An IEEE Standard Ontology for Robotics and Automation

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***Abstract*— This article discusses a newly formed IEEE-RAS (Robotics and Autonomous Systems) working group entitled Ontologies for Robotics and Automation (ORA). The goal of this working group is to develop a standard ontology and associated methodology for knowledge representation and reasoning in robotics and automation, together with the representation of concepts in an initial set of application domains. The standard provides a unified way of representing knowledge and provides a common set of terms and definitions, allowing for unambiguous knowledge transfer among any group of humans, robots, and other artificial systems. In addition to describing the goal and structure of the group, this article gives some examples of how the ontology, once developed, can be used by applications such as industrial kitting.**

I. Introduction

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

- more precisely define the concepts in the robot's knowledge representation;
- ensure common understanding among members of the community; and
- facilitate more efficient data integration and transfer of information among robotic systems.

In this article, we discuss a newly formed IEEE-RAS (Robotics and Autonomous Systems) working group entitled Ontologies for Robotics and Automation (ORA). The goal of this working group is to develop a standard ontology and associated methodology for knowledge representation and reasoning in robotics and automation, together with the representation of concepts in an initial set of application domains. The standard will provide a unified way of representing knowledge and will provide a common set of terms and definitions, allowing for unambiguous knowledge transfer among any group of humans, robots, and other artificial systems. To date, the working group has over 125 members containing a cross-section of industry, academia, and government, representing over twenty countries.

In this context, an ontology can be thought of as a knowledge representation approach that represents key concepts with their properties, relationships, rules, and constraints. Whereas taxonomies usually provide only a set of vocabulary and a single type of relationship between terms (usually a parent/child type of relationship), an ontology provides a much richer set of relationships and also allows for constraints and rules to govern those relationships. In general, ontologies make all pertinent knowledge about a domain explicit and are represented in a computer-interpretable format that allows software to reason with that knowledge to infer additional information.

It would be extremely difficult to develop an ontology that could cover the entire space of robotics and automation. Hence, the working group is structured in such a way as to take a bottom-up and top-down approach to addressing this broad domain. This group is comprised of four sub-groups entitled: Upper Ontology/Methodology(UpOM), Autonomous Robots (AuR), Service Robots (SeR), and Industrial Robots (InR).

The InR, AuR, and SeR sub-groups will produce sub-domain ontologies that will serve as a test case to validate the upper ontology and the methodology developed by UpOM. The sub-domains were determined in such a way to ensure that there would be overlap among them. Once initial versions of the ontologies are completed, they will be integrated into the overall ontology. During the integration process, as overlapping concepts are identified, a formal process will determine if these concepts should be merged, if they should be separated into two separate concepts, or if some other approach should be explored to reconcile them.

The rest of this paper is organized as follows: Section II discusses some related robotic ontology efforts that are being leveraged within this Working Group, Section III describes the overall IEEE standardization process, Section IV describes the Working Group Structure, Section V discusses two examples of application of the ontology to real-world problems, and Section VI concludes the paper.

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II. RELATED EFFORTS

In this section, we describe three efforts which have been identified as relevant to the working group's goal of developing a standard knowledge representation for robotics and automation. There are many relevant efforts in the literature which are not included here in the interest of space, including Kunze's work on a Semantic Robot Description Language [20], generic standard knowledge representations such as the Knowledge Interchange Format (KIF) [21], and work in Semantic Web Services such as [22].

RoboEarth [19]

For many years, people have used the Internet to share knowledge and to jointly accomplish tasks. Up until now, robots have not been able to have the same luxury. A European project called RoboEarth is working on building an Internet for robots. It is described as a worldwide, open-source platform that allows any robot with a network connection to generate, share, and reuse data. RoboEarth is focusing on building a knowledge-base of shared information and experiences. The ontology is represented in the Web Ontology Language (OWL).

The NIST Robot Ontology [2]

In an effort to accelerate the development and deployment of robotic tools for urban search and rescue responders, the National Institute of Standards and Technology (NIST) is developing test methods for robotic technologies applied to US&R (Urban Search and Rescue). The results of robots performing these test methods are represented in the NIST Robot Ontology. The goal of the Robot Ontology effort is to develop and begin to populate a neutral knowledge representation capturing relevant information about robots and their capabilities to assist in the development, testing, and certification of effective technologies for sensing, mobility, navigation, planning, integration, and operator interaction within search and rescue robot systems.

