterogeneous and unstructured environments. This however, imposes new requirements on communication and coordination of actions in teams, and the well-established centralized coordination approach needs to either be enhanced or replaced with a distributed approach.

Task allocation is a fundamental problem in multi-robot systems where the core requirement is to find an optimal set of heterogeneous robots that have to cooperate in order to execute a complex mission [1]. Task allocation is well known to be an NP-hard problem in multi-agent systems,

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leading to a variety of different heuristic-based approaches [2]. A critical enabler for distributed task allocation is an efficient coordination. This work examines how two different coordination approaches, an area decomposition and a space-based middleware, fit together and what their contribution in a task allocation domain can be.

We propose an algorithm for area decomposition based on a computational geometry technique of Voronoi diagram [3]. Due to the constraints posed by an unstructured and volatile environment, we adapted the construction of Voronoi cells to fit our requirements while retaining the original notion. This approach is applicable to domains where geographic positions of robots and tasks are known, which to a great extent corresponds to our agricultural use case [4]. A complementary technique, the space-based middleware, defines coordination model based on a centralized tuple space with a shared message repository, exploiting generative communication among processes. This work extends coordination capabilities of the space-based middleware XVSM (eXtensible Virtual Shared Memory) [5,6], in particular its Java-based implementation MozartSpaces. XVSM is based on a Linda tuple space model [7]. Our framework, Semantic MozartSpaces [8] introduces a new data description and query model based on RDF (Resource Description Framework) [9] and SPARQL [10], where RDF is used to construct nested blank nodes in a triple store which was implemented in Jena [11] and SPARQL is used for query and update interactions. To evaluate the performance of the integrated area decomposition algorithm and semantically enhanced MozartSpaces, we conducted series of tests in a specific precision agriculture use case.

The remainder of this paper is structured as follows: Section 2 summarizes related work. Section 3 presents proposed system architecture and Section 4 provides implementation details. Section 5 introduces the use case while Section 6 evaluates the framework. Finally, Section 7 concludes the paper and presents future work.

2. Related work

Related work is structured in three parts. The first part discusses the task allocation as a fundamental, ubiquitous, and a well-known problem in a multi robot domain. Our focus here is on utilizing semantic technologies for task allocation. This discussion is followed by a related work on various area decomposition approaches, and a systematization of some prominent space-based frameworks.

The use of semantics in task and resource modelling in robotic systems is an emergent research field. In [12] authors explore how semantic description of environments, objects, and tasks can be used to improve task planning in complex scenarios where a robot executes tasks on objects in an unstructured environment with a great number of objects. In [13] authors study a combination of the Web Service paradigm and ontology modelling for service discovery, service composition, and a task allocation. In their solution, all entities expose their functionalities as semantic Web Services allowing their discovery and composition. In SERA [14], tasks and resources are semantically described following resource description ontology. Performance tests with the SERA framework show that the centralized approach performs better than the distributed one when the number of resources is low, which is attributed to the negotiation overhead in distributed systems. In [15], an author compares the performance of the proposed semantic based matchmaking approach against the conventional keyword based matchmaking in a grid environment, and concludes that the semantic based matchmaking mechanism retrieves more closely matching resources. Authors in [16] propose a framework for semantic service discovery in a dynamic and changing environment. Similar to our implementation is the use of context information, such as a current location which facilitates the matching process. Contrary to our approach, the framework in [16] invokes and discovers services locally on robots. In our work robots query the central task repository for matching tasks descriptions, and a semantic matchmaking is performed based on the description of robots' services, and locations of tasks and robots. In our framework, when a detailed task description is generated, the execution of an area decomposition algorithm is triggered. Two-level filtration mechanism of advertised content is proposed in [17]. In the first level, the broker agent applies a semantic-based mechanism which compares a content requested by users to that advertised by providers. On the second level, the best content provider in terms of both price and quality is selected. Our work differs from the reviewed work as we use semantic approach for both the resource and task modelling. Rational for using semantics is twofold: (1) it provides a basis for automatic mapping between task requirements and available resources and thus makes the whole process more flexible, and (2) it provides a general task description language that most of the reviewed frameworks lack.

With our area decomposition approach we address a problem of robots' spatial interference which is perceived as a key stumbling block in the way to efficient robotic fleets. Reflecting on the experiments conducted in [18], the authors concluded that the larger the number of robots working in the same global workspace area, the grater the interference and the uncertainty related to the time required for task execution. The works presented in [19,20] utilize the boustrophedon cellular decomposition approach for partitioning the robots workspace. The presented approach exploits a geometric structure which is a union of non-intersecting rectangular regions that together compose the working environment. Each region is termed a cell and in each cell a coverage path is a simple back-and-forth motion. In [21] authors develop a dynamic partitioning algorithm which assigns subareas to robots during the mission. The authors argue that this dynamic approach is more flexible than the static one because in a case of a robot's failure, other robots dynamically take over his work. Authors in [4] base their task allocation algorithm on computational geometry techniques, i.e., Delaunay triangulation. Their approach is applicable to domains where geographical positions of robots and tasks are known. Voronoi diagram as another technique for space partitioning is discussed in [22]. Our space decomposition algorithm uses customized mathematical model of the Voronoi diagram. We adapted Voronoi diagram model to the requirements of our domain, i.e., to linear trajectories of robots in agricultural fields. Due to the dynamic environment where our robots