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Context-based design of robotic systems

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ABSTRACT

The need for improving the robustness, as well as the ability to adapt to different operational conditions, is a key requirement for a wider deployment of robots in many application domains. In this paper, we present an approach to the design of robotic systems, that is based on the explicit representation of knowledge about context. The goal of the approach is to improve the system's performance, by dynamically tailoring the functionalities of the robot to the specific features of the situation at hand. While the idea of using contextual knowledge is not new, the proposed approach generalizes previous work, and its advantages are discussed through a case study including several experiments. In particular, we identify many attempts to use contextual knowledge in several basic functionalities of a mobile robot such as: behavior, navigation, exploration, localization, mapping and perception. We then show how re-designing our mobile platform with a common representation of contextual knowledge, leads to interesting improvements in many of the above mentioned components, thus achieving greater flexibility and robustness in the face of different situations. Moreover, a clear separation of contextual knowledge leads to a design methodology, which supports the design of small specialized system components instead of complex self-contained subsystems.

1. Introduction

The requirement that robotic systems be flexible and robust to the uncertainties of the environment are becoming more and more compelling, as new applications of robotics in daily life are envisioned. A promising approach to meet this kind of requirement is to design the system in such a way that some of the processes, that are required on the robot, can be adapted, based on knowledge that we call contextual and that is typically handled in ad-hoc ways or not taken into account. Roughly speaking, one could argue that several tasks that are typical of mobile robots can take advantage of knowledge about context. The notion of *context* has been deeply investigated both from a cognitive standpoint[1] and from an AI perspective (see for example [29]). In the former case, the study is more focussed on the principles that underlie human uses of contextual knowledge, while in the latter case, the main point is how to provide a formal account that enables the construction of actual deductive systems supporting context representation and contextual reasoning.

The interest for context in robotics is twofold. On one side, the design and implementation of experimental systems that are focussed on cognition; on the other side, the need to improve the performance and the scope of applicability of robotic systems by providing them with high-level knowledge and capabilities. Turner [38] specifically addresses contextual knowledge in robotic applications. He characterizes context as: "any identifiable configuration of environmental, mission-related, and agent-related features". Such a definition, that we take as the basis of our approach, highlights a relationship with a more recent stream of work on the use of semantic information in robotics [18]. In particular, as discussed in Section 2, contextual knowledge can be used to represent semantic information, which in many cases corresponds to Turner's notion of contextual knowledge about the environment. Moreover, we provide an architectural framework which enables effective engineering of the systems that use such kinds of knowledge.

In this work, we show that several uses of contextual knowledge and semantic knowledge have been proposed in the literature, regarding many tasks that are typically required of mobile robots: exploration, navigation, behavior, mapping, localization and perception. For example, there are systems that can improve the map construction process, by knowing that the robot is currently moving in the corridor of an office building. However, contextual knowledge is typically not fully exploited, since it is built in each of the system modules. It seems therefore very appropriate, from an engineering perspective, to build and maintain a single representation of the contextual knowledge that can be used to improve many different processes.

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[1] Context web http://www.context-web.org/.

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The aim of the paper is to present an approach to robotic system design that allows contextual knowledge to be shared, and effectively used, in order to improve the system's performance. More precisely, we aim at pursuing *contextualization* as a design pattern, where the processes, needed in the realization of a mobile robot, are accomplished with general methods, that can be specialized (thus becoming more effective), by taking into account knowledge that is specific to the situation the robot is facing and that is acquired and represented in a shared fashion. This design pattern can be applied to many robot software architectures and, in particular, to a *hierarchical architecture* [7], where different layers correspond to different levels of abstraction. However, we define a context-based architecture, that allows for a suitable implementation of the design pattern, by requiring the explicit representation of contextual knowledge within the system. We have fully implemented our approach in re-designing our prototype mobile robot for search and rescue missions [5], and have performed several experiments, both in simulation (with USARSim[2]) and on a real robot, that show improvements of the performance due to the use of contextual knowledge.

The paper is organized as follows. We first analyze the literature on mobile robotics, highlighting several uses of contextual knowledge in the major tasks that are needed of mobile robots. We then introduce a context-based architecture and discuss the features of context-based robot design and its instantiation on our mobile robot. We then develop a case study and a set of experiments to evaluate the proposed approach. We conclude the paper with a discussion of the proposed approach and hints for future developments of contextualization in mobile robotics.

