Timeline-based Planning with Uncertainty: a Human-Robot Collaboration Case Study

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Abstract. Planning is a core field of Artificial Intelligence since its beginnings and, there are many planning techniques that have been introduced in the literature. The timeline-based approach is a particular *temporal planning* paradigm which has been successfully applied in many real world scenarios. However despite its practical success, there is not a shared view of this approach.
In this context, my PHD project aims at investigating timeline-based planning and applying this technique to solve real-world problems. The main research objectives this paper describe are: (i) formally characterize timeline-based approach to planning by taking into account also *controllability* features of a domain; (ii) develop a *planning framework* (EPSL) and propose a *methodology* for modeling and solving problems with timelines; (iii) apply the proposed approach to real-world problems.
Concerning this last point, Human-Robot Collaboration (HRC) scenarios present many critical points a planning technique must deal with in order to successfully face this kind of problems. In this regards, several characteristics of the envisaged approach to timeline-based planning, are well-suited for this kind of applications. Thus the paper presents some initial contributions for an HRC scenario within an ongoing research project.

Keywords: Timeline-based Planning, Planning with Uncertainty, Human-Robot Collaboration

1 Introduction

Timeline-based planning has been introduced in early 90s [12] and takes inspiration from the classical control theory. The idea is to control a complex system by identifying a set of features that must be controlled over time. The system is controlled by synthesizing a set of *timelines* that describe the temporal evolution of the modeled features. This approach has been successfully applied in several real world contexts (especially in space applications) and there exist several planning frameworks that have been developed and deployed in real-world P&S applications, e.g. EUROPA [2], IXTET [9] or APSI-TRF [6].

The timeline-based approach provides an expressive representation of time and temporal constraints and allows an "easy" integration of planning and scheduling within the

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same solving approach. This is a key point for addressing real-world problem where time and concurrency represent important features of the problems. However, despite its practical success of timeline-based planning, a clear and common formalization of the related planning concepts is missing. Each systems applies its own *interpretation* of timeline-based planning. Therefore, there is not a common semantics for timeline-based concepts, there are differences in the way timeline-based problems are modeled and even solved. In this context, it is not easy to compare the features of the different approaches and also make a comparison with more "standard" planning techniques like PDDL.

2 Hierarchical Timeline-based Planning with Uncertainty

In this context, my PHD project aims at investigating timeline-based planning approach in order to propose a comprehensive and shared semantics for the main planning concepts, propose a modeling and solving approach for designing effective P&S applications and realize a general-purpose planning framework which complies with the proposed *interpretation*. Specifically my PHD project pursues the idea of integrating *temporal uncertainty* and *hierarchy-based solving* capabilities. *Temporal uncertainty* allows to model more realistic domains because in real-world usually not all the relevant features of a planning domain are *controllable*. A controllability-aware solving approach allows to generate plans with some desired properties with respect to their (robust) *execution*. Moreover a hierarchy-based modeling and solving approach is well-suited to effectively address real-world problems. It allows a description of the problem at different levels of abstractions and a structured solving procedure.

At the current state of the work we have obtained some interesting results with respect to the research objectives described above. Specifically, the work [8] proposes a clear and comprehensive formalization of timeline-based planning which considers also controllability aspects of the planning domain. The work [16] introduces the Extensible Planning and Scheduling Library (EPSL), a general-purpose timeline-based planning framework which complies with the proposed semantics and implements the hierarchy-based approach by taking into account controllability features. Moreover, the EPSL framework has been successfully applied to solve real-world problems in manufacturing scenarios [3, 4], proving the feasibility and the solving capabilities of the envisaged approach. In this regards, the next three sections provide a brief description of the these contributions.

2.1 A Formal Account for Timelines with Uncertainty

A timeline-based planning domain is composed by a set of features to be controlled over time. These features are modeled by means of *multi-valued state variables* that specify causal and temporal constraints characterizing the allowed temporal behavior. A state variable describes the set of values $v \in V$ the related feature may assume over time with their flexible duration. For each value $v_i \in V$ the state variable describes also the set of values $v_j \in V$ (where $i \neq j$) that are allowed to follow v_i and the related *controllability property*. If a value $v \in V$ is tagged as *controllable* then the system can decide the actual duration of the value. If a value $v \in V$ is tagged as *uncontrollable* instead, the system cannot decide the duration of the value, the value is under the control of the *environment*. There are two types of state variable in a planning domain. The *planned variables* that model the domain features the system can control (or partially control). The *external variables* that model domain features completely outside the control of the system. External state variables model features of the *environment* the system cannot control but that must care about in order to successfully carry out activities.

The behavior of state variables may be further restricted by means of *synchronization rules* that specify additional temporal constraints between different values. Synchronization rules represent *global* constraints that describe how different features of the domain must behave together. Planning with timelines usually entails considering sequence of valued intervals and *time flexibility* is taken into account by requiring that the duration of valued intervals, called *tokens*, range within given bounds. In this regard, a *flexible plan* is composed by a set of *flexible timelines* that represent an envelop of *non-flexible* behaviors of the related domain features.

Given the concepts above, a *planning problem* is defined by a temporal horizon H, a planning domain D, a planning goal G which specifies a set of tokens and constraints to satisfy and the *observations* O which completely describes the flexible timelines for all the external variables of the domain. In this context, a flexible plan Π is a solution for a planning problem if it satisfies the planning goal and if it does not make any hypothesis on the behavior of the external variables (i.e. the plan does not change the *observation* of the problem).

2.2 Hierarchy-based Modeling and Solving Approaches

Given the concepts above it is not easy to generate an effective timeline-based specification which captures all the relevant features of the problem and provides a well-suited structure to facilitate problem solving. Hierarchical approaches, like HTN have shown good results and capabilities to effectively solve real-world problems. Indeed, hierarchy-based approaches decompose complex problems in several levels of abstractions by providing a structured specification the solving procedure may exploit to generate solutions.

