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IEEE Standard for Autonomous Robotics (AuR) Ontology

IEEE Robotics and Automation Society

Developed by the
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IEEE Std 1872.2™-2021

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Standing Committee for Standards
of the
IEEE Robotics and Automation Society

Approved 23 September 2021

IEEE SA Standards Board

Abstract: This standard extends IEEE Std 1872™-2015, IEEE Standard for Ontologies for Robotics and Automation, to represent additional domain-specific concepts, definitions, and axioms commonly used in Autonomous Robotics (AuR). This standard is general and can be used in many ways—for example, to specify the domain knowledge needed to unambiguously describe the design patterns of AuR systems; to represent AuR system architectures in a unified way; or as a guideline to build autonomous systems consisting of robots operating in various environments.

Keywords: automation, autonomous robots, IEEE1872.2™, ontology, robotics

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The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

PDF: ISBN 978-1-5044-7988-2 STD24961
Print: ISBN 978-1-5044-7989-9 STDPD24961

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Introduction

This introduction is not part of IEEE Std 1872.2-2021, IEEE Standard for Autonomous Robotics (AuR) Ontology.

There is an increasing demand from government and private agencies alike to use autonomous robots like unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), and autonomous underwater vehicles (AUVs) for tasks such as homeland security, reconnaissance, search and rescue, surveillance, data collection, and urban planning. Ontologies in autonomous robotics (AuR) provide a unified way of representing the underlying semantics that defines the vocabulary, thereby allowing precise knowledge transfer for problem solving and unambiguous communications between heterogeneous autonomous systems. Creating ontologies in autonomous robotics may have a huge impact directly and indirectly on all robotics and automation (R&A) domains. The main benefit of a domain ontology is to set standard definitions of shared concepts identified in the requirement phase, as well as to define relations between the concepts and their properties. Well-founded ontologies capture the domain terminology in both semantic and logical frameworks, which allows building a formal theory of the domain. This theory provides a much harder limit to the possible interpretations of the terms in the domain, constituting a more preferable tool for standardization work than a simple list of terms/definitions written in natural language. Furthermore, an ontology may serve further purposes as systems synthesis and operation. In the tradition of symbolic artificial intelligence, a domain ontology provides a clear set of symbols to be used in reasoning mechanisms for autonomous systems, such as classification, inference, and planning. The domain structure encoded in ontologies can be expected to provide the blueprint for application programming interfaces (APIs) in domain-specific software packages and model for databases. Another potential area to use AuR ontologies is in agent communications, where an ontology provides vocabulary and precise semantics. For instance, future unmanned systems may need to work in teams and communicate with other unmanned vehicles to share information and coordinate activities.

This standard is a follow-on to IEEE Std 1872™-2015 (IEEE Standard Ontologies for Robotics and Automation). IEEE Std 1872 CORA was created to support follow-on standards such as this one (refer to S.R. Fiorini et al [B1]).[1] CORA was developed to be a high-level standard from which domain-specific efforts could build from. 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, it was expected that sub-groups would emerge that would specialize the concepts represented in CORA. The groups are organized in two layers. The middle-layer groups develop ontologies regarding transversal notions in robotics. Lower-layer groups concern specific domains in robotics and use concepts from CORA and middle-layer groups.

The Robot Task Representation Sub-Group (P1872.1) develops 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 sub-goals that enables the human/robot to accomplish the outcome at a specific instance in time. In order to accomplish this, there is a need for a standard providing an explicit knowledge representation for robot tasks.

The AuR Sub-Group aims to create ontologies that specify the domain knowledge needed to build autonomous robots, operating in the air, ground, and underwater environments. Benefits include having a common knowledge base for the development and integration of systems from different manufacturers, which may enable interoperability and catapult design to a new level. The AuR Working Group intends to extend CORA and define domain-specific concepts and axioms. This document describes the AuR Working Group's analysis of various autonomous robots (flying, ground, underwater, etc.) to identify the components necessary to endow robots with autonomy—including the hardware and software.

[1] The numbers in brackets correspond to those of the bibliography in Annex D.

Ancillary Open Source

Participants in the IEEE 1872.2 Working Group have created ancillary files developed separately from this standard, including OWL files, and will contribute the files to the IEEE SA Open Source Platform in the project located at: <https://opensource.ieee.org/aur/owl>. These files will be available for public input, but will not be considered part of IEEE's standards development activities.

Contents

IEEE Standard for Autonomous Robotics (AuR) Ontology

1. Overview

1.1 Scope

This standard is a logical extension to IEEE Std 1872™-2015, IEEE Standard for Ontologies for Robotics and Automation.[1] The standard extends the core ontology for robotics and automation (CORA) ontology by defining additional ontologies appropriate for Autonomous Robotics (AuR) relating to the following:

a) The core design patterns specific to AuR in common robotics and automations (R&A) sub-domains
b) General ontological concepts and domain-specific axioms for AuR
c) General use cases and/or case studies for AuR

1.2 Purpose

The purpose of the standard is to extend the CORA ontology to represent more specific concepts and axioms that are commonly used in autonomous robotics. The extended ontology specifies the domain knowledge needed to build autonomous systems comprised of robots that can operate in all classes of environments. The standard provides a unified way of representing autonomous robotics system architectures across different 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 all classes of environments without continuous explicit external guidance.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).[2,3]

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

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[1] Information on references can be found in Clause 2.
[2] The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.
[3] The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 1872™-2015, IEEE Standard Ontologies for Robotics and Automation.[4,5]

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[6]

3.1 Background of autonomous robotics

"Autonomy is the extent to which a robot can sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal (either given to or created by the robot) without external control" (Beer, Fisk, and Rogers [B2]). AuR has identified the components of autonomous robotics, such as sensors, estimation, plans, actuators, control, processing elements, and communication elements.

actuator: An entity that makes some change.

communication element: An entity that passes information between the sender and the recipient.

control: Respond to the input in order to reach some desired output.

estimation: A process to infer the state, based on sensor information, previous knowledge, and some algorithm.

plan: A proposed arrangement in advance that considers a list of intended steps/actions associated with timing and resources for doing or achieving a goal in the future.

processing element: A computational element with processing capability upon which software artifacts may be deployed for execution.

sensor: An entity that measures some property of a phenomenon that may be altered/changed by some stimulus to produce, in general, a quantity.

3.2 Autonomous robotics (AuR) ontology definitions

The following definitions are part of the base concepts of the Autonomous Robotics Ontology. Those are formally defined in 4.4, where the AuR Ontology axioms are presented.

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[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
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[6] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

architectural behavior: The architectural behavior of an object is the internal organization of the flow of information that determines the object's actions. Reactive behavior, deliberative behavior, and cognitive behavior are subtypes of architectural behavior.

behavior: The behavior of an object is an element of one of the following classes: manifested behavior, engineering behavior, emergent behavior, architectural behavior, or rule behavior.

emergent behavior: The emergent behavior of an object is the set of relationships chosen to describe the object relevant interactions.

engineering behavior: The engineering behavior of an object is the description of the manifested behavior given by a set of state variables.

function: The function of an object is the role that the manifested behavior of the object plays in the event.

function execution: A function execution is an event in which the manifested behavior of an object plays a role with respect to a goal.

information interaction: An information interaction is an interaction in which there are no direct exchanges of physical forces.

interaction: 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.

manifested behavior: The manifested behavior of an object in an event is the evolution of the object's qualities and of the relationships holding among that object and any other object participating in the event.

object-centered environment: Given an event, the object-centered environment of an object in the event is a physical object comprising all the entities (with their relationships) that participate in the event and that could potentially interact with the object during the time of the event.

object-centered environment description: The object-centered environment description of an object in an event is a description of the object-centered environment in that event.

object-centered external environment description: The object-centered external environment description (EED) of an object in an event is the description of the object-centered environment without the information about the object itself.

physical interaction: An interaction in which there are direct exchanges of physical forces.

rule behavior: The rule behavior of an object is the set of rules and decision methods that an agent has and can possibly use to decide its actions.

3.3 Acronyms and abbreviations

AuR	autonomous robotics
BFO	basic formal ontology
CORA	core ontology for robotics and automation
DOLCE	descriptive ontology for linguistic and cognitive engineering
DUL	DOLCE ultralite
FOL	first-order logic
OWL	web ontology language
R&A	robotics and automation

SLAM simultaneous localization and mapping

SUMO suggested upper merged ontology

4. Concepts and axioms

4.1 Overview

This clause formally defines the main concepts and the axioms for the Autonomous Robotics Ontology of the terms and definitions of Clause 3.

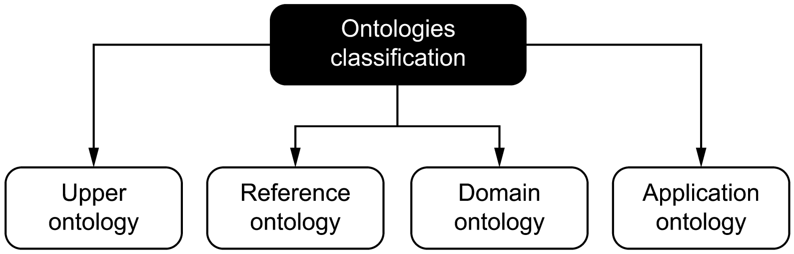
In detail, an ontology is defined to be a logical theory consisting of a set of formulas whose models approximates as well as (formally) possible the intended models, i.e., those models that satisfy the conceptualization and the ontological commitments (Guarino, Oberle, and Staab [B3]).[7]

Being a logical theory, an ontology consists of individuals, classes, relations, and axioms. The exact list changes depending on the specific logic language one adopts. Usually, an ontology is given in first-order logic (FOL) (Smullyan [B4]), or in web ontology language (OWL) (Antoniou and van Harmelen [B5]). Individuals are the objects in the ontology, the things the ontology is about. Classes are properties and are used to identify the individuals that satisfy that property. Functions provide ways to identify and relate individuals. Relations are connections across individuals or classes. Axioms are expressions in the language that use the previous elements to state what is true in the ontology.

Ontology classifications usually divide ontological systems in upper-level, reference, domain, and application (see Figure 1). An upper-level ontology focuses on broadly applicable concepts such as object, event, state, quality, and high-level relations like part hood, constitution, participation, and dependence. Examples are the suggested upper merged ontology (SUMO) (Niles and Pease [B6]), Cyc ontology (Lenat and Guha [B7]), the basic formal ontology (BFO) (Arp, Smith, and Spear [B8]), and the DOLCE foundational ontology with its extension DOLCE+DnS Ultralite (DUL) (Masolo et al. [B9]). A reference ontology is an ontology that focuses on a discipline being highly reusable within the discipline [medical, engineering, enterprise, etc. (Guarino, Oberle, and Staab [B3])]. When the ontology focuses in a more limited area, e.g., autonomous or collaborative robotics, it is called a domain ontology. This type of ontology contains vocabulary about concepts within a domain and their relationships; about the activities taking place in that domain; and about the theories and elementary principles governing that domain. The concepts in domain ontologies are usually specializations of concepts already defined in upper-level and in reference ontologies, and the same could occur with the relations. Some examples are the core ontology for robotics and automation (CORA) (IEEE Std 1872-2015) and the ontology presented in this standard.[8] An application ontology contains all the definitions needed to model the knowledge required for a particular application, e.g., robot grasping system or simultaneous localization and mapping (SLAM).