The Intelligent Systems Ontology [3]

The level of automation in combat vehicles being developed for the United States Army's objective force is greatly increased over its legacy force. This automation is taking many forms in emerging vehicles; varying from operator decision aids to fully autonomous unmanned systems. The development of these intelligent vehicles requires a thorough understanding of all of the intelligent behavior that needs to be exhibited by the system so that designers can allocate functionality to humans and/or machines. To address this, an Intelligent Systems (IS) Ontology was developed. The purpose of the ontology was to develop a common, implementation-independent, extendable knowledge source for researchers and developers in the intelligent vehicle community that will (1) provide a standard set of domain concepts along with their attributes and inter-relations, (2) allow for knowledge capture and reuse, and (3) facilitate systems specification, design, and integration.

III. IEEE-RAS STANDARDS DEVELOPMENT PROCESS

The Standing Committee for Standards Activities (SCSA) under the Industrial Activities Board (IAB) of the IEEE Robotics and Automation Society (RAS) is working together with the research and industrial communities and standards developing organizations (SDOs) to help develop standards for robotics and automation [4]. The scope of the activities of the IEEE RAS-SCSA is to formally adopt and confirm best practices in robotics and automation as standards. Within this scope, SCSA is pursuing the following objectives [5]:

- promote common measures and definitions in robotics and automation;
- promote measurability and comparability of robotics and automation technology;
- promote integratability, portability, and reusability of robotics and automation technology.

The IEEE standards development process has the following stages:

- **Project Authorization**: Each project must be supported by a technical group in the IEEE referred to as a "Sponsor" which in this case is IEEE-RAS. Once a project idea is formed and refined within the study group, it is then approved through a document called Project Authorization Request (PAR). It serves as the work authorization by the IEEE-SA (Standards Association) Standards Board and is valid for four years.
- **Develop Draft Standard**: The official standard is written by the working group consisting of researchers and developers interested in creating the standard. The working group writes the initial draft from existing documents, specifications, and discussions among members.
- **Consensus Process**: Consensus is determined by ballot. Interested persons or organizations are invited to ballot on draft standards. A ballot group within IEEE-SA receives the draft document and after reviewing and commenting on the draft (feedback from working group is possible at this stage), it votes yes (approve), no (disapprove), or abstain. Final approval of the standard is granted by the IEEE-SA Standards Board (SASB).

In July 2011, the ORA group submitted a Project Authorization Request (PAR) to the IEEE-SA Standards Board soliciting authorization to become an official working group with the goal of standardizing knowledge representation in the robotics field. In November 2011, IEEE-RAS approved the PAR to create a formal working group. We are now actively working on a set of standard ontologies and methodologies in conjunction with industry, academia, and government organizations. Once consensus is reached and a proposed standard is developed, it will be submitted to the IEEE Standards Association Standards Board (SASB) for approval as an IEEE standard. Even after the resulting standard is published, it is still possible to revise the standard in order to ensure that it is up-to-date and useful to the community.

IV. WORKING GROUP STRUCTURE

Our working group is comprised of four sub-groups entitled Upper Ontology/Methodology(UpOM), Autonomous

Robots (AuR), Service Robots (SeR), and Industrial Robots (InR), as shown in Figure 1. Each subgroup will be presented in more detail in this section.

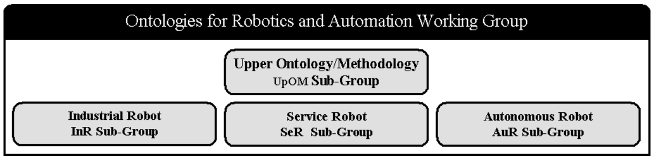

Fig. 1. ORA Group Structure

A. Service Robots Subgroup

According to the International Federation of Robotics (IFR), a Service Robot can be defined as [6] : *A robot which operates semi or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing.* This definition is provisional and not yet accepted worldwide due to the intrinsic characteristics of a service robot related to its form, structure, and application area [6]. Since service robots are increasing their share of the robotics market [7], ISO (International Organization for Standardization) is working on a standard definition for Service Robots, under the scope of the Technical Committee 184 - Sub Committee 2, Robots and Working Devices.