2. Uses of context in robotics

The use of contextual knowledge is addressed in a very broad spectrum of disciplines, here we focus our attention on the proposals addressing context in mobile robotics. We use two dimensions in order to structure our analysis: task addressed, and type of contextual knowledge. Specifically, we consider the following tasks: Behavior, Navigation, Localization and Mapping, Perception. With respect to the type of contextual knowledge, we exploit the characterization provided by Turner and consider mission related, environmental and introspective (agent-related) knowledge. For each of the cited work, we emphasize which kind of contextual knowledge is addressed, even though in most of them contextual knowledge is not explicitly identified as such. Indeed, much of the cited work refers to semantic information as high-level information about the environment. From our point of view, this semantic information constitutes, in fact, contextual knowledge about the environment. Moreover, some work also uses information about the current mission (e.g., planning information) and the state of the agent (e.g., the state of the mapping process) that we consider respectively as mission related and introspective contextual knowledge.

2.1. Behaviors

It is broadly agreed that context driven choices are useful in robotic scenarios, for adapting the robot's behavior to different situations which they may encounter during execution. This is typically addressed through plan selection (RAPS [11], ESL [15], PRS [14]), hierarchical approaches to planning [35] and meta-rules [34]. Such approaches provide very general planning frameworks, and can thus be used to manage mission related, environmental and introspective knowledge. However, the use of contextual knowledge is embedded in the planning process, and it does not address the integration between the symbolic representation and the underlying numerical data processing.

Turner [38] proposes a plan selection approach which clearly separates context and plan representation. Contexts are represented as contextual schemas (c-schemas), a frame-like knowledge structure. Each c-schema represents a particular context, that is, a particular class of problem-solving situations. A c-schema can contain mission related, environmental and introspective knowledge. Our approach follows Turner's view, by generalizing the representation of context and the types of contextual knowledge. Another relevant use of contextual knowledge is related to the design of basic behavior, where it can be used for the fine tuning of the parameters. The use of contextual knowledge for behavior specialization is suggested by Beetz et al. [3], where environmental and introspective knowledge is used to obtain smooth transitions between behaviors, by applying sampling-based inference methods. Recently, the design of effective behaviors in rough terrains has been pursued by exploiting terrain classification (see for example [33,21]). Usually, in these cases, ad-hoc representations, such as behavior maps by Dornhege and Kleiner [9], are used for representing features like the presence of ramps or open stairs. Nevertheless, this type of semantic knowledge can clearly be viewed as environmental knowledge, and can be used to select or tune behaviors. Most of the cited approaches provide rather ad-hoc solutions: our aim is to generalize them in a framework that provides for a more systematic use of contextual knowledge.

2.2. Navigation and exploration

The techniques for motion planning (see for example [24–26]) aim at providing rather general solutions. Typically, however, ad-hoc algorithms and heuristics for particular instances of the problem are needed, in order to achieve effective implementations. The use of contextual knowledge can support the specialization of general techniques to the problem at hand. For example, Coelho Jr. et al. [19] try to learn the most efficient navigation policies, together with context classification, by inferring environmental knowledge from system dynamics in response to robot motion actions.

Very often, navigation is embedded into a more complex process, such as search and exploration of the environment, where the mobile platform has to select a target and then try to reach it. When phrasing search and exploration as a multi-objective task, mission related knowledge can change the relative importance of one kind of sub-goal with respect to the other ones. For example, Calisi et al. [5] highlight that search and exploration requires a choice among, often conflicting, sub-goals as exploration of unknown areas and search for features in known areas.

Coordinated search and exploration can also benefit from contextual knowledge. For example, Stachniss et al. [36] propose a coordination algorithm which takes into account environmental knowledge by using semantic place knowledge (e.g., corridors, rooms). Sending at least one robot to explore a corridor allows for a quick discovery of the structure of the environment, and thus for a better coordination with the other robots. While the explicit use of context in navigation and exploration is presently only partially addressed, it can be systematically pursued in a system that is designed to exploit contextual knowledge.

2.3. Localization and mapping

Contextual knowledge can be used in robot mapping to describe the abstract structure of the environment. Extending metric maps with semantic knowledge (like rooms, corridors, surfaces) allows the user to interact with a mobile robot in an easy way. In

[2] usarsim.sourceforge.net.