A Suite of Ontologies for Robotics and Automation

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One of the basic requirements for any type of robot communication, whether with other robots or humans, is the need for a common vocabulary along with clear and concise definitions. With the growing complexity of tasks that robots are expected to perform as well as the need for multirobot and human–robot collaboration, the need for a standard and well-defined knowledge representation is becoming more evident.

The IEEE Standard Association's Robotics and Automation Society (RAS) recognized this need, and, in 2011, created the Ontologies for Robotics and Automation (ORA) working group. The goal of the group is to develop a standard to provide an overall ontology and associated methodology for knowledge representation and reasoning in robotics and automation together with the representation of concepts in an initial set of application domains. The standard provides a unified way of representing knowledge and provides a common set of terms and definitions, allowing for unambiguous knowledge transfer among any group of human, robots, and other artificial systems. The group grew quickly; it is now composed of 175 members representing 23 countries from a mixture of approximately 50% educational institutions, 25% private companies, and 25% government entities.

One of the basic requirements for any type of robot communication, whether with other robots or humans, is the need for a common vocabulary along with clear and concise definitions.

One of the main outputs of this group is the *IEEE Standard Ontologies for Robotics and Automation*, which is composed of a core ontology called Core Ontologies for Robotics and Automation (CORA) [4]. This standard specifies the main, most general concepts, relations, and axioms of robotics and automation (R&A), and serves as a reference for knowledge representation and reasoning in robots as well as a formal reference vocabulary for communicating knowledge about R&A between robots and humans. This standard was awarded the prestigious Emerging Technology Award by the IEEE Standards Association in December 2015. The standard was also mentioned in the National Artificial Intelligence (AI) Research and Development Strategic Plan, released by President Obama in October 2016 [5]. This strategic plan focuses on the role of AI, machine learning, automation, and robotics in addressing complex national problems. With the release of this standard, the CORA working group completed its task and was required to disband. However, many of the working group members remain involved in this work by focusing on subgroups.

CORA aims to describe what a robot is and how it relates to other concepts. It defines four big broad entities: robot part, robot, complex robot, and robotic system. The term *robot* may have as many definitions as there are authors writing about the subject. The inherent ambiguity in this term might be an issue when one needs to specify an ontology for a broad community like ours. We acknowledge this ambiguity as an intrinsic feature of the domain and, therefore, we decided to elaborate a definition based purely on necessary conditions without specifying sufficient conditions. Thus, CORA covers all entities that the community considers as a robot, at the cost of classifying some entities as robots that may be counterintuitive to some roboticists. However, the concepts in our ontology could be specialized according to the needs of specific subdomains or applications of R&A.

CORA was developed to be a high-level standard on which domain-specific efforts could build. The approach was to define concepts in CORA that were generic to all robot domains, and then these domains could specialize these concepts to address their specific information requirements. When the working group that developed CORA was created, based on the interests of the working group members, we expected subgroups to emerge that would specialize the concepts represented in CORA. Currently, we expect that groups will be organized in two layers (Figure 1). We expect that middle-layer groups will develop ontologies

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regarding transversal notions in robotics. Lower-layer groups will concern specific domains in robotics and will use concepts from CORA and middle-layer groups.

The Robot Task Representation Subgroup

The Robot Task Representation subgroup will develop a broad standard that provides a comprehensive ontology for robot task structure and reasoning. In this context, *task* refers to the concrete decomposition from goal to subgoals that enables the human or robot to accomplish the outcome at a specific instance in time. To accomplish this, there is a need for a standard providing an explicit knowledge representation for robot tasks.

This work will be a supplement to the existing standard CORA ontology. This supplement will include the presentation of concepts in an initial set of application domains (e.g., in manufacturing) where robot task representation could be useful. The ontology provides a unified way to represent knowledge about robot tasks by sharing common representations and preserving semantic meaning. It can be utilized in manufacturing control applications, where the system needs to control multiple elements of the manufacturing process.