This clause starts with an overview of the existing relations between AuR ontology and CORA (in 4.2). Then, once identified a representative set of definitions of Clause 3, the clause presents usage examples of each term and its rationale. Moreover, an ontological implementation is included, which contains examples of integration of the AuR ontology with the upper ontologies, DUL, and SUMO. First, those upper-level concepts useful for the integration are introduced (in 4.3). Then, the resulting axioms (in 4.4) are proposed and described using OWL, including examples and rationale. Note that even though the proposed ontology is based on some general terms (primitives), it does not commit to any specific upper-level ontology.

[7] The numbers in brackets correspond to those of the bibliography in Annex D.
[8] Information on references can be found in Clause 2.



NOTE—Starting from the left, this figure illustrates the most general to the most specific type of ontology.[9]

Figure 1— Ontologies classification based on hierarchy

4.2 CORA (IEEE Std 1872-2015) related concepts

The core ontology for robotics and automation, CORA, defined the main, most general concepts, relations, and axioms of robotics and automation. The AuR ontology identified related concepts that were extended to the needs of this standard.

The AuR ontology broadened the CORA definition of **physical environment** by **object-centered environment** to include not only the region where the object is placed, but also other objects and, most importantly, the interactions (in the AuR ontology sense) that may take place in an event. Moreover, the AuR ontology considers the description of the environment as an information object when it relates to the description of the object and everything around it (object-centered environment description). And separately, the description of only the external parts, i.e., not including the object itself (object-centered external environment description).

The AuR ontology definition extends the CORA definition of interaction to focus not only on the agents involved in the interaction but also in the results of the interaction, as changes both in the objects' qualities and in the relationships among the objects in the interactions during an event. Moreover, the AuR ontology further splits the concept of interaction, where a distinction is made when there exists physical interaction, and when it does not exist, which is defined as information interaction.

CORA specified the robotic environment, as a physical environment equipped with robotics systems. This definition specified the physical environment as related to the robotics systems, to include robots as a part of the environment. In this standard, this definition becomes redundant in the IEEE 1872.2 object-centered environment when the object becomes the robotic system itself. In the AuR ontology, this definition becomes redundant in the object-centered environment when the object becomes the robotic system itself.

4.3 Upper-level concepts

Useful DUL and SUMO upper-level concepts follow to provide insightful examples of integration between this proposal, DUL, and SUMO. Definitions are extracted from the respective public available formal ontologies (DUL and SUMO).[10,11] In the integration process, every term in 4.3.1 is treated equivalently to the one listed in the same slot in 4.3.2 (e.g., **Information object** is equivalent to **Proposition**). More details can be found in Annex B.

There are lots of relationships that have been used from upper-level DUL and SUMO ontologies. Some of them are general (especially the ones presented in DUL such as 'is participant in' and 'has constituent,' etc.) and they have been used in several positions wherever fits.

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[9] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.
[10] The DOLCE+DnS Ultralite (DUL) ontology is available at:
http://ontologydesignpatterns.org/wiki/Ontology:DOLCE+DnS_Ultralite.
[11] The Suggested Upper Merged Ontology (SUMO) is available at: https://www.ontologyportal.org.

4.3.1 Useful DUL concepts

The following DUL concepts have been exploited to define the AuR-DUL integration:

event: Any physical, social, or mental process, event, or state.

goal: The description of a situation that is desired by an agent, and usually associated to a plan that describes how to actually achieve it.

information object: A piece of information, such as a musical composition, a text, a word, a picture, independent from how it is concretely realized.

physical object: Any object that has a proper space region. The prototypical physical object has also an associated mass, but the nature of its mass can greatly vary based on the epistemological status of the object (scientifically measured, subjectively possible, imaginary).

quality: Any aspect of an entity (but not a part of it) that cannot exist without that entity. For example, the way the surface of a specific physical object looks like, or the specific light of a place at a certain time, are examples of quality, while the encoding of a quality into e.g., a physical attribute should be modeled as a region.

role: A concept that classifies an object.

4.3.2 Useful SUMO concepts

The following SUMO concepts have been exploited to define the AuR-SUMO integration:

attribute: Qualities that cannot or are chosen not to reify into subclasses of.

case role: The class of predicates relating the spatially distinguished parts of a process.

corpuscular object: A self-connected object whose parts have properties that are not shared by the whole.

process: The class of things that happen and have temporal parts or stages.

proposition: Propositions are abstract entities that express a complete thought or a set of such thoughts. A proposition is a piece of information, an abstraction that may have multiple representations: strings, sounds, icons, etc.

4.3.3 Useful DUL and SUMO relationships

The following DUL relationships have been exploited to define the AuR DUL axioms:

hasConstituent: 'Constituency' depends on some layering of the world described by the ontology. For example, scientific granularities (e.g., body-organ-tissue-cell) or ontological 'strata' (e.g., social-mental-biological-physical) are typical layerings. Intuitively, a constituent is a part belonging to a lower layer. Since layering is actually a partition of the world described by the ontology, constituents are not properly classified as parts, although this kinship can be intuitive for common sense. A desirable advantage of this distinction is that a discussion can be had, for example, of physical constituents of non-physical objects (e.g., systems), while this is not possible in terms of parts.

hasPart: A schematic relation between any entities.

hasParticipant: A relation between an object and a process.

isClassifiedBy: A relation between a concept and an entity.

isParticipantIn: A relation between an object and a process.

isQualityOf: A relation between entities and qualities.

The following SUMO relationships are used for the SUMO axioms:

agent: (agent ?PROCESS ?AGENT) means that ?AGENT is an active determinant, either animate or inanimate, of the process ?PROCESS, with or without voluntary intention.

involvedInEvent: (involvedInEvent ?EVENT ?THING) means that in the process ?EVENT, the Entity ?THING plays some case role.

subProcess: (subProcess ?SUBPROC ?PROC) means that ?SUBPROC is a subprocess of ?PROC. A subprocess is understood as a temporally distinguished part (proper or not) of a process.

The relationships that do not exist in SUMO have been inherited from DUL.

More information about the concepts used from upper-level ontologies can be found in Annex A. Annex B shows the method adopted to deduce the mapping between DUL and SUMO upper-level ontologies.

4.4 Autonomous robotics (AuR) concepts, hierarchy, and axioms

From Clause 3, a set of representative definitions have been considered. For each definition, its DUL and SUMO hierarchies follow, together with the axioms required for the integration. Hierarchies and axioms are presented using Protégé (Musen [B10]). Moreover, examples are included to make clearer and easier the understanding and reusing of each definition. With this goal, every rationale is also detailed.

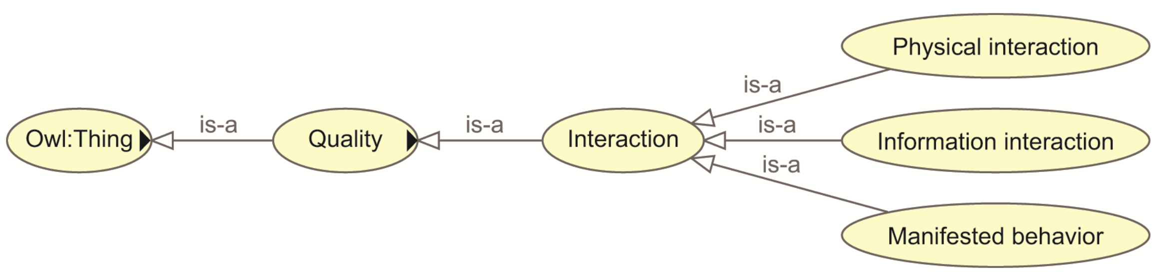
4.4.1 Interaction

This subclause includes the hierarchy and axioms of **Interaction**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept follows:

a) DUL

1) Hierarchy

The DUL hierarchy of the **Interaction** concept is shown as follows:



That means:

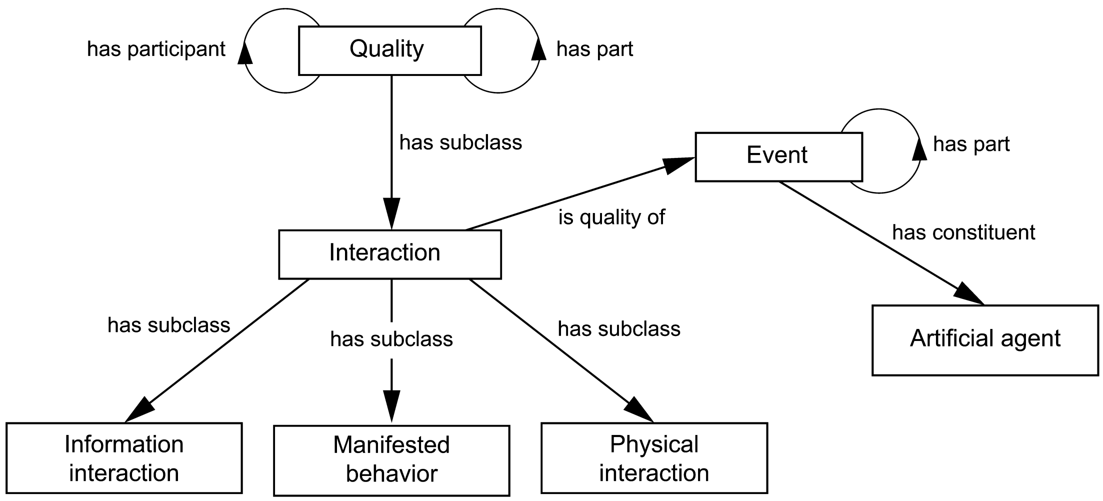
Interaction is a subclass of **Quality**.

Interaction is a superClass of the following:

— **Information interaction**
— **Physical interaction**
— **Manifested behavior**

2) Axioms

The DUL axioms of **Interaction** are shown as follows:



These axioms include the following upper-level axioms from DUL:

Quality *has constituent* **Quality**
Quality *has part* **Quality**
Event *has part* **Event**
Event *has participant* **Artificial agent**

and the following axioms proper of **Interaction**:

Interaction *is a quality* of some **Event**
Interaction *has constituent* **Quality**
Interaction *has part* **Quality**

Then, the axioms for **Physical interaction** and **Information interaction** can be deduced as follows:

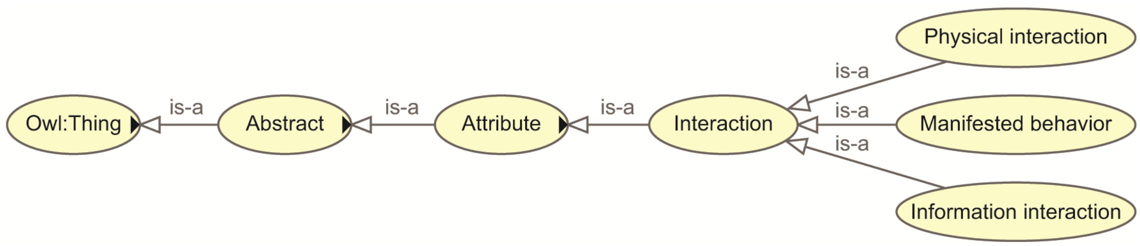
Physical interaction *is a quality* of some **Event**
Physical interaction *has constituent* **Quality**
Physical interaction *has part* **Quality**

