IEEE Standard for Autonomous Robotics Ontology

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1. Introduction

The IEEE1872.2 Autonomous Robotics (AuR) Ontology Working Group has recently developed the Autonomous Robotics Ontology standard. This standard is a logical extension to IEEE 1872-2015 Standard Ontologies for Robotics and Automation, CORA [1]. The standard extends the CORA ontology by defining additional ontologies appropriate for Autonomous Robotics (AuR) relating to:
1) The core design patterns specific to AuR in common R&A sub-domains;
2) General ontological concepts and domain-specific axioms for AuR; and
3) General use cases and/or case studies for AuR.

This standard ontology specifies the domain knowledge needed to build autonomous systems consisting of robots that can operate in all classes of unstructured environments. The standard provides a unified way of representing Autonomous Robotics system architectures across different Robotics and Automation (R&A) domains, including, but not limited to, aerial, ground, surface, underwater, and space robots. This allows unambiguous identification of the basic hardware and software components necessary to provide a robot, or a group of robots, with autonomy (i.e. endow robots with the ability to perform desired tasks in unstructured environments without continuous explicit human guidance). The stakeholders for the standard include: Robot designers and builders; Robotics researchers; Robot industry experts; Robot users; Policy makers.

Working group members are from a cross-section of industry, academia, and government that represents over twenty countries and six continents. The group has organized weekly teleconference meetings from 2011. The official kick-off meeting on AuR took place at IEEE International Symposium on Robot and Human Interactive Communication, Lisbon, Portugal, in September 2017. Since then, the working group has reached the following milestones:
1. Development of standard vocabularies.
2. Development of a functional ontology for R&A.
3. Checking/validation of relationship using functions as a basis for relationship checking.
4. Using AuR ontology for conceptual design of robotic applications.

2. Ontologies and robotics

As a computational model, an ontology generally involves classes, relations, axioms, and class instances [2]. The knowledge represented in the ontology can be used along

with other system engineering models to devise general framework for the autonomous system, e.g., autonomous robots. Indeed, ontologies have been widely used for autonomous robotics during the last years [3], but the lack of a standard creates ambiguity and inconsistencies in the domain knowledge.

Knowledge representation formalisms such as ontologies, are useful approaches to harmonizing terminology and allowing its reusability. Hence, from an ontological viewpoint, the standard has been developed to be widely adopted. This is achieved in two ways. First, the standard does not commit to a specific top-level ontology. Indeed, the ontology definitions are compatible and aligned to two distinct top-level ontologies, namely DOLCE [4] and SUMO [5]. In this way, systems developed adopting this standard can interoperate with foundational views (like DOLCE) as well as with practitioner-driven views (like SUMO). This choice is important because in robotics research teams are already experimenting with different ontologies, and in particular with the two mentioned above. The other choice that foster a broad adoption of the standard is the coverage of the definitions. These introduce many concepts, from interaction to function, from environment to behavior. By defining these concepts and exemplifying their use, the standard allows to model a very large class of scenarios with a single or multiple agents (robots and possibly humans) and with different types of interactions (e.g. physical or information based). In particular, the standard makes a clear distinction between the behavior of a robot and the function performed via such behavior. In this way the standard facilitates the analysis of the robot's activities, for instance it allows to systematically compare what the robot is supposed to do and what it actually does.

3. AuR basic concepts and relationships

Amongst the several concepts and relationships defined in the AuR ontology, in this section we highlight basic concepts that are present in usual robot deployments, e.g., as described in the use case (section 4). Although the standard incorporated SUMO and DOLCE as top-level ontologies, we present a short description of some concepts and relationships, devised based on DOLCE. The AuR axioms are formalized using the Web Ontology Language (OWL)[1] and include definitions, axioms, examples, and rationale.

