Computer Communications 36 (2013) 1024–1038

Contents lists available at SciVerse ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Target to sensor allocation: A hierarchical dynamic Distributed Constraint Optimization approach

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ARTICLE INFO

Article history:
Received 3 December 2011
Received in revised form 15 October 2012
Accepted 2 January 2013
Available online 9 January 2013

Keywords:
Constraint Optimization Problem
Multi-agent systems
Sensor networks
Target to sensor allocation

ABSTRACT

Distributed target allocation and tracking is an important research problem. This problem is complex but has many applications in various domains, including, pervasive computing, surveillance and military systems. In this paper we propose a technique to solve the target to sensor allocation problem by modeling the problem as a hierarchical Distributed Constraint Optimization Problem (HDCOP). Distributed Constrain Optimization Problems (DCOPs) tend to be computationally expensive and often intractable, particularly in large problem spaces such as Wireless Sensor Networks (WSNs). To address this challenge we propose changing the sensor to target allocation as a hierarchical set of smaller DCOPs with a shared system of constraints. Thus, we avoid significant computational and communication costs. Furthermore, in contrast to other DCOP modeling methods, a non-binary variable modeling is employed to reduce the number of intra-agent constraints. To evaluate the performance of the proposed approach, we use the surveillance system of the Regional Waterloo Airport as a test case. Two DCOP solution algorithms are considered, namely, the Distributed Breakout Algorithm (DBA) and the Asynchronous Distributed Optimization (ADOPT). We evaluate the computational and communication costs of these two algorithms for solving the target to sensor allocation problem using the proposed hierarchical formulation. We compare the performance of these algorithms with respect to the incurred computational and communication costs.

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1. Introduction

Distributed Constraint Optimization Problems (DCOPs) provide a good formalism for representing problems where each agent is responsible for assigning a value from its finite domain to its variable. These agents coordinate their choice of values so as to find value assignments that minimize the constraint cost. Two agents are constrained if they share a constraint. Each constraint cost is a function of the values of the involved variables. The cost of a solution is the sum of all the constraint costs, depending on the values assigned to the variables in the solution. The goal of solving a DCOP, which is an NP-hard problem [1], is to find an assignment of values to all variables that minimizes the constraint costs. DCOP is a generalized form of the Distributed Constraint Satisfaction Problem (DCSP) [2,3]. Many real-world problems can be modeled as DCOPs. Resource allocation in sensor networks [4,5], event scheduling [6,7], and synchronization of traffic lights [8] are examples of these real world problems.

Sensor to target allocation is an important problem in many sensing applications, including surveillance, traffic management, habitat monitoring, to name a few. In this problem, there are a set of moving targets and a set of sensors, each sensor having limited sensing, computational, and communication capabilities. The objective is to find a suitable assignment of sensors to targets such that the number of constraint violations is minimized. Constraints can be used to represent restrictions on sensors, for example, to set the maximum number of sensors to track a target, and/or the maximum number of targets to be tracked by one sensor. The problem setup changes over time due to sensor and/or target mobility. In order to relax the computational complexity of the problem it is divided into instances, and the solution of each is assigned to a solver.

In this paper, the target to sensor allocation problem in a complex sensor network is modeled as a hierarchical and dynamic DCOP. Most sensor networks, such as those employed in surveillance systems or in military systems, tend to deal with large and complex sensor networks that are composed of many sensors and numerous dynamic targets. This complexity should be carefully considered in any modeling technique contemplated for addressing the problem. This paper, unlike previously cited DCSP/DCOP target allocation problems [6,9–13], first divides the main problem

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http://dx.doi.org/10.1016/j.comcom.2013.01.001

into several DCOP sub-problems, which themselves are divided further into smaller DCOP sub-problems. At each level, each DCOP employs non-binary variables to construct a model of the problem. Constraints that are shared by different sub-problems define another DCOP at the next level of the proposed hierarchical structure.

The remainder of this paper is organized as follows: Section 2 introduces DCSP/DCOP formally and touches on related research on target allocation in wireless sensor networks; focusing primarily on previous research conducted on DCSP/DCOP modeling of the target to sensor allocation problem. In Section 3, the target to sensor allocation problem is formulated. Section 4 introduces the proposed modeling technique. Section 5 presents the "hierarchical non-binary variable DCOP" approach in details. In Section 6 complete DCOP algorithms versus incomplete ones are discussed. Section 7 reports work conducted to test the proposed hierarchical approach in the context of two important DCOP algorithms, DBA and ADOPT. ADOPT and DBA are also used to solve the same problem in its simple non-hierarchical form as previously introduced by [14]. The performance of the proposed algorithm is compared with ADOPT and DBA with respect to three parameters: "constraint violation cost", "number of messages" and "number of constraint checks". Conclusions and future work are provided in Section 8.