Information interaction *is a quality* of some **Event**
Information interaction *has constituent* **Quality**
Information interaction *has part* **Quality**

b) SUMO

1) Hierarchy

As shown in Annex B, DUL **Quality** is equivalent to SUMO **Attribute**. The SUMO hierarchy for **Attribute** follows. From this information, the overall SUMO hierarchy for **Interaction** becomes easily deductible as:



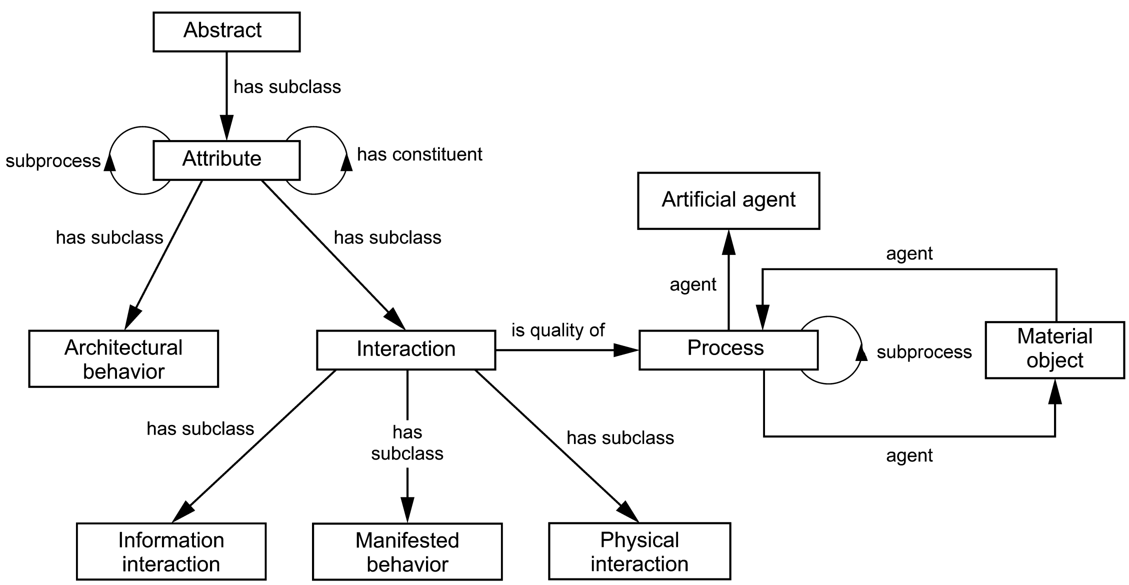
Interaction is a subclass of Attribute.

Interaction is a superClass of the following:

- **Information interaction**
- **Physical interaction**
- **Manifested behavior**

2) Axioms

DUL **Quality** is equivalent to SUMO **Attribute**. Moreover, DUL **Event** is equivalent to SUMO **Process**. As a result, the following SUMO axioms are applicable:



The SUMO axioms of **Interaction** are as follows:

Attribute *has constituent* **Attribute**
Attribute *subprocess* **Attribute**
Process *subprocess* **Process**
Process *agent* **Artificial agent**

and the following axioms proper of **Interaction**:

Interaction *is a quality* of some **Process**
Interaction *has constituent* **Attribute**
Interaction *subprocess* **Attribute**

Then, the axioms for **Physical interaction** and **Information interaction** can be deduced as follows:

Physical interaction *is a quality* of some **Process**
Physical interaction *has constituent* **Attribute**
Physical interaction *subprocess* **Attribute**

Information interaction *is a quality* of some **Process**
Information interaction *has constituent* **Attribute**
Information interaction *subprocess* **Attribute**

c) Examples

1) Interaction

i) The book has been on the table for 10 min (interaction between the book and the table such that their relationship has not changed in the given 10 min).

ii) As Mary walked into the room the robot constantly moved close to her (interaction during the event such that the distance relationship between Mary and the robot reduced at a constant rate).

iii) The robot detected a crack in the pipe during an inspection (during an inspection event the interaction between the robot and the pipe moved from zero to one crack flag).

2) Physical interaction

The robot picks up the mug (this is a direct interaction between the robot and the mug during the picking up event).

NOTE—An exchange of magnetic forces is a case of physical interaction.

3) Information interaction

A robot visually searching for cracks in a pipe (this is an indirect interaction between the robot and the pipe during the inspection event).

NOTE—Most interactions are both physical and information.

d) Rationale

Interaction—Interaction refers to the way the relationships among objects change over time. This means that the interaction among two or more objects is a quality of the event in which they participate. The very happening of an event implies the existence of an interaction among the participants. The relationships among the objects can be of different types: relative movement, exertion of physical force, exchange of information etc. but not negative. For instance, "the robot is not seeing (or cannot see) the mug" is not expressing a relationship relevant for an interaction. An interaction does not require goals, purposes, or intentions.

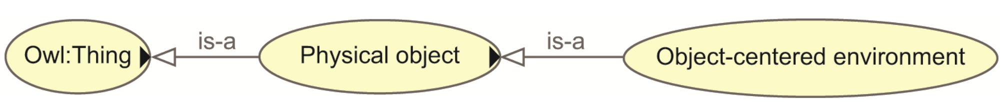
4.4.2 Object-centered environment

This subclause includes the hierarchy and axioms of **Object-centered environment** expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL

1) Hierarchy

The DUL hierarchy of the **Object-centered environment** concept follows:

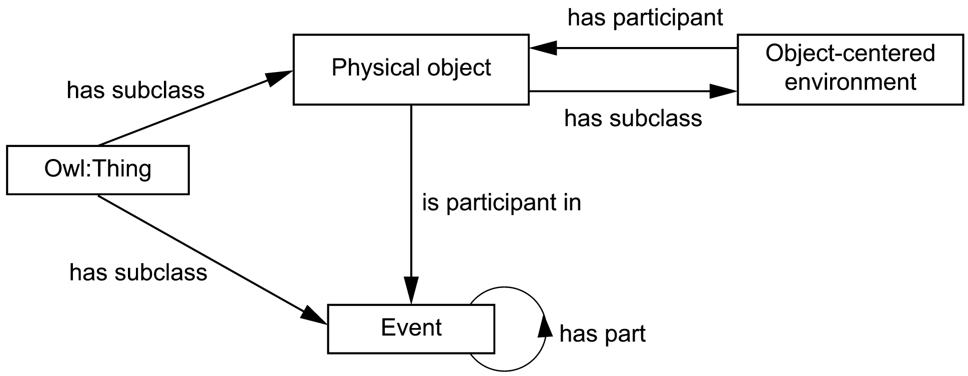


That means:

Object-centered environment is a subclass of **Physical object**

2) Axioms

The DUL axioms of **Object-centered environment** are as follows:



It exploits the following upper-level axioms from DUL:

Physical object *is participant in* some **Event**
Event *has part* **Event**

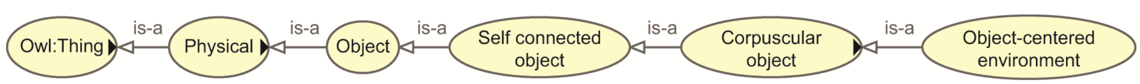
and the following axioms specific of **Object-centered environment:**

Object-centered environment *is participant in* some **Event**
Object-centered environment *has participant* some **Physical object**

b) SUMO

1) Hierarchy

As shown in Annex B, DUL **Physical object** is equivalent to the SUMO **Corpuscular object**, whose hierarchy is as follows:

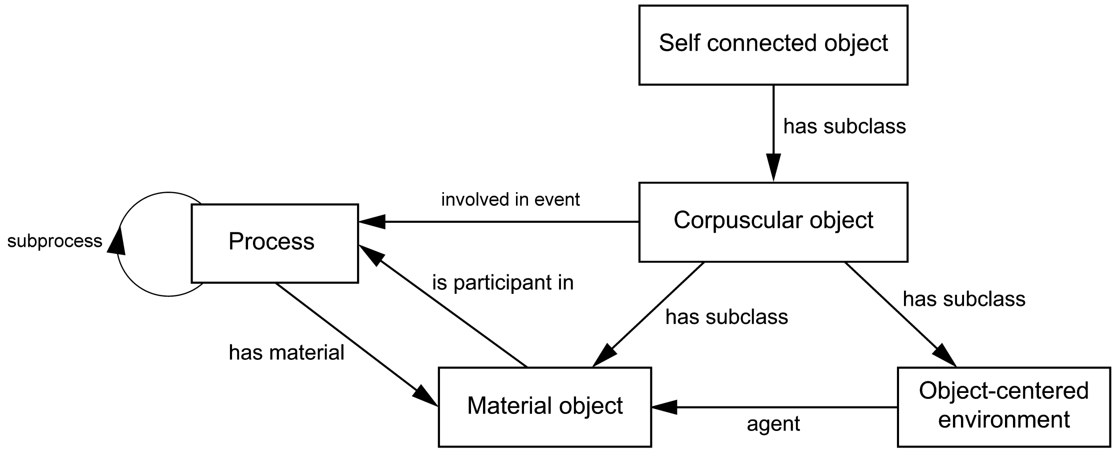


The SUMO hierarchy for **Object-centered environment** can be deduced similarly to the way used for **Interaction**:

Object-centered environment is a subclass of **Corpuscular object**

2) Axioms

DUL **Physical object** is equivalent to the SUMO **Corpuscular object.** Moreover, DUL **Event** is equivalent to SUMO **Process**. Thus:



It exploits the following upper-level axioms from SUMO:

Corpuscular object *involved in event* some **Process**
Process *subprocess* **Process**

and the following axioms specific of **Object-centered environment**:

Object-centered environment *involved in event* some **Process**
Object-centered environment *agent* some **Material object**

c) Examples

1) The environment of an industrial robotic arm in an event is the physical object that has as location, the spatial area that the robot can potentially reach during the time of the event, and has material components, the objects participating in the event with which the robot could potentially interact during the event.

2) The environment of a robotic system composed of a rover and a drone in an event includes the environment of the rover and the environment of the drone in that event.

3) A vacuum cleaner robot and a surveillance robot have different environments even when they are in the same location (say, the same room) because they have different navigation and perception systems, and thus can potentially interact with different entities.

d) Rationale

The environment in the sense of the AuR ontology standard is centered in a given object. Despite the world is 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.