There exist several general robotics standards that have been considered in the standardization of service robots.

- ISO 8373:1994, ISO 9787:1999, ISO 11593:1996, ISO 14539:2000, for industrial robotics. (under revision to include Service Robots);
- ASTM International E2521-07, for Urban Search and Rescue Robotic Operations;
- AIAA (American Institute for Aeronautics and Astronautics: S-066-1995, for Space Automation and Robotics;
- JIS (Japanese Industrial Standard) B 0144:2000, JIS B 0185:2002, JIS B 0186:2003, JIS B 0187:2005, TR B 0010:1999, for Assembly, Intelligent, Mobile, Service, and Personal Robots.

Other efforts to define ontologies for service robots include RoSta [8] and "Ontology-Based Unified Robot Knowledge for Service Robots in Indoor Environments" [9].

The goal of the SeR subgroup is to develop a standard ontology and associated methodology for knowledge representation and reasoning in service robots, together with the representation of concepts in an initial set of application domains. This group will focus on the representation of concepts within the standard ontology in an initial set of applications, e.g., medical applications, cleaning & housekeeping, search & rescue, etc. These follow the application fields identified by the IEEE-RAS Technical Committee on Service Robots [10]. In the context of service robots, an ontology will define the relations between skills (knowledge) and the physical devices and the rules that the computational intelligence approaches use to reason based on the task that is to be performed and the environment where the robot is performing the task.

B. Autonomous Robots Subgroup

Future unmanned systems need to work in teams with other unmanned vehicles to share information and coordinate activities. The private sector and government agencies have found applications of unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and autonomous underwater vehicles (AUVs) for homeland security, reconnaissance, surveillance, data collection, urban planning, etc. There is an increasing demand in surveillance and map building using UAVs, UGVs, and AUVs. Not only do they make dangerous tasks safer for humans, autonomous unmanned systems (including aerial, ground, and underwater) are also better for the environment and cost less to operate. Potential applications of autonomous systems include: law enforcement, disaster management, defense, natural resource conservation, etc.

The focus of the AuR sub-group is cooperation, coordination, and communication of multiple UAVs, UGVs, and AUVs. The system ontologies should be able to model entities and relationships of multiple autonomous systems at the global mission level. At the individual system level, the ontologies should model the decision-making ability, control strategies, sensing abilities, mapping, environment perception, motion planning, communication, and autonomous behaviors, etc.

The ontologies will serve as a framework for working out concepts of employment with multiple vehicles for a variety of operational scenarios with emphasis on collaborative and cooperative missions. They will capture and exploit the concepts to support the description and the engineering process of autonomous systems. The following packages need to be developed for the system ontologies:

- **Device**: describes devices such as sensors and actuators;
- **Control strategy**: controls the autonomous systems for navigation;
- **Perception**: uses sensor information for state estimation and world representation;
- **Motion planning**: plans motions in the perceived world;
- **Knowledge representation**: represents knowledge about problems and solutions in order to make decisions.

C. Industrial Robots Subgroup

Robots have been used in industry for many years for assembly, particularly for pick-and-place operations and welding. Industrial applications of robots have been primarily implemented as inflexible fixed automation, in which the same sequence of actions is repeated hundreds or thousands of times. The cost of developing the applications is usually quite high. Hence, building them is cost effective only if they are in operation for long periods once development is complete. The challenge of expanding industrial use of robots is to make them flexible. That is, they need to be information driven so that they can reliably perform different sequences of actions on command. The cost of generating the information that drives the actions must be kept down and the information must be accurate.

Usually, an industrial robot is used within the confines of a workstation (for welding, kitting, etc.) in a controlled environment, differently from a service robot that can move freely and acts in an uncontrolled environment. Besides, an industrial robot is likely to be taking commands from an automated workstation controller rather than taking them from a human as service robots and autonomous robots are likely to do. Thus, industrial robots require a highly structured set of commands. Making the initial determination of whether a command has been carried out correctly is usually a function of the robot, not the workstation controller. The workstation controller needs to know whether its commands are carried out correctly, however, so having a highly structured set of status messages to send to a workstation controller is also required of industrial robots.