In this regard, the proposed modeling approach identifies two additional state variables with respect to the *external* ones introduced by the formalization. The *primitive variables* model the set of *low-level tasks* that can be directly executed by the system to control. The *functional variables* model the *complex tasks* that can be performed by combining the available primitive ones. Namely functional variables abstract the behavior of the system by modeling the functional capabilities it can perform. Thus, synchronization rules define a *hierarchical task decomposition* which decomposes the values of functional variables in terms of temporal constraints between values of variables at different hierarchical levels going from functional values to primitive values (complex domains may have several *functional layers* between the top of the hierarchy and the primitive layer). The resulting hierarchical structure of the domain is then exploited by the solving process through domain independent heuristics that encode useful information for problem resolution.

2.3 A General-purpose P&S Framework

The hierarchical timeline-based planning approach with uncertainty pursued within the PHD project has been implemented by developing a general-purpose planning framework called EPSL (*Extensible Planning and Scheduling Library*). EPSL provides a modular and general-purpose software library to support the design of timeline-based applications [16].

The key point of EPSL modularity is the *planner interpretation*. Indeed, in the EPSL framework, a planner is a compound element whose solving process is affected by the specific set of *modules* applied. Thus, EPSL-based P&S applications are obtained as the composition of several modules each of which is responsible for managing a particular aspect of the problem resolution. Moreover, EPSL relies on and extends the representation functionalities of APSI-TRF framework [6] by introducing the modeling and reasoning capabilities needed for dealing with the *temporal uncertainty* of the domain.

In this regard, EPSL complies with the pursued approach to timelines therefore, it provides solving capabilities to generate plans showing some desired properties with respect to the *controllability* problem. Specifically, EPSL-based planners try to generate *pseudo-controllable* plans, where *pseudo-controllability* represents a necessary but not sufficient requirement for *dynamic controllability* [11] which represents the most interesting property concerning temporal uncertainty and robust execution in real-world scenarios.

3 Human-Aware Planning with Uncertainty: a HRC case study

Industrial robots have demonstrated their capability to meet the needs of many application domains, offering accuracy, efficiency and flexibility of use. A current pursued challenge is the co-presence of robot and human in the same work environment collaborating in a common goal. In general when robot-worker collaboration is needed, there are a number of open issues to be taken into account, first of those is human safety that needs to be enforced in a comprehensive way. A key open trend in manufacturing is the design of shared fenceless working spaces in which safe human-robot collaboration is seamlessly implemented. In general, future human-robot-systems will necessarily be able to dynamically adapt their actions in a cost-effective way, act safely and allow for preserving the specific competences and skills of human workers in their interactions with robots. Classical approaches are not very efficient to face the different dynamics of the human behaviors. In this regard, they often require major overhauls of the control code in order to adapt the system to the specific needs of the human or the production process.

In such contexts, planning techniques can provide the flexibility needed to dynamically adapt the control process. As part of the overall FOURBYTHREE control architecture, a dynamic task planner is to provide continuous task synthesis features, safety critical properties at execution time, and user modeling ability for adapting tasks to the particular human at work. The integration of plan synthesis and continuous plan execution has been demonstrated in both the main approaches to Artificial Intelligence planning: *timeline based* planning (e.g., [14]) and *PDDL-based* (e.g., [5]). In scenarios of human robot interaction important problems have been addressed: (a) *human aware* planning has been explored for example in [15], (b) the interaction of background knowledge for robotic planning in rich domain (addressed for example in [10], (c) synthesis of safety critical plans to guarantee against harmful states (relevant in co-presence with humans) is addressed in [1] and [13]).

A possible application of the envisaged approach to timeline-based planning is represented by the HRC scenarios considered within the research project FOURBYTHREE[1]. In general, HRC scenarios represent an interesting application context for the objectives of my PHD project. Indeed, this kind of applications entail features like the capability of managing the *temporal uncertainty* of the *human behavior*, managing temporal flexible events/activities and a hierarchical specification of the production processes, that are well-suited for the proposed timeline-based approach. In such a context, there are several features the planning framework must care about in order to control the robot and guarantee a safe collaboration with the human operator. In particular, it is possible to identify three main features to address: (i) *supervision*, to represent and satisfy the production requirements to complete the factory processes; (ii) *coordination*, to assign tasks to the human and the robot according to the desired *collaboration modalities*; (iii) *uncertainty*, to manage the *temporal uncertainty* about the activities of the human operator that the system cannot control.

Thus, we are currently developing an EPSL-based task planning framework which models the human as a *planned variable* where all values are *uncontrollable*. It means that the dynamic task planing framework must plan for coordinating robot's and human's tasks to be performed by not making any hypothesis on the actual duration of human's operations. Indeed, human's tasks are *uncontrollable*, so the system must carry out robot's tasks by dynamically adapting to the actual behavior of the human. The dynamic task planning framework leverage the capabilities of the hierarchical timeline-based planning with uncertainty approach in order to realize a *human aware planning mechanism* which provides the robot with the capability to safely interact with the human. In this regards, the work [7] shows some initial but promising results.

4 Conclusions

This paper has described the research context and the main objectives of my PHD project. Specifically, the paper has briefly described the main results obtained that concern the formal characterization of timeline-based planning with uncertainty, the hierarchy-based modeling/solving approach and the development of EPSL, a general purpose framework which concretely applies the proposed approach and provides the reasoning capabilities for generating pseudo-controllable plans. Finally the paper has introduced an on-going work concerning an HRC scenario in a manufacturing context which shows many features that may show the capabilities of the envisaged approach to timeline-based planning.

[1] http://www.fourbythree.eu

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