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Time-informed task planning in multi-agent collaboration

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Abstract

Human-robot collaboration requires the two sides to coordinate their actions in order to better accomplish common goals. In such setups, the timing of actions may significantly affect collaborative performance. The present work proposes a new framework for planning multi-agent interaction that is based on the representation of tasks sharing a common starting and ending point, as petals in a composite daisy graph. Coordination is accomplished through temporal constraints linking the execution of tasks. The planner distributes tasks to the involved parties sequentially. In particular, by considering the properties of the available options at the given moment, the planner accomplishes locally optimal task assignments to agents. Optimality is supported by a fuzzy theoretic representation of time intervals which enables fusing temporal information with other quantitative HRI aspects, therefore accomplishing a ranking of the available options. The current work aims at a systematic experimental assessment of the proposed framework is pursued, verifying that it can successfully cope with a wide range of HRI scenarios.

Keywords: Multi-criteria planning; Time-informed planning; Daisy planner; Multi-agent collaboration; Human-robot interaction

1. Introduction

Efficient and realistic human-robot collaboration encompasses crucial temporal and synchronization aspects which are typically overlooked in contemporary robot planning literature. In recent years though, there is a steadily increasing interest to explore the role of time in multi-agent collaboration setups (Chao, 2012; Effinger, Williams, Kelly, & Sheehy, 2009; Hoffman, 2013; Maniadakis & Trahanias, 2014). Multi-agent synchrony is typically achieved by introducing constraints that aim to maximize coincidence in the parallel activities of independent robots (Morris, 2014; Morris, Muscettola, & Vidal, 2001; Shah, Stedl, Williams, & Robertson, 2007; Smith, Gallagher, Zimmerman, Barbulescu, & Rubinstein, 2007).

Simple Temporal Networks (*STNs*) provide the basis to deal with temporal constraints in planning problems. To manage temporal constraints, *STNs* are typically mapped to the equivalent Distance Graphs (*DGs*) to check the existence of no negative cycles and thus prove the consistency and dispatchability of the plan (Dechter, Meiri, & Pearl, 1991). Along this line, recent works have considered back propagation rules to dynamically preserve dispatchability of plans (Morris, 2014; Shah et al., 2007), address temporal problems with choice (Shah & Williams, 2008), or reason between interacting agents (Boerkoel & Durfee, 2013).

Despite the effectiveness of relevant approaches, *STNs* exhibit an inherent limitation to deal with event sequences where start and end points coincide; such behaviors are termed "*daisy behaviors*" in the current work, as will be explained in Section 4 of the paper. The coincidence of start and end points creates *STN* loops which enable the

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identification of negative circles in the equivalent *DG*, therefore suggesting the inconsistency of the relevant plans.

Disjunctive Temporal Constraint Networks (*DTCNs*) have been used as a basis for tackling such problems by considering the temporal properties of all possible assignments of tasks to agents, in order to select the best full plan (Shah & Williams, 2008). Besides the issue of computational complexity in case that many tasks have to be assigned to many agents, this approach is rather fragile, in the sense that unexpected events may destroy the execution of the plan and thus initiate re-planning. The same basic idea is followed in Effinger et al. (2009), by implementing an extensive AND/OR search tree over the possible plan executions.

A common limitation of all works outlined above, regards the treatment of time in isolation, without the ability to jointly consider other quantitative criteria that may affect collaboration. Along this line, the time-informed multi-criteria evaluation of plans is particularly new in the multi-agent interaction literature. The only work we are aware of is (Gombolay, Wilcox, & Shah, 2013), in which the planner aims at minimizing annoyance among agents and thus practically avoids team members collaboration.

The present work puts forward a new framework for studying multi-agent interaction, assuming the daisy-like representation of tasks and the use of fuzzy numbers to encode temporal information. The latter facilitates the direct use of time in mathematical calculations and thus the detailed analysis of graph properties, in order to take better-informed planning decisions.

In the literature, fuzzy times are used for many years in job scheduling problems (Deng, Chen, Zhang, & Mahadevan, 2012; Dubois, Fargier, & Prade, 1995). It is therefore surprising that, to the best of our knowledge, it is the first time they are employed in the context of dynamic multi-agent collaboration. Interestingly, fuzzy arithmetic facilitates mixing temporal criteria with any other numerically represented information regarding multi-agent interaction. The latter paves the way for pursuing immediate, locally optimal assignment of tasks to agents, in order to better direct human-robot collaboration towards the accomplishment of the common goal. Due to the simplicity of fuzzy number calculus, the current approach does not introduce any workload compared to contemporary approaches, therefore resulting to an easily implemented and particularly fast solution for multi-criteria, time-informed human-robot planning.

In contrast to previous works on scheduling multi-agent interaction that prepare full plans of agents' activities for all future moments (e.g. Gombolay et al., 2013; Shah & Williams, 2008), the proposed planner adopts an immediate, short-term planning approach, that enables taking locally optimal decisions, after considering the circumstances at the given moment. Accordingly, the planner operates as a light-weight process and at the same time minimizes the chances for re-planning in the case of unexpected events.

To facilitate the systematic evaluation of the proposed framework, the planner is integrated into a simulated robot environment with two humanoids, one having the role of master (representing the human) and the other having the role of slave (representing the robotic partner). The proposed approach is assessed on "multi-agent collaboration for salad preparation". The jobs assumed for the collaborating agents are mapped to a *daisy graph* with petals representing the tasks that can be undertaken by single agents. The proposed planer assigns tasks to the agents, considering (i) the time required for their execution and (ii) the quality of performance each agent may achieve. In that way, the planner takes short-term optimal decisions that, despite they cannot guarantee global optimality, result into very flexible and effective multi-agent synergies, as witnessed by the assumed results of the present study.

We use the objective metrics proposed in Hoffman (2013) to assess the performance of the planner in four realistic human-robot interaction scenarios that simulate (i) human's leading role, (ii) self-motivated human actions, (iii) possible delays on task execution, and (iv) human preferences with respect to tasks. The obtained results show that the daisy planner is capable to reduce the idle time of agents and at the same time enforce their concurrent performance to improve collaboration.

The rest of the paper is structured as follows. The next section links the current work with the broader research in time perception and robotics. Then we discuss the representation of time intervals as fuzzy numbers, which enables making calculations with time. The presentation of the daisy planner comes in the following section, discussing in detail how the proposed architecture facilitates time-informed multi-agent coordination. Experimental results of the proposed planning framework in action are presented in Section 5, followed by discussion on the obtained results. The last section concludes the present work, highlighting also directions for extending the proposed framework.

2. Mind-time interactions

The sense of time is an essential capacity of humans, animals, birds, fishes, even plants, as described in Cashmore (2003). Time perception is among the first competencies evolved in biological systems, which means it has affected the subsequent evolution of nearly all cognitive modalities (Gerstner, 2012; Paranjpe & Sharma, 2005). Additionally, many time processing modalities mature very early in the human developmental procedure in order to provide a stable basis for other cognitive skills to develop (Droit-Volet, 2013). As a result, time is suggested to be the dimension that is dominantly used in the perception of complex stimuli (followed by space) (Navon, 1978). These remarks promote the notion of time as one of the most influential factors in the functionality of cognitive systems.