2. Background

2.1. Distributed Constraint Satisfaction and Optimization

DCSP refers to the distributed form of the Constraint Satisfaction Problem (CSP). It involves multiple autonomous agents, each agent holding one or more variable. DCSP was first discussed by Sycara et al. [15] and Yokoo et al. [16]. CSP as the basis of DCSP is formally defined as follows [15,16]:

- A set of n variables: $V = \{X_1, X_2, \ldots, X_n\}$
- A set of finite, discrete domains for each variable: $D = \{D_1, D_2, \ldots, D_n\}$
- A set of constraints: $R = \{R_1, R_2, \ldots, R_m\}$, where $R_i = (d_{i1}, d_{i2}, \ldots, d_{ij})$ is a predicate defined on the Cartesian product $D_{i1} \times D_{i2}, \ldots, \times D_{ij}$. If the value assignment of these variables satisfies this constraint, the predicate returns true; otherwise it returns false.

The goal of DCSP is to assign values to all variables that satisfy all the constraints in R. Each agent attempts to reach this goal not only by satisfying its local constraints but also by communicating with other agents to resolve external conflicts. Agents are expected to communicate with one another because their goals are interrelated. For example, in order to solve its sub-problem, an agent may cause conflicts for other agents.

In this paper, it is assumed that agents can communicate with one another by exchanging messages and that the receiver agent receives messages exactly in the order they were sent, of course, after a finite delay. It is further assumed that each agent only controls one variable. Thus, the name of the agent can be the same as that of the variable it holds and manages. Each agent has complete information about the constraints on its variable.

DCOP is the optimization version of DCSP in which each constraint has a cost and the purpose of a DCOP solver is to minimize the constraint violation costs. Dynamic DCOP is a pair $\langle P_{initial}, \Delta \rangle$ in which $P_{initial}$ is the initial DCOP and $\Delta : P_t \rightarrow P_{t+1}$ is a function that maps a DCOP at time t to a new DCOP at time $t+1$ by adding or removing constraints. The advantage of using this definition for Dynamic DCOP is that solving Dynamic DCOP is as hard as solving multiple DCOPs [17]. Using this definition one can think of Dynamic DCOP as a sequence of DCOPs. This sequential definition of Dynamic DCOP is reported by a number of researchers (c.f. [17–20]). Similar notation is used in reference [21] for defining Dynamic CSP. Based on this definition, a dynamic DCOP is a set of DCOPs: $\{P_0, P_1, P_2, \ldots\}$. The amount of change from P_t to P_{t+1} can be measured by the number of added or removed constraints.

In contrast to the notation used in [22] in which a continuous version of dynamicity is considered, this paper defines Dynamic DCOP as a sequence of DCOP snapshots. Of course the notation considered in this paper is more common.

2.2. Related work

A significant amount of recent research has focused on target to sensor allocation in sensor networks. Lesser et al. [23] consider various methods for target to sensor assignment in wireless sensor networks. Ortiz et al. [24] explore a class of partially centralized methods. In these methods, a leader called "mediator" does a hill-climbing search in a subset of the solution space and sends its search results as a proposal to the group. Group members, in response, send their information to the mediator with the objective of reaching a satisfactory proposal. This method is partially centralized since it centralizes the information of a subset of the problem in the mediator node. Although mediation based approaches are much better than fully centralized ones, in comparison to fully distributed approaches, they still suffer from problems such as a single point of failure and computational overload of the central node.

Yadgar et al. [25] were the first to propose a hierarchical structure in large scale wireless sensor networks. Their proposed structure employs an event driven method such that when events occur they are reported to the top of the hierarchy in a bottom-up manner. Responses to the reported events are processed in a top-down manner. The main drawback of this structure is that it cannot respond to events rapidly.

Horling et al. [26] introduced an organizational framework for task allocation in large scale wireless sensor networks. In this framework, the environment is first partitioned by the agents into regions according to the location of the sensor nodes. Much of the communication is limited to within the regions. Thus, this method reduces the energy used by the sensors as a result of limiting the communication range to a small region. However, when a target moves from one region to another, target to sensor allocation becomes difficult.

Another important effort at solving the target allocation problem in sensor networks has adopted the Distributed Constraint Satisfaction Problem (DCSP) as a formulation environment. The target to sensor allocation is then tackled using DCSP algorithms.

Various aspects of DCSP have been explored in the context of target to sensor allocation. For example, [27–29] investigate a number of existing DCSP algorithms to determine their potential in solving the problem. They focus on a category of algorithms in which the solution process is distributed. The investigation analyzes the performance of asynchronous backtracking (ABT) and asynchronous weak commitment search (AWC) algorithms [27]. Furthermore, the investigation evaluates the impact of different network traffic conditions on the performance of the selected algorithms. Fernandez et al. [27] present another approach that falls into this category of DCSP-based approaches. Mapping the task allocation problem of a large scale sensor network to a distributed constraint satisfaction problem is over simplified in this method. Furthermore, no proper distributed constraint satisfaction algorithm is identified to work on the complex task allocation problem in large scale sensor networks.

Some research in this field has focused more on solving the allocating problem in sensor networks with less emphasis on

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