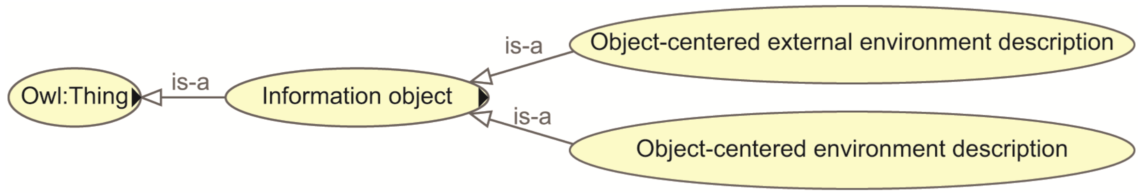
4.4.3 Object-centered environment description and Object-centered external environment description

This subclause includes the hierarchy and axioms of **Object-centered environment description** and **Object-centered external environment description**, expressed in DUL and SUMO, respectively. Usage examples and rationales of these concepts is as follows:

a) DUL

1) Hierarchy

The DUL hierarchy of **Object-centered environment description** and **Object-centered external environment description** concepts is as follows:



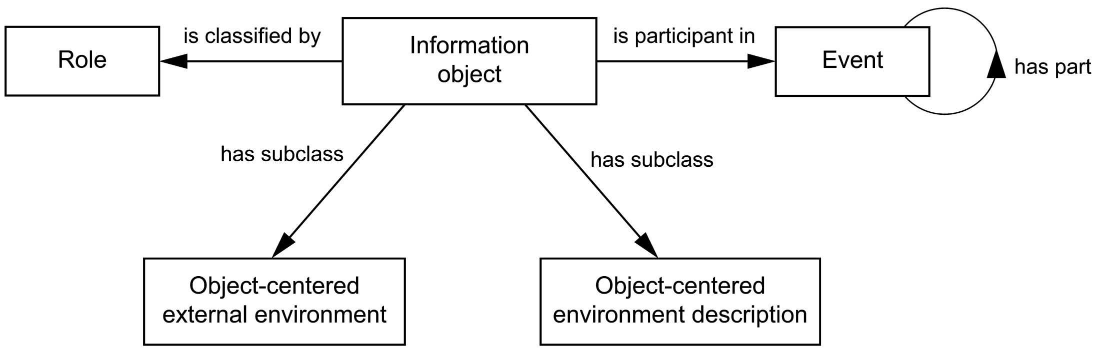
That means:

Object-centered environment description is a subclass of **Information object**

Object-centered external environment description is a subclass of **Information object**

2) Axioms

The DUL axioms of **Object-centered environment description** and **Object-centered external environment description**, are as follows:



It exploits the following upper-level axioms from DUL:

Information object *is classified by* some **Role**
Information object *is participant in* some **Event**

and the following axioms specific of **Object-centered environment description** and **Object-centered external environment description**:

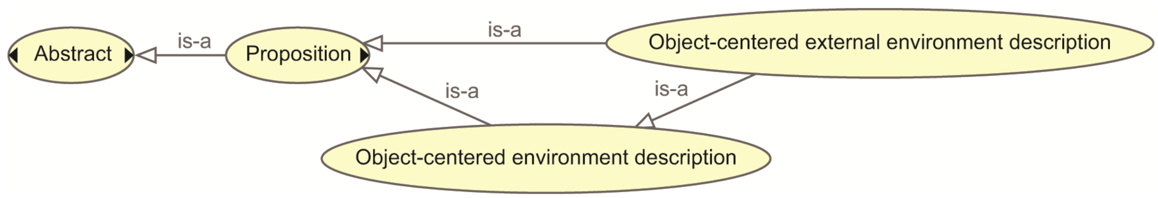
Object-centered environment description *is classified by* some **Role**
Object-centered environment description *is participant in* some **Event**

Object-centered external environment description *is classified by* some **Role**
Object-centered external environment description *is participant in* some **Event**

b) SUMO

1) Hierarchy

As shown in Annex B, DUL **Information object** is equivalent to SUMO **Proposition**, whose hierarchy follows:



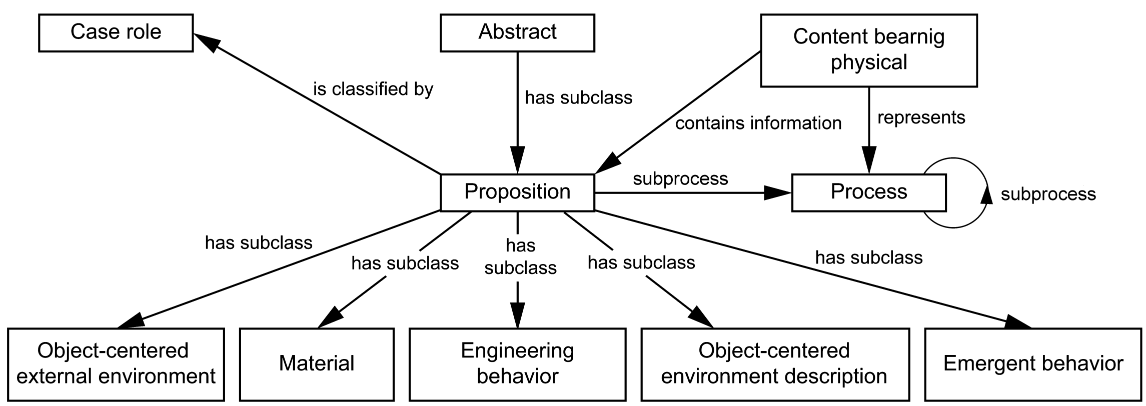
The SUMO hierarchy for **Object-centered environment description** and **Object-centered external environment description** become:

Object-centered environment description is a subclass of **Proposition**

Object-centered external environment description is a subclass of **Proposition**

2) Axioms

DUL **Information object** is equivalent to SUMO **Proposition.** Moreover, DUL **Role** is equivalent to SUMO **Case Role** and DUL **Event** is equivalent to SUMO **Process.** The following SUMO axioms for **Object-centered environment description** and **Object-centered external environment description** result:



It exploits the following upper-level axioms from SUMO:

Proposition *is classified by* some **Case role**
Proposition *subprocess* some **Process**

and the following axioms specific of **Object-centered environment description** and **Object-centered external environment description**:

Object-centered environment description *is classified by* some **Case role**
Object-centered environment description *subprocess* some **Process**

Object-centered external environment description *is classified by* some **Case role**
Object-centered external environment description *subprocess* some **Process**

c) Example

Consider a factory, where the robot can move. At a first thought, the environment can be seen as the whole factory. The environment can be modeled with an RGB-D sensor that moves along the factory. In this sense there is an object centered environment description of the factory, obtained with that object (RGB-D sensor). Then, the robot, or several, will use the representation of the environment seen by the camera, with a given ground truth. The robot, or robots, will move within the factory and need to register its seen object centered environment description, e.g., obtained from a laser, with the ground truth object-centered environment description (obtained from the RGB-D sensor).

d) Rationale

The environment description of an industrial robotic arm is what is known about the environment. Two robots may have the same (or almost the same) environment but use different environment descriptions, as the description of the environment may depend on the robots' capabilities (e.g., perception, reasoning, acting) and the robot's knowledge base.

NOTE—The object internal environment is simply the state of the object; the object internal environment description is the description of the state of the object.

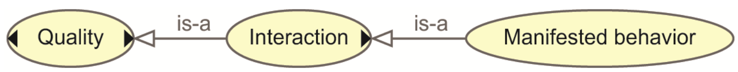
4.4.4 Manifested behavior

This subclause includes the hierarchy and axioms of **Manifested behavior**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL

1) Hierarchy

The DUL hierarchy of **Manifested behavior** follows:



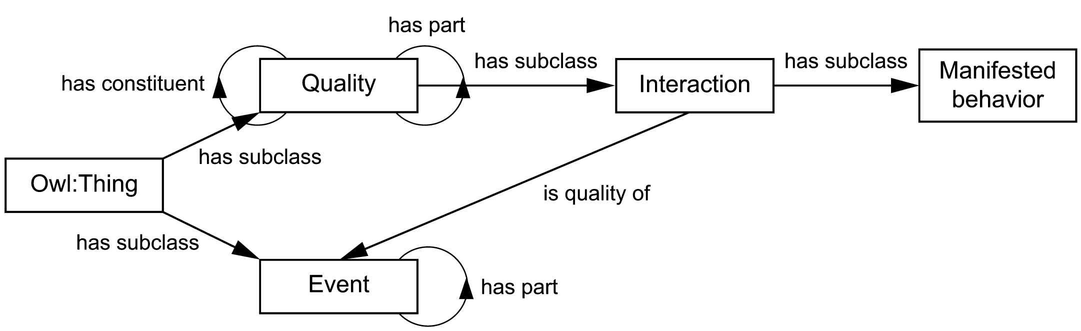
That means:

Manifested behavior is a subclass of **Interaction**

where **Interaction** has been defined in 4.4.1 as a subclass of DUL **Quality**

2) Axioms

The DUL axioms of **Manifested behavior** are as follows:



It exploits the following upper-level axioms from DUL:

Manifested behavior *has part* only **Quality**
Manifested behavior *has constituent* only **Quality**
Manifested behavior *is quality of* some **Event**

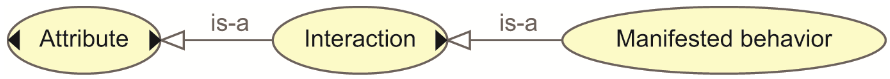
b) SUMO

1) Hierarchy

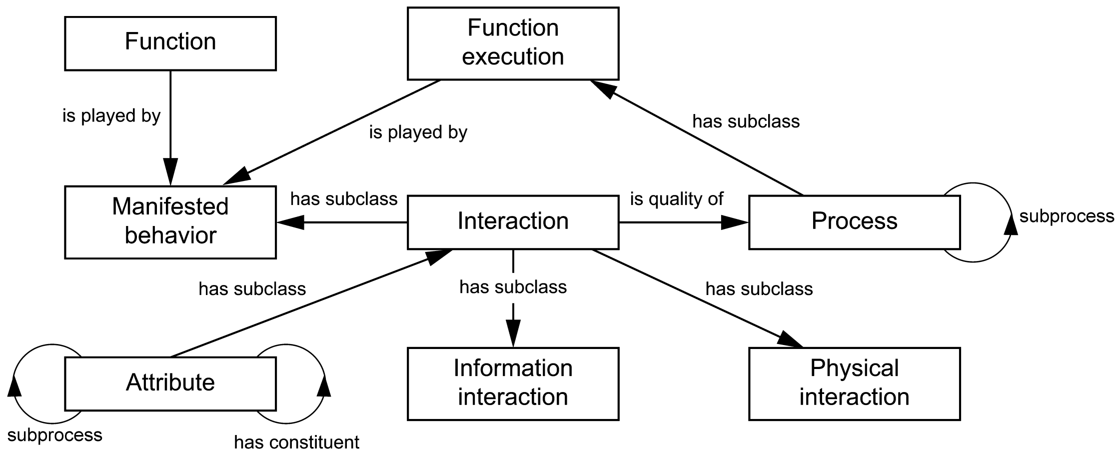
As for DUL:

Manifested behavior is a subclass of **Interaction**

From 4.4.1, **Interaction** is a subclass of SUMO **Attribute**. The resulting hierarchy is as follows:



2) Axioms



Manifested behavior *subprocess* only **Attribute**
Manifested behavior *has constituent* only **Attribute**
Manifested behavior *is quality of* some **Process**

c) Example

1) An inspection robot navigates along pipes in a facility to detect cracks in the pipes. The manifested behavior of the robot in the inspection event includes the change of the robot's battery charge level, which decreases as the robot travels (the battery charge level is a quality of the robot). It also includes the change of the robot‘s location and spatial relationships that change during robot navigation; the location of the robot is a quality of the robot; and the spatial relationships are (relational) qualities of the robot. The manifested behavior also includes the quality of the robot's sensors, which may vary (change) or remain stable (no change) during the inspection.

2) A cleaning robot acts in a domestic environment and has the task to clear a table of trash located on top of it. The manifested behavior of the robot in the event of moving an item into the trash bin includes the evolution of the robot's location quality and the spatial relationships that change over time, such as that the robot is first near the table but later near the trash bin. It also includes the relationship of getting in contact with the item, of maintaining this contact relationship during navigation, and of losing it when the robot drops the item into the trash bin.

d) Rationale

The manifested behavior depends on the object's environment and is a restriction of the interaction in which the object participates. A manifested behavior is object-centered and does not depend on an observer.