Intelligence for deciding what the robot should do is likely to reside in the workstation controller so that the only kind of intelligence required of the robot will be to determine how to carry out specific activities, such as moving an object from one place to another or welding a seam.

The InR group will focus on automated robotic workstations, not just on robots. This group will select an application that is currently not fully automated but in which fuller automation seems feasible. A prime candidate is kitting, as discussed in section V. Scenarios for the functioning of the application will be constructed. Next, it will be determined what knowledge is needed to carry out the scenarios.

D. Upper Ontology/Methodology Subgroup

The UpOM group has a goal to address high-level aspects for the ontology development, which include, but are not limited to:

- Define the ontologies to be used;
- Coordinate the sub-ontologies built by other groups;
- Mediate the communication between the groups;
- Consolidate the sub-ontologies into a global ontology;
- Evaluate the ontology.

1) Starting Point: Upper-Level and Domain Ontologies: We will reuse the concepts and formalisms of existing upper level ontologies to build the foundation of our ontology. The Upper Level Ontologies will have high-level concepts that are linked to those used in the domain ontologies. In addition, they provide support to make ontological decisions as transparent as possible in the resulting domain ontology. Examples of these ontologies are SUMO [11] and UFO [12]. Beside considering upper level ontologies, we will investigate existing domain ontologies, like OntoSensor [13] and spatial ontology developed by Chella et al. [14].

2) Interaction between the Groups: The activities developed by InR, SeR, and AuR groups, supported by the UpOM group, are based on the methodology proposed in METHONTOLOGY [15] and consist of the following phases:

1) **Environment Study** aims to acquire information on the platform to be used, the users, and applications where the ontology will be integrated. In this step, each group will perform this study independently;
2) **Conceptualization** provides a conceptual model related to the information acquired, including not only the concepts identified but also their relationships. In this step, a set of intermediate models are built by each group. When a model is mature, it will be submitted to the UpOM group to be reviewed and to gain agreement with the other groups, according to the protocol discussed in Section IV-D.3. The UpOM will then perform the merging process, which will generate a new ontology from the input ontologies;
3) **Formalization and Implementation** transforms the conceptual model into a computable model. In our case, we use OWL (Web Ontology Langauge), its variations (OWL-DL), and RDF (Resource Description Framework) to describe concepts, services, etc;
4) **Evaluate** checks the consistency of the ontology according to the methods described in Section IV-D.4. This step is executed whenever necessary;
5) **Maintenance** will be performed whenever new/altered/corrected knowledge is inserted into the ontology. This process will also follow the protocol defined in Section IV-D.3;
6) **Documentation** aims to produce a document that will be used to modify and/or reuse the ontology *a posteriori*.

The UpOM group will divide the domain of interest into sub-domains to be investigated individually. For each sub-domain, the activities listed above will be performed and each group will produce a partial ontology based on the information collected in its field. For instance, considering the sensor sub-domain, the InR will build a sensor ontology from the information gathered from the industrial robots field. The same will happen for AuR and SeR groups. The ontologies produced by each group will be merged into a unique sensor ontology. This ontology corresponds to a small part of the global ontology that will contain concepts and definitions not only about the sensors, but also about actuators, objects in the environment, etc.

3) Communication Protocol: To guarantee that the ontologies elaborated by each group are globally consistent, we need a communication protocol to manage conflicts arising from the independently developed ontologies. We propose to use Co4, developed by Euzenat [16], because it helps to manage the communication of large and spatially distant groups. Furthermore, this protocol is derived from the successful peer-review process performed by journals.

Figure 2 shows an example of communication between the groups UpOM, InR, SeR, and AuR. In (a), the InR group sends a proposal for incorporating concepts/ definitions in the ontology (step 1). The UpOM group evaluates this request and submits the proposal to other groups for comments (step 2). In (b), the SeR and AuR groups evaluate the proposal according to a set of criteria, like redundancy, inconsistencies, and so on. Then a decision with comments is provided by each group separately (step 3) and consolidated by the UpOM. The UpOM will broadcast the decision (acceptance,