For any autonomous robot, the concept of *environment* is essential. The environment in the sense of the AuR ontology standard is centered on a given object. As such, it was defined as the ***Object-centered environment***. Despite the world being the same, each object has its own environment model where it can execute actions. Several object oriented environment models can be linked/registered to facilitate interactions between objects, e.g., robots. The concept of an ***Object-centered environment*** briefly states that in a given event, the object-centered environment comprises all the entities (with their relationships) that participate in the event and that could potentially interact with the object. The happening of an event implies the interaction amongst the participants. In this sense, the concept of ***Interaction,*** states that given an event, the interaction among (some or all) the objects participating in it, is the change of the objects' qualities and their relationships during the event. Moreover, for an object, in the environment, that has some ***Function***, its ***Manifested behavior*** in an event is the evolution of the object's

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[1] Web Ontology Language, https://www.w3.org/OWL/

qualities and of the relationships holding among that object and any other object participating in the event.

The relationships of some concepts in the standard, DOLCE, CORA, are presented in the remaining parts. In Figure 1, are depicted concepts and its relationships of *Interaction*, which are part of the axioms of the ontology. For example: *Interaction is the quality of* some *Event* ; *Manifested behavior is a subClass of Interaction*.
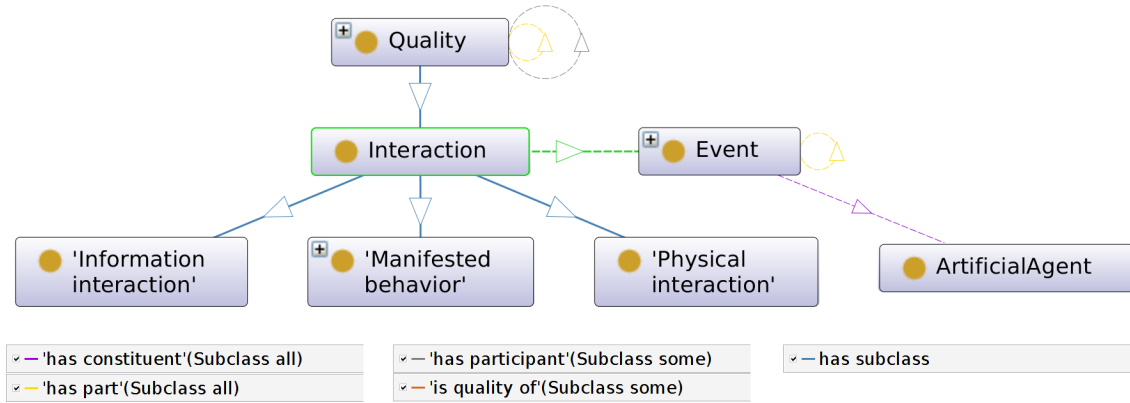

Figure 1: AuR ontology diagram of the concept *Interaction*.

In figure 2, are depicted concepts and their relationships of *Object-centered environment*, which is part of the axioms of the ontology. For example: *Object-centered environment is a participant in* some *Event* ; *Object-centered environment has participant* some *Physical object*.
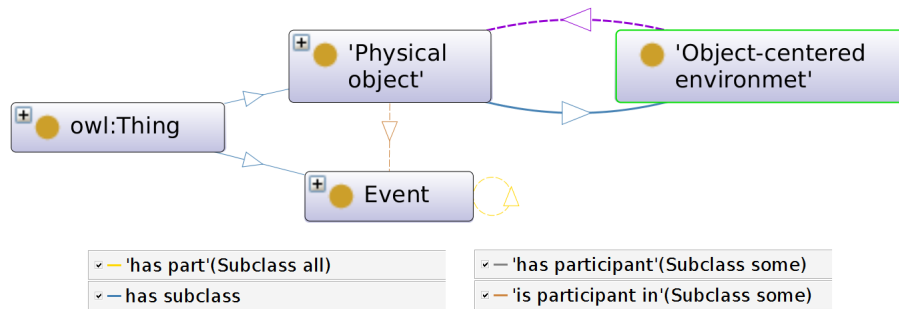

Figure 1: AuR ontology diagram of the concept *Object-centered environment*.

Section 4 presents a short description of a case study that implements some of the concepts described in AuR ontology, CORA and DOLCE.