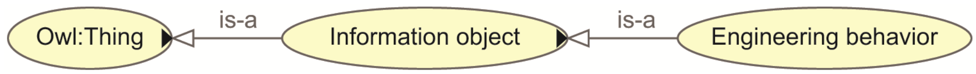
4.4.5 Engineering behavior

This subclause includes the hierarchy and axioms of **Engineering behavior**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL

1) Hierarchy

The DUL hierarchy of **Engineering behavior** follows:

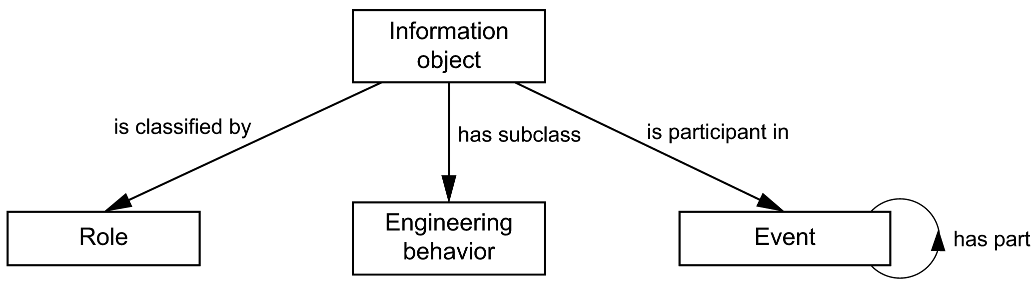


That means:

Engineering behavior is a subclass of **Information object**

2) Axioms

The DUL axioms of **Engineering behavior** are as follows:

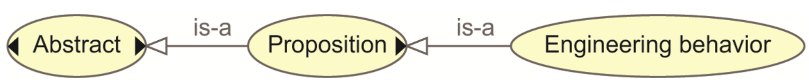


It exploits the following upper-level axioms from DUL:

Engineering behavior *is classified by* some **Role**
Engineering behavior *is participant in* some **Event**

b) SUMO

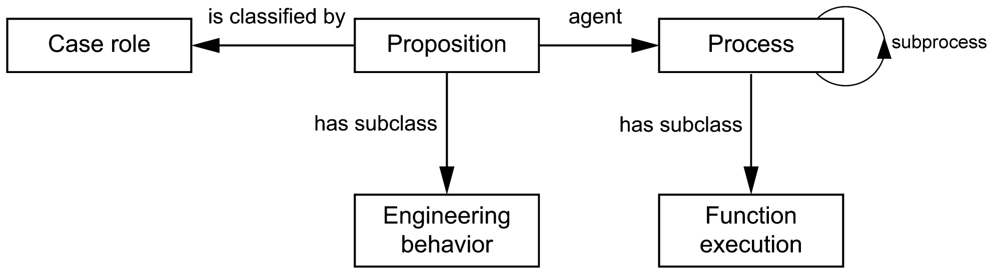
1) Hierarchy



DUL **Information object** is equivalent to SUMO **Proposition**, whose hierarchy is depicted in 4.4.3. As such, the SUMO hierarchy of **Engineering behavior** is as follows:

Engineering behavior is a subclass of **Proposition**

2) Axioms



Engineering behavior *is classified by* some **Case role**
Engineering behavior ***agent*** some **Process**

c) Example

The cleaning robot velocity increases from 0 to 1 (m/s) in 2 s.

d) Rationale

The engineering behavior provides an operational view of the manifested behavior as it requires to fix a set of state variables, and to focus on how they describe changes in the object's qualities and relationships.

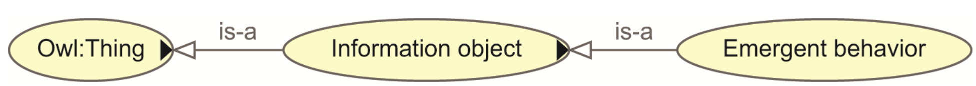
4.4.6 Emergent behavior

This subclause includes the hierarchy and axioms of **Emergent behavior**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL

1) Hierarchy

The DUL hierarchy of **Emergent behavior** follows:

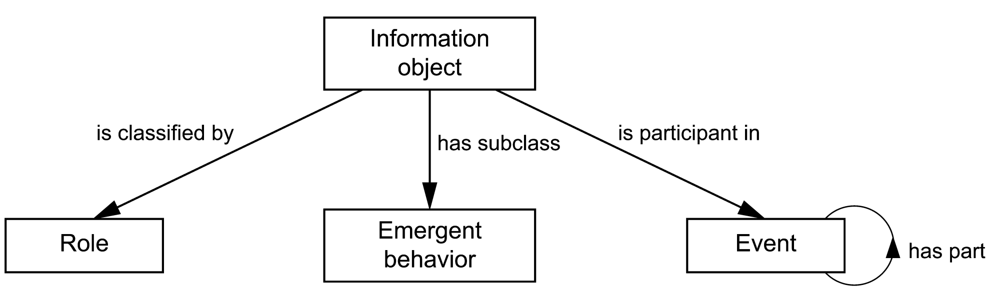


That means:

Emergent behavior is a subclass of **Information object**

2) Axioms

The DUL axioms of **Emergent behavior** are as follows:

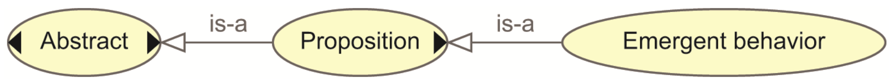


It exploits the following upper-level axioms from DUL:

Emergent behavior *is classified by* some **Role**
Emergent behavior *is participant in* some **Event**

b) SUMO

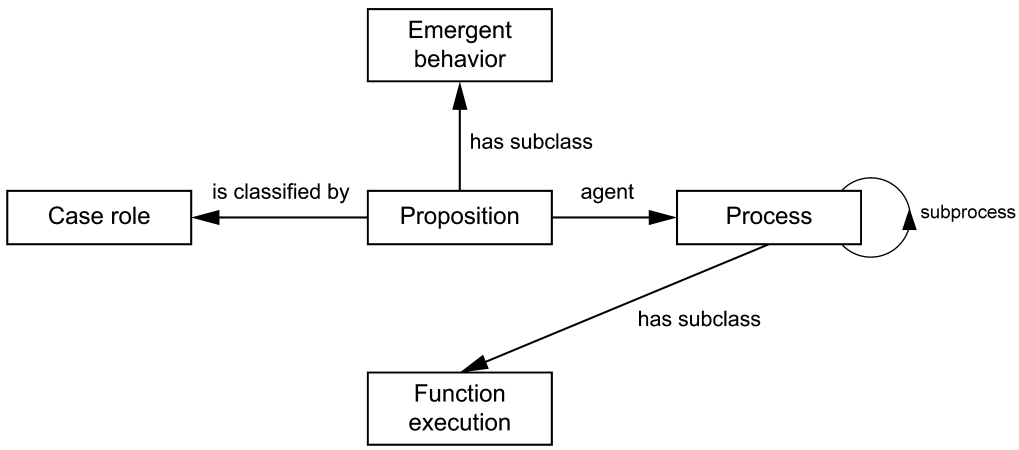
1) Hierarchy



As in 4.4.5, DUL **Information object** is equivalent to SUMO **Proposition.** Thus:

Emergent behavior is a subclass of **Proposition**

2) Axioms



Emergent behavior *is classified by* some **Case role**
Emergent behavior ***agent*** some **Process**

c) Example

A swarm of cleaning robots clean a contaminated area of interest and show self-organization behavior that emerges from the individual interactions between the robots. Self-organizing formation is an emergent process of making whole forms by local interactions of distributed simple autonomous elements without global information at all, and without depending on the initial position and orientation of the elements. The set of relationships are as follows: maintain distance for separation, maintain heading/angle for alignment, maintain position with regard to time for coherence.

d) Rationale

The emergent behavior is the result of a choice of what to focus upon in the interaction at stake. The emergent behavior differs from a manifested behavior because the latter considers all the relationships manifested by the object. The emergent behavior differs from the engineering behavior because the latter fixes the set of state variables once for all, i.e., independently from the focused event.

4.4.7 Rule behavior

This subclause includes the hierarchy and axioms of **Rule behavior**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL

1) Hierarchy

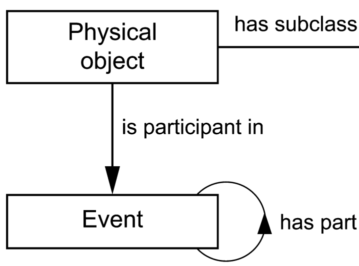
The DUL hierarchy of **Rule behavior** concept is as follows:

That means:

Rule behavior is a subclass of **Physical object**

2) Axioms

The DUL axioms of **Rule behavior** are as follows:

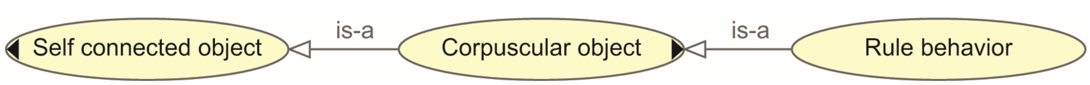


It exploits the following upper-level axioms from DUL:

Rule behavior *is participant in* some **Event**

b) SUMO

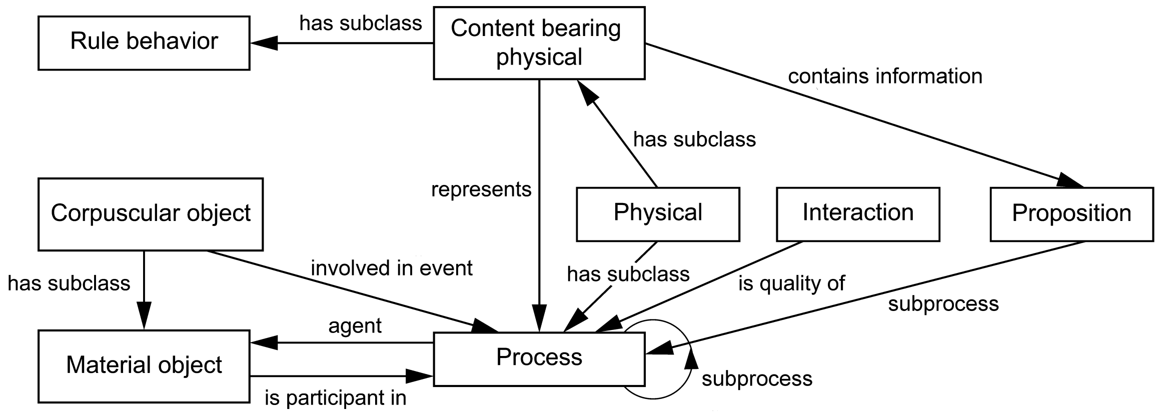
1) Hierarchy



DUL **Physical object** is equivalent to the SUMO **Corpuscular object**, whose hierarchy is depicted in 4.4.2. As a consequence:

Rule behavior is a subclass of **Corpuscular object**

2) Axioms



Rule behavior *involved in event* some **Process**

c) Examples
   1) The robot's behavior accords to the law's safety requirements.
   2) A cleaning robot collects data selectively based on the novelty or quality of the data.
   3) A cleaning robot changes sampling rate based on the available throughput.
   4) A group of cleaning robots switches from centralized to distributed coordination based on the availability of the bandwidth.

d) Rationale

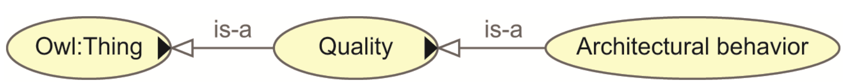
   A rule behavior describes the set of rules e.g., the decision taking to switch between different architectural behaviors, from reactive to deliberative to cognitive.