Our work plan for developing the standard has two aspects. The first is to develop the task ontology, extending CORA and capturing vocabularies for robot task representation by requirements analysis and surveying the literature. The final decision-making on

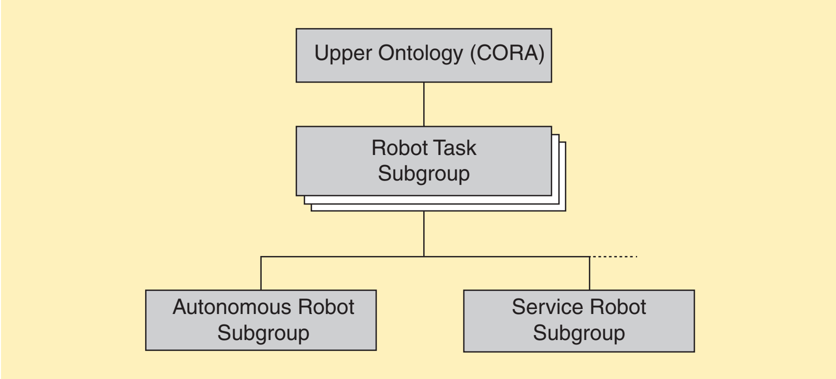

Figure 1. The structure of IEEE ORA efforts. The subgroups in gray are now active; the ones in white are planned.

