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Deliberation for autonomous robots: A survey

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ABSTRACT

Autonomous robots facing a diversity of open environments and performing a variety of tasks and interactions need explicit deliberation in order to fulfill their missions. Deliberation is meant to endow a robotic system with extended, more adaptable and robust functionalities, as well as reduce its deployment cost.

The ambition of this survey is to present a global overview of deliberation functions in robotics and to discuss the state of the art in this area. The following five deliberation functions are identified and analyzed: planning, acting, monitoring, observing, and learning. The paper introduces a global perspective on these deliberation functions and discusses their main characteristics, design choices and constraints. The reviewed contributions are discussed with respect to this perspective. The survey focuses as much as possible on papers with a clear robotics content and with a concern on integrating several deliberation functions.

1. Introduction

We are interested here in autonomous robots in industrial, service or field applications, and in robotized systems such as spacecrafts, AUVs, UAVs or self-driving cars. These systems interact *autonomously* with their environment through sensory-motor capabilities and may have to *act deliberately* in order to fulfill their mission. Acting deliberately means performing actions that are motivated by some intended objectives and that are justifiable by sound reasoning with respect to these objectives. Deliberation is any computational function required to act deliberately. From the perspective of robotics, the interest is not on deliberation *per se* but on acting deliberately.

Robots without autonomy do not need much deliberation. These robots extend the acting capabilities of human operators who are in charge of decision making, possibly with the support of advice and planning tools, e.g., as in surgical robotics and other teleoperated applications. Autonomous robots may or may not require explicit deliberation. Deliberation is not needed for autonomous robots working in fixed, well-modeled environments, as for most fixed manipulators in manufacturing applications. Neither would deliberation be required if all feasible missions consist of repeating a single task, e.g., as for a vacuum cleaning or a lawn-mowing robot. In these and similar cases, deliberation takes place at the design stage. Its results are directly implemented in the robot controller.

Autonomous robots facing a *diversity of environments*, a *variety of tasks* and a *range of interactions* cannot be preprogrammed by foreseeing at the design stage all possible courses of actions they may require. These robots need to perform some explicit deliberation. In short: *autonomy plus diversity entail the need for deliberation*.

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Deliberative robots are desirable in applications where the environment is open-ended and largely unknown and tele-operation is constrained, as in most exploration robotics. They are needed in service applications in dynamic and changing environments with semantically rich tasks and human interactions. Domestic and personal robots are demanding in deliberation capabilities. Even for applications in closed and well structured environments with a reduced range of tasks, where engineered robotics operations are feasible and have been demonstrated successfully (e.g., in automated warehouses), deployment and adaptation costs can be reduced by deliberation capabilities. Deliberation can endow a robotic system with extended, more flexible and robust functionalities; it can reduce its deployment cost.

Deliberation is a very active and critical research field in intelligent robotics. It covers a wide spectrum of problems and techniques at the intersection of Robotics and Artificial Intelligence. Deliberation has to closely interact with sensing and actuating. It does not stop at planning and is not reducible to a single function. It critically requires the coherent integration of several deliberation functions. It involves numerous open problems ranging from knowledge representation, acquisition and verification, to scalable reasoning algorithms and architecture issues.

This research field is of interest to several communities in Robotics and Artificial Intelligence. It is covered by a vast literature. Several books and survey papers review the state of the art for a few focused deliberation functions, e.g., planning [91], monitoring [169], goal reasoning [213], recognition of actions and plans [129], architectures [127], or human–aware navigation [130]. A historical perspective of the links between Robotics and AI, from which this survey paper stems, is sketched in [107]. However, to our knowledge there is no global overview of deliberation functions in robotics, of the challenges they pose and the techniques needed for their design and implementation. The lack of a global vision hinders progress in the field toward coherent and more integrated contributions.

The ambition of this paper is to contribute to such an overview. It undertakes this objective by surveying some of the contributions to deliberation functions and putting them into perspective with respect to a global understanding of deliberate action and its integrative requirements. To keep a reasonable scope, we will not survey human–robot and multi-robot interaction and cooperation issues (but of few references relevant beyond interaction issues). Despite this focus, the covered field is not easily amenable to a unifying perspective. It remains excessively broad, fragmented in topics and approaches, but also in time: often, the same line of research spans and matures over a dozen years and as many publications. We believe that taking a global view to deliberation in robotics is a useful step for understanding the state of the art and permitting further advances.

This paper does not propose a unifying theory of deliberation. It presents a comprehensive view of deliberation functions in robotics. It discusses their main characteristics, design choices and constraints for achieving them. The surveyed literature for each deliberation function is discussed with respect to this global perspective.

Given the breadth of the field, this survey cannot exhaustively cover all relevant contributions. We restricted ourselves to papers on deliberation functions with a clear robotics content, and, whenever possible, with a concern for the integration of several deliberation functions. Some of the reviewed contributions are only briefly mentioned, while representations and techniques for a few typical approaches are informally presented.

The next section presents a global view of deliberation functions and their requirements for various robotics applications; it outlines the main options faced by a designer of a deliberation system. The rest of the survey develops an analysis of several contributions to deliberation functions (Sections 3 to 7). Two main functions, namely planning and acting, are extensively discussed, while the survey is more illustrative for the monitoring, observing and model acquisition functions. However the corresponding sections are essential to the global view advocated for here. This analysis is followed by a discussion and synthesis section (Section 8), then a conclusion with a perspective on future research.

Beyond the wealth and variety of approaches, the take-home message of this survey can be sketched as follow:

- deliberation in robotics does not reduce to task planning,
- acting is a context and task dependent reaction to events and refinement of planned actions into commands,
- hierarchy of action refinements over several levels of state and action spaces is essential,
- monitoring needs strong links to prediction in planning and acting,
- observing requires significant deliberation, it does not reduce to signal processing,
- integrated and consistent representations and the acquisition of corresponding models are a clear bottleneck.

2. Design of a robotics deliberation system

2.1. Deliberation functions

Let us first clarify our terminology. An *action* is a process that changes the state of the robot and its environment; this includes perception and information gathering actions. An action can be viewed at different levels of abstraction *hierarchy*. It is *primitive* at some level and *compound* at the next level. E.g., open(door) is a primitive action at an abstract level and a compound task to be refined, when needed, into a collection of concrete actions. A *command* is a primitive action at the lowest level of the hierarchy. Commands can be directly executed by the robot platform. The *platform* is a collection of devices and sensory-motor functions integrating sensing and closed-loop actuation. Choosing the appropriate command and monitoring that the context remains within a command functioning envelope is part of deliberation. The execution of a command does not need deliberation capabilities. For example, grasp(handle) is a command which, under appropriate