4.4.8 Architectural behavior

This subclause includes the hierarchy and axioms of **Architectural behavior**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL
   1) Hierarchy

   The DUL hierarchy of **Architectural behavior** concept is as follows:

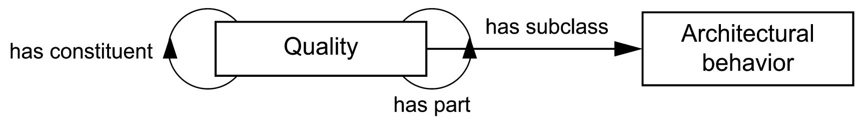


   That means:

   Architectural behavior is a subclass of **Quality**

   2) Axioms

The DUL axioms of **Architectural behavior** are:

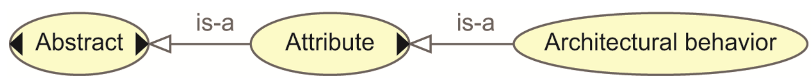


It exploits the following upper-level axioms from DUL:

Architectural behavior *has part only* **Quality**
Architectural behavior *has constituent only* **Quality**

b) SUMO

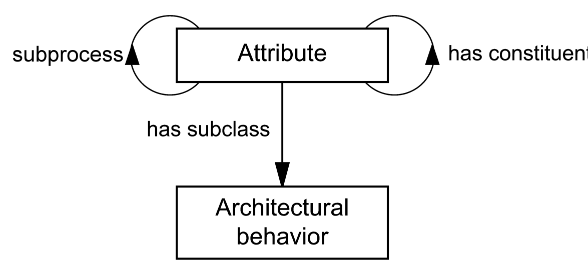
1) Hierarchy



DUL **Quality** is equivalent to SUMO **Attribute**, whose hierarchy is depicted in 4.4.1. Then:

Architectural behavior is a subclass of **Attribute**

2) Axioms



Architectural behavior *subprocess* only **Attribute**
Architectural behavior *has constituent* only **Attribute**

c) Examples

The robot's behavior is deliberative/reactive/cognitive.

1) **Reactive behavior:** The robot reacts to changes in the environment without explicitly reasoning about it (sense-act or stimulus-response behavior).
   i) Reactive behavior example:
      A cleaning robot backs up when collides against an obstacle.
2) **Deliberative behavior:** A goal-oriented robot follows sense-decide-act cycle to achieve its goal.
   i) Deliberative behavior examples:
      i) A cleaning robot decides to go back to charging stations when it runs out of battery.
      ii) A cleaning robot plans to perform routine cleaning in a specific area of interest, executes this plan, and spends more time to clean area when more dirt is detected.
3) **Cognitive behavior:** A goal-oriented robot follows sense-aware-decide-act-learn-adapt cognitive cycle to achieve its goal.

i) Cognitive behavior examples:
  i) A cleaning robot adapts with contextual information (context is any information that characterizes the situation).
  ii) A façade-cleaning robot recognizes the architectural properties of the façade and adapts its motion accordingly.
  iii) A façade-cleaning robot equipped with different cleaning mechanisms/tools recognizes the type of stain on the window and finds the best way to deal with it.

d) Rationale

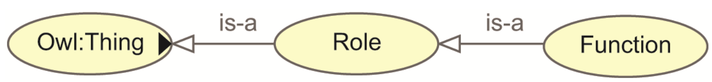
Architectural behavior makes sense from internal viewpoint of the robot, that is how robots are built. These ontological notions represent knowledge about the architecture of the robot. They are justified by the architecture of a robot and, ideally, they contribute to explain the manifested/emergent behaviors. Note that if a robot is built with a reactive behavior but it breaks before using it, then there will never be any manifested behavior.

4.4.9 Function

This subclause includes the hierarchy and axioms of **Function**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL
  1) Hierarchy

  The DUL hierarchy of **Function** concept is as follows:

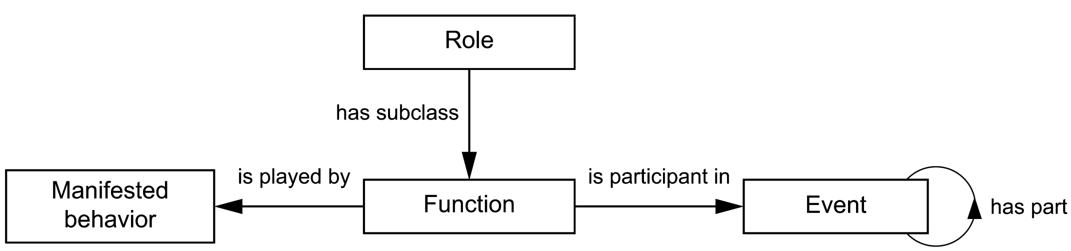


That means:

Function is a subclass of **Role**

  2) Axioms

  The DUL axioms of **Function** are as follows:

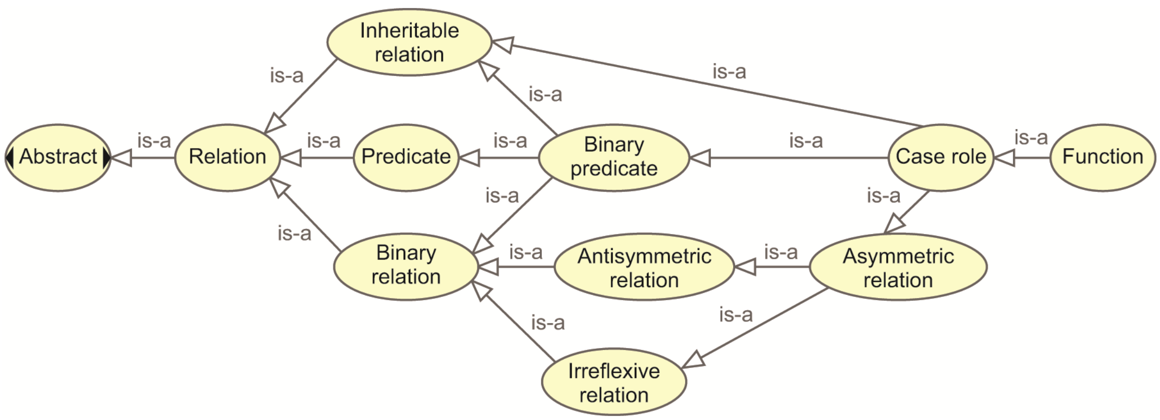


It exploits the following upper-level axioms from DUL:

Function *is played by* only **Manifested behavior**
Function *is participant in* some **Event**

b) SUMO
  1) Hierarchy

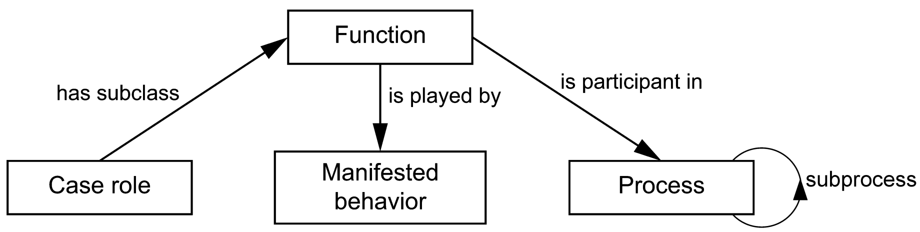
  DUL **Role** is equivalent to SUMO **Case role**, whose hierarchy follows:



Thus:

Function is a subclass of **Case role**

2) Axioms



Function *is played by* only **Manifested behavior**
Function *is participant in* some **Process**

c) Example

The robot is surveilling the area; it is sensing and analyzing the data. (The robot has the function to surveil the area by manifesting the sensing and the data analyzing behaviors.)

d) Rationale

An object has a function in an event if its behavior causally contributes to the achievement of the function goal. A function needs a goal/task to be identified. Examples of functions are as follows: acquisition of information (via sensing behavior); physical modification of objects (via force exertion behavior through actuators); object classification (via reasoning behavior), etc.

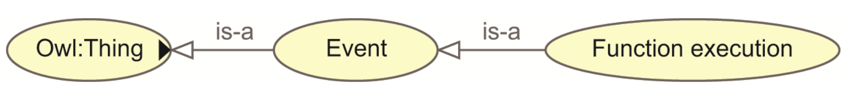
4.4.10 Function execution

This subclause includes the hierarchy and axioms of **Function execution**, expressed in DUL and SUMO, respectively. Usage examples and rationale of this concept is as follows:

a) DUL

1) Hierarchy

The DUL hierarchy of **Function execution** concept is as follows:

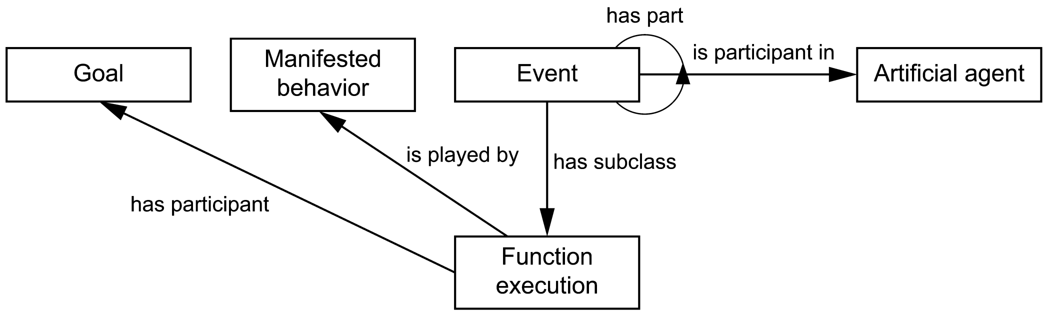


That means:

Function execution is a subclass of **Event**

2) Axioms

The DUL axioms of **Function execution** are as follows:



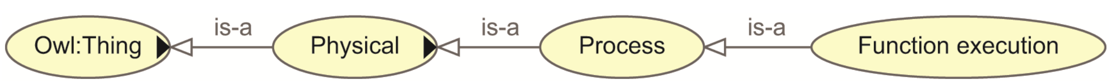
It exploits the following upper-level axioms from DUL:

Function execution *has part* some **Event**
Function execution *has participant* **Artificial agent**
Function execution is *participant* in **some Goal**
Function execution *is played by* only **Manifested behavior**

b) SUMO

1) Hierarchy

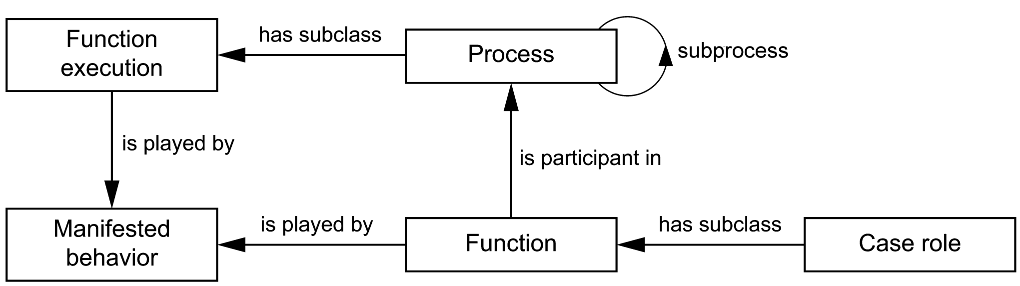
As depicted in 4.4.1, DUL **Event** is equivalent to SUMO **Process**. The hierarchy of SUMO **Process** follows:



Thus:

Function execution is a subclass of **Process**

2) Axioms



Function execution *subprocess* some **Process**
Function execution *is played by* only **Manifested behavior**

c) Example

The robot communicates its position. (The robot executes the function “making its location known” via a sending behavior where data are its coordinates.)

