Planning with Sensing for a Mobile Robot

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Abstract. We present an attempt to reconcile the theoretical work on reasoning about action with the realization of agents, in particular mobile robots. Specifically, we present a logical framework for representing dynamic systems based on description logics, which allows for the formalization of sensing actions. We address the generation of conditional plans by defining a suitable reasoning method in which a plan is extracted from a constructive proof of a query expressing a given goal. We also present an implementation of such a logical framework, which has been tested on the mobile robot "Tino".

1 Introduction

In recent years there has been an attempt to reconcile the theoretical work on reasoning about action with the realization of agents, in particular mobile robots. Such a field of research has been referred to as *Cognitive Robotics* [10].

A mobile robot can indeed be regarded as an intelligent agent, that is designed both to achieve high-level goals and to be able to promptly react and adjust its behavior based on the information acquired through the sensors. Reactive capabilities are necessary to cope with the uncertainties of the real-world; action planning is important as well, if the robot is faced with situations where the knowledge of the environment is incomplete, subject to varying constraints. The integration of the two kinds of functionalities mentioned above is a critical issue in the design of intelligent agents.

The work reported in the present paper builds on a previous proposal [3], which provides a formal framework for reasoning about action derived from *dynamic logics* [16] and exploits the correspondence between such logics and *description logics.* A number of features that had been analyzed for description logics have proved useful for reasoning about action. Specifically, we have extended the language with an epistemic operator interpreted in terms of minimal knowledge, that allows us to express the knowledge about actions in such a way that we can effectively address the planning problem. We have implemented our proposal for reasoning about action on the mobile robot "Tino", which belongs to the *Erratic* family [8]. The implementation relies on the reasoning facilities offered by the knowledge representation system CLASSIC.

In this paper we extend the previous proposal with the ability of expressing sensing actions [18,11,6], i.e. knowledge producing actions that affect the agent's

Constructs	PDLs	DLs	DL Semantics
Atomic concept/proposition	A	A	$A^{\mathcal{I}} \subseteq \Delta$
Atomic role/action	R	R	$R^{\mathcal{I}} \subseteq \Delta \times \Delta$
Named individual	—	s	$s^{\mathcal{I}} \in \Delta$
True	$\mathtt{tt}$	$\top$	Δ
False	$\mathtt{ff}$	$\bot$	$\emptyset$
Conjunction	$C \wedge D$	$C \sqcap D$	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$
Disjunction	$C \vee D$	$C \sqcup D$	$C^{\mathcal{I}} \cup D^{\mathcal{I}}$
Negation	$\neg C$	$\neg C$	$\Delta \setminus C^{\mathcal{I}}$
Universal quantification	$[R]C$	$\forall R.C$	$\{d \in \Delta \mid \forall d'.(d,d') \in R^{\mathcal{I}} \Rightarrow d' \in C^{\mathcal{I}}\}$
Existential quantification	$\langle R \rangle C$	$\exists R.C$	$\{d \in \Delta \mid \exists d'.(d,d') \in R^{\mathcal{I}} \wedge d' \in C^{\mathcal{I}}\}$
Inclusion assertion	$C \Rightarrow D$	$C \sqsubseteq D$	$C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ for every $\mathcal{I}$
Instance assertion	—	$C(s)$ $R(s_1, s_2)$	$s^{\mathcal{I}} \in C^{\mathcal{I}}$ $(s_1^{\mathcal{I}}, s_2^{\mathcal{I}}) \in R^{\mathcal{I}}$ for every $\mathcal{I}$

Table 1. Description logic $\mathcal{ALC}$

knowledge, but not the environment. We also extend the implementation with the ability of devising and executing conditional plans. From the point of view of the formalism, a new kind of axioms for sensing actions and the ability of propagating knowledge to successor states (in a controlled way) is introduced. From the point of view of the implementation, we design a more powerful method for devising the plan, and extend the capabilities of the plan execution component and of the underlying control system by providing new behaviors realizing the sensing actions.

The paper is organized as follows. We first recall the basic elements of our approach. We then focus on sensing actions and on the method for devising plans in the presence of this kind of actions. We finally describe the implementation of the new features in our robot "Tino".

2 Epistemic DL-based framework for representing actions

Our general framework for representing dynamic systems was originally proposed in [3]. It follows the lines of Rosenschein's work [16], based on propositional dynamic logics (PDLs) [9], and it makes use of the tight correspondence between PDLs and description logics (DLs) [19,4] that allows for considering PDLs and DLs as notational variants of each other. We use the notation of DLs, focusing on the well-known DL $\mathcal{ALC}$, corresponding to the standard PDL with atomic programs only. Table 1 summarizes the syntax and the semantics of $\mathcal{ALC}$ and the corresponding PDL. In addition, we use the two nonmonotonic modal operators: a *minimal knowledge operator* **K** and a *default assumption operator* **A**. These are interpreted according to the nonmonotonic modal logic *MKNF* [12], and give rise to the so-called autoepistemic description logic $\mathcal{ALCK_{NF}}$ [5]. We do not have the space here to formally introduce such a logical framework, we refer the reader to [3] and [5]. Rather, we give an intuition of the underlying semantics.

The interpretation structures of DLs (PDLs) are essentially *graphs* labeled both on nodes and arcs. *Nodes*, called *individuals* in DLs, (states in PDLs) are