4. AuR case study

To validate the standardized concepts, a motivation example is presented. Suppose a dual-arm manipulator (rA), that is mounted on a table and has to prepare a cup of coffee, depicted in figure 3. The cup is on a shelf, far from the table itself. A mobile manipulator robot (rB) helps rA by picking up the cup and placing it in a position that rA can reach [6].
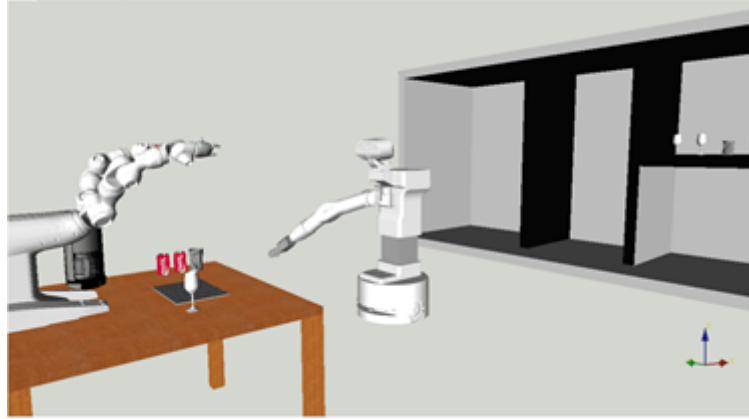
Figure 3: A two-robot table-top manipulation task in an indoor scenario.
This scene has been generated using The Kautham Project [7]

To correctly carry out the task, the two robots should have the same knowledge about the environment, its entities, and each other's capabilities. They also need a common vocabulary to share this information. In particular, they need the concepts and relations standardized in the AuR standard and in CORA [1]. For example, they need the CORA concept of **Robot**, which depicts the features of each agent involved in the use case. **RobotGroup** defines the robots as a group that must cooperate to fulfill the mission while **Plan** describes the set of actions that each robot should perform to accomplish its own assignment. Finally, every decision is communicated to the other robot through a **Communication Element** that guarantees cooperation and collaboration. From POS [1], the case study inherits the concepts of **Position**, **Orientation**, and **Pose** measures useful to describe the location of objects in the world. From the current standard, **Interaction** models the robot cooperation between each other and with the objects of the environment. E.g., when rB is detecting the cup, an indirect **Information Interaction** arises between the robot and the cup. When it picks up the cup, a direct **Physical Interaction** arises. **Object-centered environment**, instead, represents the physical object whose location is the spatial area that robots can potentially reach. It includes the set of material components that are the objects participating in the event (e.g., the cup, the shelf, and the table). In this context, every robot is equipped with an **Object-centered Environment Description** of the environment in which it is operating: the table setup for rA and its surroundings for rB. Such characterizations will be exhaustive enough to make robots cooperate when sharing tasks and space. Finally, multiple examples can demonstrate the need for **Manifested behavior**. When navigating, the manifested behavior of rB includes the change of both its location and spatial relationships. It also depicts the quality of the robot sensors, which may change during the exploration of the environment. When rB picks and places the cup, its manifested behavior includes the evolution of both the robot's location quality and the spatial relationships. It also models the action of getting in contact with the item, maintaining this contact during navigation, and losing it when the robot puts the object on the table. Similar considerations characterize the manifested behavior of rA.

5. Conclusion and current status

One of the first benefits of the aforementioned IEEE standard has been the high level of cooperation among different sectors such as academia and industry, to come up with a

common ground to describe autonomous robotics, zooming in from a general standard on robotics CORA on the specificities of the autonomous robot's domain.

The IEEE development process has allowed us to share different viewpoints and to identify the features and the essential components to describe autonomous robots. As a result, a specific ontology for autonomous robotics has been developed, paying attention to the structural, behavioral and functional aspects of this kind of systems. This ontology sets the ground for future specifications of the requirements and tasks to be fulfilled when describing and designing any autonomous robot.

As a final part of the developing process of IEEE standards, in April 2021, voting members of the Working Group voted to move the draft to SA Ballot. Shortly after, voting members of the IEEE RAS Standards Committee (SC) voted to move the draft to SA Ballot. Invitations were sent to participants who have indicated an interest in IEEE myProject™ for the project, to receive ballot invitations and other notifications. After that, individuals enrolled in the ballot group to participate in the SA Ballot. In May 2021, a Mandatory Editorial Coordination (MEC) was completed prior to the initiation of the SA ballot in June 2021. The working group has been polishing the architecture and vocabulary in order to publish the standard by the end of 2021.

Acknowledgments

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