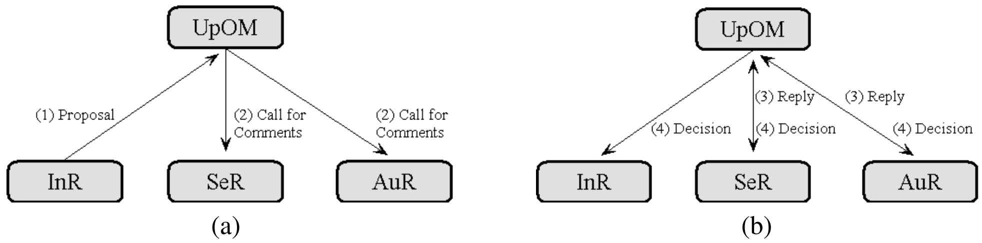

Fig. 2. Communication using Co4.

rejection, or conditional acceptance) with comments (step 4). If there is a general agreement, all groups receive an acceptance decision and the knowledge is incorporated into the global ontology. If a conditional acceptance decision is provided, the InR will adjust its initial proposal and could resubmit it. Otherwise, the initial proposal is discarded.

4) Evaluation: The evaluation process aims to check if the ontology correctly expresses the real world according to its concept, taxonomy, and axioms. It should be performed as soon as possible during the lifetime of the ontology development process. We consider two evaluation processes: the method proposed by Gómez-Pérez [17], in the METHONTOLOGY, and the method proposed by Guarino and Welty [18] called OntoClean. METHONTOLOGY uses the following criteria to evaluate the ontology: consistency, completeness, conciseness, expandability, and sensitiveness. Ontoclean uses philosophical notions of *Rigidity*, *Identity*, and *Unity* to remove subclass-of relations. The properties of a class are associated to these notions and compared to those of super- and sub-classes. This allows one to "clean" the ontology by removing problematic relationships between classes, since they expose inappropriate or inconsistent classifications.

V. Ontology Applications

In this section, we describe two domains that could benefit from the standard ontologies described in the previous sections and describe how those ontologies could be used.

A. AUVs

With the growing use of autonomous and semi-autonomous platforms and the increased data flows in modern maritime operations, it is critical that the data is handled efficiently across multiple platforms and domains. At present, knowledge representation for autonomous underwater vehicles (AUV) is embryonic and targets simple mono-platform and mono-domain applications, therefore limiting the potential of multiple coordinated actions between agents. Consequently, the main application for autonomous underwater vehicles is information gathering from sensor data. In a standard mission flow, data is collected during the mission and then post-processed off-line. However, as decision making technologies evolve towards providing higher levels of autonomy, embedded service-oriented agents require access to richer data representations. These higher levels of information will be required to provide knowledge representation for contextual awareness, temporal awareness, and behavioral awareness. In order to achieve autonomous decision making, the service oriented agents in the platform must be supplied with the same level of knowledge as the operator. This can be achieved by using a semantic world model and a set of ontologies for each of the agent's domains. These ontologies should be developed to represent the information required for vehicle situation awareness.

Existing approaches propose three discrete levels of vertical segmentation of ontologies: upper/foundation, core/domain, and applications. Upper/foundation ontologies represent the very basic principles which meet the practical need of a model that has as much generality as possible, to ensure re-usability across different domains. On the other hand, core/domain ontologies provide a global and extensible model into which data originating from distinct sources can be mapped and integrated. This canonical form can then provide a single knowledge base for cross-domain tools and services (e.g., vehicle resource/capabilities discovery, vehicle physical breakdown, and vehicle status). While application ontologies provide an underlying formal model for tools that integrate source data and perform a variety of extended functions. As such, higher levels of complexity are tolerable and the design should be motivated more by completeness and logical correctness than by human comprehension. Raw data gets parsed from sensors into assertions during the mission using an adapter. Some domains of these application ontologies could be found, for example, in the field of diagnostics of the vehicle and the planning of the mission.

B. Kitting

Anyone who has ventured into a department store has seen consumer kits. These come in the form of holiday gift packs where several related, but different products are packaged into a single box. There are also more industrial applications of kitting as part of a manufacturing assembly process. In this case, all of the parts for a particular assembly operation are pre-grouped into a kit which is sent to an assembly station for construction. The idea is to reduce material handling and processing times while improving assembly processes by providing the exact mix of components required for each assembly operation. In this context, an ontology can be used as both an aid for data organization and an underlying technology to enable reasoning techniques that can cope with some of the more common failures that are associated with a kitting station.

