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A taxonomy for task allocation problems with temporal and ordering constraints

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ABSTRACT

Previous work on assigning tasks to robots has proposed extensive categorizations of allocation of tasks with and without constraints. The main contribution of this paper is a specific categorization of problems that have temporal and ordering constraints. We propose a novel taxonomy that emphasizes the differences between temporal and ordering constraints, and organizes the current literature according to the nature of those constraints. We summarize widely used models and methods from the task allocation literature and related areas, such as vehicle routing and scheduling problems, showing similarities and differences.

1. Introduction

What is multi-robot task allocation? Think of a shipping company that sells an item every hour; a robot at the warehouse could receive that order, fetch the item, pack it, and prepare it for pickup by a postal service. What happens when the company sells 20 items every hour? What about 20 items every minute? What about 20 items a second? Amazon, a popular shopping website, sold 36.8 million items on an especially popular shopping day in 2013. With 426 items ordered per second that day, a single robot would be hard-pressed to keep up with the orders. If the warehouse used a large team of robots, each robot would have to plan an efficient route through the warehouse to fetch items for shipping without colliding with other robots, without taking items that another robot is handling, all while planning its route around fetching items that are out-of-stock but will be restocked soon.

Allocation of tasks with constraints on when, where, and in what order they need to be done is an important class of problems with many real-life applications, such as warehouse automation, pickup and delivery, surveillance at regular intervals, space exploration, and search and rescue.

Gerkey and Matarić [1] have proposed a widely accepted taxonomy for multi-robot task allocation (MRTA) problems, which is based on the main characteristics of robots, tasks, and time, as follows:

- *Single-task robots (ST) vs. multi-task robots (MT)*: ST robots can do at most one task at a time, while MT robots can work on multiple tasks simultaneously.
- *Single-robot tasks (SR) vs. multi-robot tasks (MR)*: SR tasks require exactly one robot in order to be completed, while multiple robots are needed to complete an MR task.
- *Instantaneous (IA) vs. time-extended (TA) assignments*: In IA, tasks are allocated as they arrive, while in TA, tasks are scheduled over a planning horizon.

The iTax taxonomy [2] adds a level above Gerkey's taxonomy, focusing on interrelated utilities and constraints among tasks, both for individual robots and across robots, and for complex tasks which can be partitioned in many different ways into simpler tasks. We are interested in considering a different aspect, specifically the temporal and ordering constraints that might exist between tasks.

The nature of the temporal constraints in MRTA problems is very broad; for example, in search and rescue domains tasks are discovered over time and have to be done as quickly as possible. In dynamic environments, robots might arrive late to some tasks and might miss some. On the other hand, some surveillance tasks require not to arrive late to tasks. In some cases tasks need to be executed in a specific order, such as in urban disaster scenarios in which police must clear blockades from roads before ambulances can travel to carry injured people. Some tasks may need to be done concurrently, as in surveillance where robots have to track people while avoiding obstacles.

Our main contribution is an extension to Gerkey and Matarić [1] taxonomy, where we expand the time-extended (TA) part to include temporal and ordering constraints. We consider temporal constraints expressed in the form of time windows (TA:TW) and ordering constraints expressed in the form of synchronization and precedence constraints (TA:SP). To emphasize the importance of this class of problems we propose the definition of multi-robot

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task allocation problems with temporal and ordering constraints as MRTA/TOC.

In this paper we also explore the following research questions:

- What models and methods from related research areas can be applied to this class of problems?
- What are the main types of temporal and ordering constraints used in multi-robot task allocation?
- What are the most commonly used optimization objectives? Are they predominantly temporal-based, distance-based, or multi-objective?
- What are the main solution approaches used for the different parts of the taxonomy? are the methods deterministic or stochastic? are the temporal constraints hard or soft? are the algorithms centralized or distributed?
- Which questions for this class of problems have been answered well, and which remain largely open?

We begin by summarizing the terminology used in the paper, and defining the class of multi-robot task allocation problems with temporal and ordering constraints (MRTA/TOC) in Section 2. In Section 3 we relate this class of problems to problems in other areas, setting the ground for our exploration of models and methods in those areas. In Section 4 we present temporal and ordering models. In Section 5 we review the most common optimization objectives considered in the literature. Our taxonomy is introduced in Section 6. Task execution and the dynamics therein are discussed in Section 7. Solution approaches are outlined in Section 8. We discuss open issues, future directions, and final thoughts in Section 9.