NOTE—Usually a manifested behavior counts as several function executions. For example, the manifested behavior of a robot moving from a location to another is the execution of several functions (only high-level functions are listed): “move,” “make noise,” “vibrate,” etc.

d) Rationale

An object executes a function in an event. In robotics, this function execution is often considered an action that the robot performs. A manifested behavior might involve several function executions.

Annex A

(informative)

Full definitions of DUL and SUMO

This annex provides the complete definitions of the DUL and SUMO concepts exploited when integrating the proposed AuR ontology with DUL and SUMO, respectively (see Clause 4). In detail, A.1 includes the DUL definitions, while A.2 depicts the SUMO definitions.

A.1 DUL

DUL definitions are as follows:

— ***Event***: Any physical, social, or mental process, event, or state. More theoretically, events can be classified in different ways, possibly based on 'aspect' (stative, continuous, accomplishment, achievement, etc.), on 'agentivity' (intentional, natural, etc.), or on 'typical participants' (human, physical, abstract, food, etc.). No special direction is taken since events are related to observable situations and can have different views at the same time. If a position has to be suggested here anyway, the participant-based classification of events seems the most stable and appropriate for many modeling problems.

— ***Information object***: A piece of information, such as a musical composition, a text, a word, a picture, independently from how it is concretely realized.

— ***Physical object***: Any object that has a proper space region. The prototypical physical object has also an associated mass, but the nature of its mass can greatly vary based on the status of the object (scientifically measured, subjectively possible).

A.1.1 Alternative aspectual views

Consider a same event 'rock erosion in the Sinni valley'—it can be conceptualized as an accomplishment (what has brought a certain state to occur), as an achievement (the state resulting from a previous accomplishment), as a punctual event (if the time interval of the erosion is collapsed into a time point), or as a transition (something that has changed from a state to a different one). In the erosion case, there could be good motivation to shift from one aspect to another: causation focus, effectual focus, historical condensation, or transition (causality).

The different views refer to the same event, but are still different: how to live with this seeming paradox? A typical solution, e.g., in linguistics (cf. Levin's aspectual classes)[12] and in DOLCE Full (cf. WonderWeb D18 axiomatization)[13] is to classify events based on aspectual differences. But this solution would create different identities for the same event, where the difference is only based on the modeler's attitude. An alternative solution is applied here and exploits the notion of (observable) situation; a situation is a view, consistent with a description that can be observed of a set of entities. It can also be seen as a 'relational context' created by an observer on the basis of a 'frame.' Therefore, a situation allows to create a context where each particular view can have a proper identity, while the event preserves its own identity. For example, ErosionAsAccomplishment is a situation where rock erosion is observed as a process leading to a certain achievement—the conditions (roles, parameters) that suggest such views are stated in a description, which acts as a 'theory of accomplishments.'

[12] More information is available at: https://web.stanford.edu/~bclevin/bls00.pdf.
[13] More information is available at: https://content.iospress.com/articles/applied-ontology/ao210259.

Similarly, ErosionAsTransition is a situation where rock erosion is observed as an event that has changed a state to another—the conditions for such interpretation are stated in a different description, which acts as a 'theory of state transitions.' Consider that in no case the actual event is changed or enriched in parts by the aspectual view.

A.1.2 Alternative intentionality views

Similarly to aspectual views, several intentionality views can be provided for the same event. For example, one can investigate if an avalanche has been caused by immediate natural forces, or if there is any hint of an intentional effort to activate those natural forces. Also, in this case the event as such has no different identities, while the causal analysis generates situations with different identities, according to what description is taken for interpreting the event. On the other hand, if the possible actions of an agent causing the starting of an avalanche are taken as parts of the event, then this makes its identity change because a part is being added to it. Therefore, if intentionality is a criterion to classify events or not, this depends on if an ontology designer wants to consider causality as a relevant dimension for events' identity.

A.1.3 Alternative participant views

A slightly different case is when the basic participants to an event are considered. In this case, the identity of the event is affected by the participating objects, because it depends on them. For example, if snow, mountain slopes, wind, waves, etc., are considered as avalanche basic participants, or if water, human agents, etc., are added that makes the identity of an avalanche change. Anyway, this approach to event classification is based on the designer's choices, and more accurately mirrors lexical or commonsense classifications (see WordNet 'supersenses' for verb synsets). [14]

Ultimately, this discussion has no end, because realists may keep defending the idea that events in reality are not changed by the way they are described, while constructivists may keep defending the idea that, whatever 'true reality' is about, it cannot be modeled without the theoretical burden of how it is observed and described. Both positions are in principle valid, but, if taken too radically, they focus on issues that are only partly relevant to the aim of computational ontologies, which only attempt to assist domain experts in representing what they want to conceptualize a certain portion of reality according to their own ideas. For this reason, in this ontology both events and situations are allowed, together with descriptions, in order to encode the modeling needs, independently from the position (if any) chosen by the designer.

a) ***Quality***: Any aspect of an entity (but not a part of it) that cannot exist without that entity. For example, the way the surface of a specific PhysicalObject looks like, or the specific light of a place at a certain time, are examples of quality, while the encoding of a quality into e.g., a PhysicalAttribute should be modeled as a Region. From the design viewpoint, the Quality-Region distinction is useful only when individual aspects of an Entity are considered in a domain of discourse. For example, in an automotive context, it would be irrelevant to consider the aspects of car windows for a specific car, unless the factory wants to check a specific window against design parameters (anomaly detection). On the other hand, in an antiques context, the individual aspects for a specific piece of furniture are a major focus of attention, and may constitute the actual added value, because the design parameters for old furniture are often not fixed and may not be viewed as 'anomalies.'

b) ***Role***: A concept that classifies an object.

A.2 SUMO

SUMO definitions are as follows:

— ***Attribute***. Qualities that cannot or are chosen not to reify into subclasses of.

[14] Available at : https://wordnet.princeton.edu/.

- ***Case role***. The Class of Predicates relating the spatially distinguished parts of a Process. Case Roles include, for example, the agent, patient or destination of an action, the flammable substance in a burning process, or the water that falls in rain.
- ***Corpuscular object***. A Self Connected Object whose parts have properties that are not shared by the whole.
- ***Process***. The class of things that happen and have temporal parts or stages. Examples include extended events like a football match or a race, actions like Pursuing and Reading, and biological processes. The formal definition is: anything that occurs in time but is not an Object. Note that a Process may have participants 'inside' it which are Objects, such as the players in a football match. In a 4D ontology, a Process is something whose spatiotemporal extent is thought of as dividing into temporal stages roughly perpendicular to the time-axis.
- ***Proposition***. Propositions are Abstract entities that express a complete thought or a set of such thoughts. As an example, the formula '(instance Yojo Cat)' expresses the Proposition that the entity named Yojo is an element of the Class of Cats. Note that propositions are not restricted to the content expressed by individual sentences of a Language. They may encompass the content expressed by theories, books, and even whole libraries. It is important to distinguish Propositions from the ContentBearingObjects that express them. A Proposition is a piece of information, e.g., that the cat is on the mat, but a ContentBearingObject is an Object that represents this information. A Proposition is an abstraction that may have multiple representations: strings, sounds, icons, etc. For example, the Proposition that the cat is on the mat is represented here as a string of graphical characters displayed on a monitor and/ or printed on paper, but it can be represented by a sequence of sounds or by some non-latin alphabet or by some cryptographic form.

Annex B

(informative)

Mapping SUMO and DUL

B.1 Information object ↔ Proposition

The DUL definition of Information object states the following:

Information object: A piece of information, such as a musical composition, a text, a word, a picture, independently from how it is concretely realized.

In SUMO there exists the definition of musical composition:

Musical Composition: MusicalComposition refers to the conception of a musical arrangement, not including any LyricalContent. [MusicalComposition is a subclass of Music ⊆ Proposition ⊆ Abstract].

Subsuming useful information from SUMO:

Proposition: Propositions are Abstract[15] entities that express a complete thought or a set of such thoughts. As an example, the formula '(instance Yojo Cat)' expresses the Proposition[16] that the entity named Yojo is an element of the Class[17] of Cats. Note that propositions are not restricted to the content expressed by individual sentences of a Language.[18] They may encompass the content expressed by theories, books, and even whole libraries. It is important to distinguish Propositions from the ContentBearingObjects[19] that express them. A Proposition is a piece of information, e.g., that the cat is on the mat, but a ContentBearingObject is an Object[20] that represents this information. A Proposition is an abstraction that may have multiple representations: strings, sounds, icons, etc. For example, the Proposition that the cat is on the mat is represented here as a string of graphical characters displayed on a monitor and/or printed on paper, but it can be represented by a sequence of sounds or by some non-latin alphabet or by some cryptographic form. [Proposition is a subclass of Abstract].

As a result:

DUL → **Information Object**

SUMO → **Proposition**

[15] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=Abstract
[16] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=Proposition
[17] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=Class
[18] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=Language
[19] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=ContentBearingObject
[20] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=Object

B.2 Physical object ↔ Corpuscular object

The DUL definition states the following:

Physical object: Any Object that has a proper space region. The prototypical physical object has also an associated mass, but the nature of its mass can greatly vary based on the epistemological status of the object (scientifically measured, subjectively possible, imaginary).

According to WordNet, the noun “physical_object” has one sense(s): a tangible and visible entity; an entity that can cast a shadow; “it was full of rackets, balls and other objects”. The SUMO equivalent mapping of “physical_object” is Corpuscular Object.

From SUMO:

Corpuscular Object: A SelfConnectedObject whose parts have properties that are not shared by the whole.

As a result,

DUL → **Physical Object**

SUMO → **Corpuscular Object**

B.3 Event ↔Process

According to WordNet, the noun “event” has four sense(s):

- A phenomenon located at a single point in space-time; the fundamental observational entity in relativity theory. SUMO Mappings: Process (subsuming mapping).[21]
- Something that happens at a given place and time. SUMO Mappings: Process (equivalent mapping).
- A phenomenon that follows and is caused by some previous phenomenon; “the magnetic effect was greater when the rod was lengthwise”; “his decision had depressing consequences for business”; “he acted very wise after the event.” SUMO Mappings: Process (subsuming mapping).
- A special set of circumstances; “in that event, the first possibility is excluded”; “it may rain in which case the picnic may be canceled.” SUMO Mappings: SubjectiveAssessmentAttribute (subsuming mapping).[22]

The DUL definition states the following:

Event: Any physical, social, or mental process, event, or state.

In SUMO there are the definitions for the following:

a) Psychological process: The performance of some composite cognitive activity; an operation that affects mental contents; “the process of thinking”; “the cognitive operation of remembering.” [subclass of BiologicalProcess ⊆ InternalChange].
b) State change: Any process where the PhysicalState[23] of part[24] of the patient[25] of the process changes. [subclass of Internal Change].