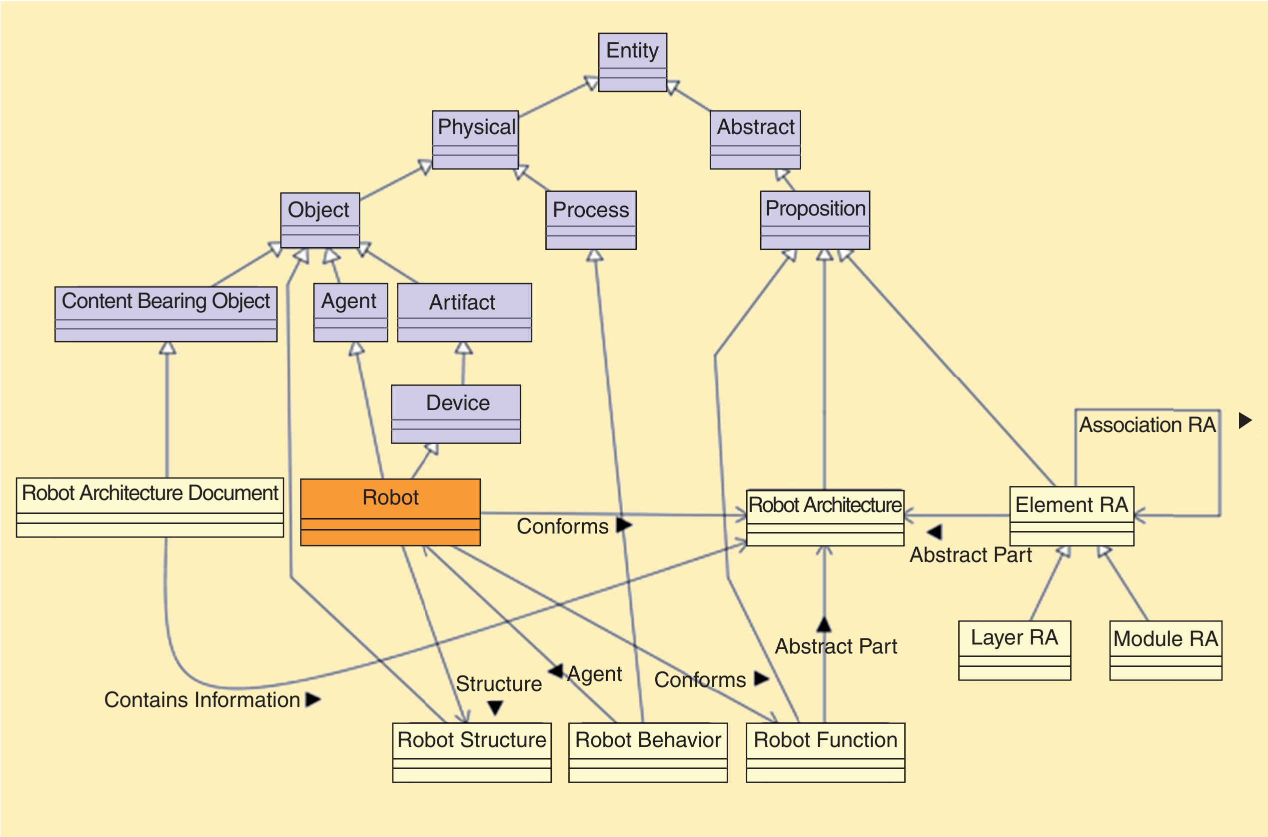

Figure 2. ROA basic concepts and relationships [3].

vocabularies will be achieved through consensus between different group members. The second aspect is to develop a task repository, which will provide a set of instances that could be used for robotic implementation and validation of the task ontology.

The standard provides a unified way of representing knowledge and provides a common set of terms and definitions, allowing for unambiguous knowledge transfer among any group of human, robots, and other artificial systems.

The task ontology formally defines what a task is, and specifies the properties of tasks, the properties of the hierarchy in which tasks are placed, and the ways in which the performance of the capabilities required to accomplish the tasks are measured. The task repository enables the community to build up a shared catalog of tasks and capabilities along with their relationships (based on elements within the task ontology). The purpose of the overall standard is to ensure common representations and frameworks when tasks are described, so the knowledge represented in the task ontology defines the structure and content of the tasks in the task repository.

Although the task ontology will be the official standard when completed, the task repository is necessary to help validate the standard and to provide an avenue that makes the standard more useful and practicable in the industry.

The Autonomous Robot Subgroup

In 2016, the IEEE RAS Standing Committee approved the Autonomous Robot (AuR) subgroup as a study group (SG) to determine whether sufficient interest and resources exist to develop an IEEE draft standard. The AuR-SG aims to create a standard ontology that specifies the domain knowledge needed to build autonomous robots, operating in the air as well as in ground and underwater environments. Benefits include having a common knowledge base for the development and integration of systems from different manufacturers, which will enable interoperability and catapult design to a new level.

The AuR-SG intends to extend CORA and define domain-specific concepts and axioms. The AuR-SG will analyze the various autonomous robots (e.g., flying, ground, underwater) to identify the components necessary to endow robots with autonomy, including the needed hardware and software. To develop the standard ontology for autonomous systems, the AuR-SG has adopted the following approach:

1) Develop standard vocabularies for architectural concepts in IEEE 1471/IEC 42010 [with a focus on Robot Parts (RParts)].

2) Develop a functional and formal ontology for R&A.
3) Check/validate relationship concepts, using function as a basis for relation checking.
4) Use the developed vocabularies and ontology for the conceptual design of sample robot applications by extending concepts of IEEE 1471/ IEC 42010 [1] and CORA (focus on RParts) [2].

As part of the architectural concepts development, the AuR-SG has proposed the Robot Architecture (ROA) ontology (Figure 2) to define the architectural concepts and relations. Envisaged as a conceptual framework, ROA will facilitate information exchange about robot architectures between human and robots. Users of ROA will instantiate ROA concepts to represent information about specific as well as generic architectures. For example, architectural diagrams in robot literature can be thought of as instances of ROA. The conceptualization described below is akin to the metamodels of concept representation languages, such as Unified Modeling Language (UML). Once the concepts, architecture, and core components for autonomous systems are described, case studies will be developed. The AuR-SG is currently working on defining key concepts to address the functional features and capabilities of autonomous robots, such as behavior, function, goals, and tasks, and the relations among them.

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