2. MRTA/TOC: Multi-robot task allocation with temporal and ordering constraints

2.1. Terminology and abbreviations

We define the terminology we use informally as follows:

- A *robot* is an autonomous agent responsible for performing some actions. Alternative names for robots are physical agents, unmanned vehicles, and rovers. Robots in MRTA are typically modeled as holonomic or point robots, since the focus is not on low level control of robot motion.
- A *team* is a set of robots that work together. A team is often called a *coalition* when it is dynamic, i.e. formed to do some tasks and disbanded after that [3].
- A *task* is an action to be performed, also referred to as a work unit, activity, waypoint, or customer request. In some scheduling literature tasks are divided into jobs [4], but in other cases jobs are made of tasks [5].
- A *time window* is a time interval, which starts with the earliest time a task can start, and ends with the latest time the task can end. If the earliest time is not given, the latest time is referred to as the *deadline*. A time window is said to be *closed* if both start and end times are given.
- *Synchronization constraints* specify temporal constraints among tasks, for instance, they have to start at the same time.
- *Precedence constraints* specify partial ordering relationships between pairs of tasks, for instance, a task has to be completed before another task can start.
- A *schedule* is a timetable in which each task has a specific time to start, end, or both. In some cases each robot has its own individual schedule (e.g. [6]), while in others all robots share a single schedule.
- The *makespan* is the time difference between the end of the last task and the start of the first task.
- A *route* is a sequence of locations to visit. Routes and schedules are often used interchangeably, but schedules always concern time, while routes concern physical locations.
- A *task release* refers to a task becoming available for execution. Task release can be deterministic if the release time is known upfront, dynamic if the release time is stochastic, or sporadic if it is governed by unknown probabilities; task release is periodic when the same task is released at regular intervals.

We use the following acronyms:

- MRTA/TOC for Multi-Robot Task Allocation with Temporal and Ordering Constraints.
- MIP for Mixed Integer Programming, and MILP if the objective function and constraints are linear.
- TOPTW for Team Orienteering Problem (TOP) with Time Windows.
- VRPTW for Vehicle Routing Problem (VRP) with Time Windows.
- JSP for job-shop scheduling problems.

2.2. Problem formulation

We assume there is a finite set of robots and of tasks. A robot may have a location, speed, route, and/or schedule. A task may have a location, earliest start, latest finish time, expected duration, cost, demand, and reward.

Constraints on tasks can be in the form of time windows, which specify the window of time when the task can be done. It is assumed that a robot which reaches a task location before the earliest start time will wait until the earliest start. Ordering constraints specify a dependency between pairs of tasks. They are usually represented as directed acyclic graphs, where each node in the graph represents a task, and each edge indicates a precedence constraint. In addition to precedence constraints, ordering constraints can be synchronization constraints, which specify, for instance, that two tasks have to start at the same time or that a task has to start a specific amount of time after another task finishes.

We use the term *synchronization constraints* when there is a specific time involved and *precedence constraints* when it is only an ordering constraint. In the Operation Research literature, the term General Precedence Relationship (GPR) is used to indicate both those types of constraints, i.e., task j has to start within a time window after the completion of task i, or task j can start any time after the end of task i [7,8].

The objective is to optimize some function of the cost (or reward) for doing the tasks for all the robots. Cost can be a temporal measure (e.g. makespan), or a spatial measure (e.g. distance traveled). Commonly used optimization objectives are described later in Section 5.

3. Connections with other problems

Multi-robot task allocation (MRTA) started in earnest in the 90's, when researchers started pulling together teams of robots to accomplish multiple tasks. MRTA draws from a variety of areas in mathematics and operations research as well as computer science and robotics, including assignment problems, distributed computing, distributed AI, and scheduling.

The search for robust approaches to MRTA focused on how the robots perform in complex environments, leading researchers to add features like time windows for tasks, spatial constraints, and probabilistic and stochastic models to handle uncertainty. Solutions take different approaches, such as auctions, market-based

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