[21] At the time of publication, this was an active link. Available at:
http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?flang=SUO-KIF&lang=EnglishLanguage&kb=SUMO&term=Process
[22] At the time of publication, this was an active link. Available at:
http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?flang=SUO-KIF&lang=EnglishLanguage&kb=SUMO&term=SubjectiveAssessmentAttribute

c) Internal change: Processes which involve altering an internal property of an Object, e.g., the shape of the Object, its coloring, its structure, etc. Processes that are not instances of this class include changes that only affect the relationship to other objects, e.g., changes in spatial or temporal location. [subclass of Process].

And the SUMO formal definition of Process is as follows:

Process: The class of things that happen and have temporal parts or stages. Examples include extended events like a football match or a race, actions like Pursuing and Reading, and biological processes. The formal definition is: anything that occurs in time but is not an Object. Note that a Process may have participants 'inside' it which are Objects, such as the players in a football match. In a 4D ontology, a Process is something whose spatiotemporal extent is thought of as dividing into temporal stages roughly perpendicular to the time-axis.

As a result:

DUL → **Event**

SUMO → **Process**

B.4 Quality ↔ Attribute

According to WordNet, the noun "quality" has five sense(s):

— A degree or grade of excellence or worth; "the quality of students has risen"; "an executive of low caliber". SUMO Mappings: SubjectiveAssessmentAttribute (subsuming mapping).
— High social status; "a man of quality". SUMO Mappings: SubjectiveAssessmentAttribute (subsuming mapping).
— An essential and distinguishing attribute of something or someone; "the quality of mercy is not strained"—Shakespeare. SUMO Mappings: Attribute (subsuming mapping).
— (Music) the distinctive property of a complex sound (a voice or noise or musical sound); "the timbre of her soprano was rich and lovely"; "the muffled tones of the broken bell summoned them to meet". SUMO Mappings: SoundAttribute (subsuming mapping).
— A characteristic property that defines the apparent individual nature of something; "each town has a quality all its own"; "the radical character of our demands." SUMO Mappings: Attribute (subsuming mapping).

From DUL:

Quality: Any aspect of an Entity (but not a part of it), which cannot exist without that Entity. For example, the way the surface of a specific PhysicalObject looks like, or the specific light of a place at a certain time, are examples of Quality.

In WordNet, the light of a place at a certain time is defined as the visual effect of illumination on objects or scenes as created in pictures; "he could paint the lightest light and the darkest dark". This definition is mapped as a SUMO VisualAttribute.

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[23] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=PhysicalState
[24] At the time of publication, this was an active link. Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=part
[25] At the time of publication, this was an active link.Available at: http://sigma.ontologyportal.org:8080/sigma/Browse.jsp?lang=EnglishLanguage&flang=SUO-KIF&kb=SUMO&term=patient

In SUMO:

a) *VisualAttribute*: The Class of visually discernible properties. [subclass of Perceptual Attribute ⊆ Relational Attribute ⊆ Attribute ⊆ Abstract].
b) ***Attribute***: Qualities that cannot or are chosen not to reify into subclasses of.

As a result,

DUL → **Quality**

SUMO → **Attribute**

B.5 Role ↔ Case role

According to WordNet, the noun “role” has four sense(s):

— Normal or customary activity of a person in a particular social setting; “what is your role on the team?” SUMO Mappings: IntentionalProcess (subsuming mapping).
— What something is used for; “the function of an auger is to bore holes”; “ballet is beautiful but what use is it?”. SUMO Mappings: Attribute (subsuming mapping).
— The actions and activities assigned to or required or expected of a person or group; “the function of a teacher”; “the government must do its part”; “play its role.” SUMO Mappings: Position (subsuming mapping).
— An actor’s portrayal of someone in a play; “she played the part of Desdemona.” SUMO Mappings: DramaticActing (subsuming mapping).

From DUL:

Role: A Concept that classifies an Object.

Starting from Position, the SUMO useful definitions follow:

a) *Position*: A formal position of responsibility within an Organization. Examples of positions include president, laboratory director, senior researcher, sales representative, etc., (subclass of SocialRole).
b) *OccupationalRole*: RelationalAttribute ascribing to a CognitiveAgent a relation towards some activity or a set of activities he or she performs during a TimeInterval as his or her main activity. Be it for a longer period of time as a means of earning a living, a leisure activity or an activity the person is engaged in for a short period of time (subclass of SocialRole).
c) *SocialRole*: The Class of all Attributes that specify the position or status of a CognitiveAgent within an Organization or other Group (subclass of Relational Attribute ⊆ Attribute ⊆ Abstract).

Other useful information from SUMO:

— ***CaseRole***: The Class of Predicates relating the spatially distinguished parts of a Process. CaseRoles include, for example, the agent, patient or destination of an action, the flammable substance in a burning process, or the water that falls in rain (subclass of Asymmetric/InheritableRelation ⊆ … ⊆ Relation ⊆ Abstract).

As a result,

DUL → **Role**

SUMO → **Case Role**

Annex C

(informative)

Case study

C.1 Introduction

One of the problems that service and industrial robotics deal with is to bring bi-manual manipulators with navigation capability to work in semi-structured collaborative scenarios, which requires an efficient and flexible way to execute tasks, like serving a cup in a cluttered environment. Usually, for those tasks, combining symbolic and geometric planning is necessary. Moreover, the integration of perception models with cognitive knowledge should guide the planning. The result is a sequence of actions that will be executed depending on the current state of the world.

C.2 Task description

This subclause proposes a motivation example to validate the concepts standardized in Clause 4. It includes two collaborative robots that share workspace knowledge to accomplish a table-top manipulation task in an indoor scenario. In detail, a dual-arm robot (robotA) and a mobile manipulator (robotB) share the scene, and a set of objects are randomly located on a table in front of the dual-arm robot and on a shelf, far from the table itself. The task asks robotA to prepare a cup of coffee on the table. Initially, the cup is on the shelf. Due to the robotA reachability limitations, robotB must assist the beverage preparation by picking the cup from the shelf and placing it on the table (see Diab et. al [B11]).

C.3 Knowledge representation

The task is challenging because, to correctly carry it out, the two robots should have the same knowledge about the environment, its entities, and each other's capabilities. Moreover, any planner used to solve this task needs an exhaustive semantic description of the scene able to answer questions such as: what are the robots in the environment? What are the capabilities of these robots? What are the sensors associated with the environment? What are these sensors detecting? What are the object features? What are the relations of the objects? And some other questions highlighted through the case study. Combining a Knowledge Base with the task and motion planners will facilitate finding the answer to these questions. Such a Knowledge Base needs to be composed of an ontology able to define the robots, so as to make them able to cooperate. It will depict the objects populating the workspace, making agents aware of them. It will collect the actions that every robot can perform. Generality, the ontology can be exploited as a dataset useful to deduce meaningful information from data generated by the planners. Moreover, it will be the common language letting robots interoperate with each other.

All these concepts have been introduced in CORA and in this document. Thus, they become essential for the implementation of an ontology able to facilitate task and motion planning in many robotics domains where robots autonomously act within an environment and share the workspace with other agents. Details about how such concepts have been exploited in this case study follow.

C.3.1 Concepts and relations used from IEEE Std 1872-2015

This subclause highlights the concepts used from IEEE Std 1872-2015 as follows:

a) Concepts from CORA
   1) **Robot**: It depicts the features of each robot used (e.g., the set of links and joints).

   2) **Robot group**: It describes robotA and robotB as a group of robots that must cooperate to accomplish the assigned task.

b) Concepts from Pos
   1) ***Position measure***: It describes the position of an object in the world (e.g., the position of the cup on the shelf).
   2) ***Orientation measure***: It describes the orientation of an object in the world (e.g., the orientation of the cup).
   3) ***Pose measure***: It describes both the position and orientation of an object in the world (to locate the robots in the scene, to identify the feasible grasping poses, etc.).

c) Relations from Pos:
   1) ***Positioned at***: It relates an object with its ***position measure*** value so as to determine the object position (e.g., it relates a cup to the position it is occupying in the space).
   2) ***Oriented at***: Every ***orientation measure*** is attributed to objects through this relation.
   3) ***Pose***: Every ***pose measure*** is attributed to objects through this relation.

C.3.2 Concepts and relations used from IEEE Std 1872.2

The following concepts have been repeated from the current standard, see 3.1:

a) ***Sensor***: It includes the characteristics of each sensor composing the robots (e.g., to find the cup on the shelf, robotB should exploit its vision sensor).
b) ***Plan***: It describes the plan that each robot should perform to accomplish its assignment (e.g., the motion plan that brings robotB from the table to the shelf and vice versa, the plan it should actuate to pick up the cup, the plan that robotA has to accomplish to prepare the coffee).
c) ***Actuator***: Every robot is composed of a set of actuators that make them accomplish the plans.
d) ***Control***: Every actuator moves thanks to a control law that changes the robot joint configuration from the current to the goal one.
e) ***Processing element***: Every plan is computed by means of a processing element that enables agents taking the suitable decisions to reach the goal.
f) ***Communication element***: Every decision is communicated to the robots to guarantee cooperation and collaboration.

The following concepts have been repeated from the current standard, see 3.2:

— ***Interaction***: Robots interact between each other and with the objects populating the environment. For example, when robotB is detecting the cup, an indirect ***information interaction*** arises between the robot and the cup during the detection event. When it picks up the cup, a direct ***physical interaction*** arises between the robot and the cup during the picking up event.
— ***Object-centered environment***: The use case environment is the workspace where robots are acting. It is represented as a physical object whose location is the spatial area that the robots can potentially reach during the event. Moreover, this physical object includes a set of material components that are the objects participating in the event with which robots can potentially interact (e.g., the cup, the shelf, and the table). In this context, robotA is equipped with a vision sensor and can model its workspace—the table. In this sense, it has an ***object-centered environment description*** of the environment in which this robot is operating. The robotB is equipped with both vision sensors and a laser. The robot is given the capability of modeling its surroundings—table, shelf, and the open area in between them. It provides a second ***object-centered environment description*** of the scene. Robots will operate while taking into consideration their environment descriptions. Such characterizations will be exhaustive enough to make robots cooperate when sharing tasks and space.

- ***Manifested behavior***: During robotB navigation, its manifested behavior includes the change of both its location and spatial relationships. As pointed out in 4.4.4, the robot location is a quality of the robot itself; the spatial relationships, instead, are relational qualities of the robot. The manifested behavior also includes the quality of the robot sensors, which may change during the exploration of the environment. Even when robotB picks up the cup from the shelf and puts it down on the table, the manifested behavior of the agent in the event of moving an item from one location to another 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 robotA manifested behavior.
- ***Architectural behavior***: Robot behaviors are reactive as robots react to changes in the environment without explicitly reasoning about them (sense-act behavior). Behaviors are also deliberative as it can be assumed that, for example, robotB will decide to support robotA when detecting that the capabilities of the former (navigation) can overcome the limitations of the latter (sense-decide-act behavior). Finally, behaviors are also cognitive as robot actions will be adapted according to the contextual information (context is any information that characterizes the situation).
- ***Function***: robotA has the function of preparing the beverage. robotB has the function of helping the manipulator robot by picking up the cup to fill with coffee.

Annex D

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

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