Overview and Questions for Temporal Planning with Uncertainty in the Environment

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Abstract

Automated temporal planning requires coping with uncontrollable actions. This is particularly true of the spacecraft application domain. Therein, there is an ongoing effort towards the definition of representation and reasoning frameworks for finding a plan robust to the uncontrollability and inherent uncertainty of the domain, based either on constraint satisfaction or game theoretical approaches. In this position paper, we first analyse and summarise key notions from the different approaches using a unifying notation. Then we pinpoint questions emerging from our analysis.

Introduction

Classical planning (Ghallab, Nau, and Traverso 2004) imposes several assumptions such as atomic duration of actions and their controllability. In case of application domains like a spacecraft (Cesta et al. 2011), such assumptions are too limitative: the spacecraft need to execute a plan in what can be viewed as a 2-agent environment, consisting of the spacecraft and the possibly uncooperative nature. The presence of nature as the second agent means that the spacecraft cannot control the durations of some actions or fix their temporal relations. In this setting, a temporal planning framework can be used instead of the classical one: time becomes an explicit component, and the duration of actions can be uncertain; temporal relations between actions can be formalised as temporal constraints, qualitative or metric/quantitative (Gennari 1998).

This problem was previously studied by several authors, e.g., (Muscettola 1993; Abdeddaïm et al. 2007; Cesta et al. 2009), whose work was motivation and inspiration for ours.

Problem Definition

Hereby, we will consider the bounded version of the temporal planning problem, where we restrict the search of a solution within the semi-open interval $\mathcal{H} = [0; H)$ with a finite upper bound H known as **planning horizon**. For simplicity, we will consider a clock to be an integer counter and therefore the planning horizon is restricted to integers. The length of the horizon $\mathcal{H}$ depends on the goal. Having time explicitly, one can then introduce the notion of **component**, which is a generic entity whose properties vary over time (Cesta et al. 2009); examples of components are state variables (see below) and resources. In the remainder, we mainly concentrate on state variables, whose values correspond to **actions**.

Definition 1 *A **state variable** is a tuple* $x = \langle \mathcal{V}, \mathcal{T}, \mathcal{D} \rangle$*, where* $\mathcal{V} = \{v_1, \ldots, v_n\}$ *is the set of values,* $\mathcal{T} : \mathcal{V} \to 2^{\mathcal{V}}$ *is the value transition function and* $\mathcal{D} : \mathcal{V} \to \mathbb{N} \times \mathbb{N}$ *is the value duration function.*

A specific temporal behaviour of a state variable over the horizon $\mathcal{H}$ can be formalised as a timeline made of **temporal assertions** of the form $x@[t_{i-1}, t_i) : v_i$, stating that the value for x_i in the interval $[t_{i-1}, t_i)$ is v_i (Ghallab, Nau, and Traverso 2004).

Definition 2 *A **timeline of length** H for the state variable* $x = \langle \mathcal{V}, \mathcal{T}, \mathcal{D} \rangle$ *is a sequence of temporal assertions,* $TL_x = x@[t_0, t_1) : v_1, \ldots, x@[t_{k-1}, t_k) : v_k$*, such that:*

1. $\forall\, 0 < i \leq k : v_i \in \mathcal{V}$*, that is,* v_i *is a value of* x*;*
2. $\forall\, 0 < i < k : v_{i+1} \in \mathcal{T}(v_i)$*, that is,* v_{i+1} *is a **legal** successor of* v_i*;*
3. $\forall\, 0 < i \leq k : (t_i - t_{i-1}) \in \mathcal{D}(v_i)$*, that is, the duration of* v_i ***complies** with the value duration function;*
4. $t_0 = 0$ *is the beginning of the timeline and* $t_k = H$ *is the end of the timeline.*

For example, consider a ground station being a component of the planning domain. It is modelled by a state variable $x_{station}$ with $\mathcal{V}$, $\mathcal{T}$ and $\mathcal{D}$ defined as follows:

$$\begin{array}{ll} \mathcal{V} = \{avail, unav\}, & \\ \mathcal{T}(avail) = unav, & \mathcal{T}(unav) = avail, \\ \mathcal{D}(avail) = [10; 20], & \mathcal{D}(unav) = [0; +inf]. \end{array}$$

One possible behaviour of the ground station, captured by the timeline $TL_{station}$, is as follows:

$$\begin{array}{c} \text{station}@[0; 5) : unav; \\ \text{station}@[5; 20) : avail; \\ \text{station}@[20; 80) : unav \end{array}$$

The values of different components, which are state variables, are correlated by synchronisation rules:

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Definition 3 *A **synchronisation** is an implication rule* $\langle TL, v\rangle \Rightarrow \{\langle TL_i, v_{i_j}, r_{i_j}\rangle; i, j \in I\}$ *that constraints the occurrence of reference value* v *on reference timeline* TL *with the occurrence of target values* v_{i_j} *on target timelines* TL_i *so that* v *and* v_{i_j} *relate through a temporal relation* r_{i_j}*, qualitative or quantitative.*

A **domain theory** for the set $\mathcal{X} = \{x_1, \ldots, x_n\}$ of state variables is a set of synchronisation rules for the variables in S. Then, a **temporal planning domain** is a pair consisting of a set $\mathcal{X}$ of state variables and a domain theory for $\mathcal{X}$. The notion of temporal planning problem is defined accordingly.

Definition 4 *A **temporal planning problem** is a tuple* $P = \langle \mathcal{X}, \mathcal{S}, \mathcal{G}, \mathcal{H}\rangle$*, where* $\mathcal{X} = \{x_1, x_2, \ldots\}$ *is a set of state variables,* $\mathcal{S}$ *is a domain theory for* $\mathcal{X}$*,* $\mathcal{H} = [0; H)$ *is a planning horizon and* $\mathcal{G}$ *is a set of goals formulated as temporal assertions, possibly ordered by priorities or preferences.*

Plans and Flexible Plans

In the literature, we often find the definition of **plan** for a temporal planning problem as a set of timelines, one for each state variable. However, that notion of plan does not take care of the inherent uncertainty of the environment. In order to take uncertainty into account, we need to introduce a notion of 'flexible plan'. First, we say that a timeline is **flexible** when the transition between two consecutive values of a state variable happens during an interval instead of at a fixed timepoint, i.e., t_i of Definition 3 does not have an exact execution time but it is restricted to an interval so that $t_i \in [a, b)$ for some times a, b. Then, we can define a **flexible plan** as a plan with at least one flexible timeline. The flexibility allows us to capture the uncertainty by having intervals instead of timepoints, and it prevents the plan from direct execution as some timepoints do not have a fixed execution time. Three types of strategies for obtaining a flexible plan are possible, that is, weak, strong and dynamic, see (Morris, Muscettola, and Vidal 2001). Dynamic controllable strategies represent a trade-off between the robustness of the plan and the ability of constructing the strategy on-the-fly.

The Advanced Planning and Scheduling Initiative (Cesta et al. 2009) (APSI) suggests a framework where the task of automated reasoning for finding a plan is split into five layers, each addressing only a part of the overall reasoning. On the *1st* layer, the temporal constraints r_{i_j} of Definition 3 are resolved. The layer maintains a dynamically controllable Simple Temporal Network with Uncertainty (STNU) (Morris, Muscettola, and Vidal 2001). The *2nd* layer is responsible for satisfying the constraints within the state variable, in other words, it makes sure that the value transition function does not get violated. The *3rd* layer resolves the inter-component constraints, which are stated in the domain theory. The *4th* layer plans towards the individual goals. The *5th* layer is responsible for satisfying multiple-goal optimisation, if it is requested by the task. It is represented as a hyper-graph with nodes corresponding to single goals and edges corresponding to preferences and priorities over them. This layer is responsible for optimising the behaviour, if preferences or a cost function over the goals are given.

Open Questions

After analysing the work summed up above, we tried to apply the suggested APSI separation to it. Our analysis triggered a series of challenging research questions that we list as follows.

Questions about temporal constraints. How is the qualitative temporal information of the synchronisation rules translated to the STNU, which is metric? In addition, dynamically controllable STNUs are polynomial (Rossi, Venable, and Yorke-Smith 2006), whereas the classical temporal constraint satisfaction problem over the Allen Interval Algebra (IA) is NP-complete; it is polynomial if we only consider sub-algebras, like CA, of IA. What are the necessary qualitative temporal constraints emerging in the spacecraft application domain, e.g., of (Cesta et al. 2011). Can they be translated into STNUs or do we need a more expressive metric framework? What is the computational cost of the translation? Moreover, do we really need the translation into STNUs or can we think of dynamically controllable temporal qualitative problems, e.g., over CA?

Questions about layers. The reasoning layers are hierarchically ordered and the communication among them is restricted: the information from the 1st layer does not propagate to the rest of the framework; the other layers may impose or retract assertions to the layer directly superior to them while they can propagate assertions to inferior layers. How can information at the first layer be propagated? Can the communication intra layers be optimised by means of simplification rules that can detect 'trivial' inconsistencies?

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