Kitting fails to reach its full potential for savings when the supply chain fails and parts or components are not available for kit construction, or when a kit is not properly filled. Part availability failures can be due to problems such as inaccurate data on component location, delays in internal logistics in keeping components available for the kitting station, or failure of a supplier to provide sufficient components. Kit construction errors may be due to problems such as human error in kit construction (when the kit is produced by a human), by robot errors caused, for example, by dropped parts, or by part damage. When faced with part availability failures, some organizations choose to construct incomplete kits that must be completed when components become available. This presents additional knowledge challenges when it comes time to finish the incomplete kits and in making decisions about the usefulness of partial kit construction.

A set of ontologies is being developed to represent the knowledge required for kitting operations. It is envisioned that all of the ontologies being developed for the IEEE working group will share the same upper ontology. For kitting, we will draw on its representation of low level concepts such as an object's pose, as well as high level concepts such as the capabilities of the robot cell and effectors, and representations of trajectories for part movements. Domain specific representations will need to be developed that include items such as the final kit configuration. A desired outcome of this effort is to allow an off-the-shelf robotic system to interface with this framework and construct kits. Since the system will not be customized for a specific kit, rapid retasking of the kitting cell will be possible.

VI. Conclusion/Future Work

In this article, we have described the IEEE-RAS Ontologies for Robotics and Automation Working Group. Specifically, we describe its goal, structure, approach, and some applications that we envision the resultant ontology could be applied towards. Though the scope of developing an ontology for the whole robotics and automation domain is large, the working group is making it more manageable by taking a top-down and bottom-up approach. From the top-down, the group is identifying an upper ontology to serve as the "umbrella" for all detailed domain ontologies and is developing an overall methodology to provide a structure for how to add new concepts. From a bottom-up approach, three subgroups are exploring the areas of autonomous robots, service robots, and industrial robots independently to ensure that the detailed information requirements for these areas are represented. It is envisioned that other sub-groups will be formed as additional sub-domains gather enough interest from members of the working group. Although this working group is very new, momentum is strong with over 125 participants from all over the world signing up to make the ontology a reality. Membership in the working group is available for anyone that is interested. If the reader would like to join, please visit `https://groups.google.com/forum/\#!forum/ieeeraswg` to request to be added to the mailing list.

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References

[1] S. Bechhofer, I. Horrocks, C. Goble, and R. Stevens. OilEd: a reasonable ontology for the semantic web, in Proc. of the Joint German Austrian Conference on AI, number 2174 in Lecture Notes In Artificial Intelligence Springer-Verlag, 2001, pp. 396-408.
[2] C. Schlenoff and E. Messina. A Robot Ontology for Urban Search and Rescue, Proceedings of the CIKM 2005 Workshop on Research in Knowledge Representation for Autonomous Systems, 2005.
[3] C. Schlenoff, R. Washington, T. Barbera, C. Manteuffel and S. Dungrani. A Standard Intelligent Systems Ontology, Proceedings of the SPIE Defense and Security Symposium, unmanned Ground Vehicle Technology VII Conference, Orlando, FL, 2005.
[4] R. Madhavan, W. Yu, G. Biggs, C. Schlenoff and H-M Huang. IEEE-RAS Standing Committee for Standards Activities: History and Status Update. Journal of the Robotics Society of Japan. May 2011.
[5] Operating Procedures and Policies of the IEEE Robotics and Automation Standing Committee for Standard Activities. April 2007.
[6] International Federation of Robotics, Service Robots, http://www.ifr.org/service-robots/, visited at 30th November 2011.
[7] World Robotics, International Federation of Robotics, 2011.
[8] RoSta - Robot Standards and Reference Architectures, http://www.robot-standards.eu/ , visited at 30th November 2011.
[9] G. H. Lim, I.H. Suh and H. Suh. Ontology-Based Unified Robot Knowledge for Service Robots in Indoor Environments, IEEE Transactions on Systems, Man, and CyberneticsPART A: Systems and Humans, vol. 41, no. 3, May 2011.
[10] IEEE-RAS Technical Committee on Service Robots, http://www.service-robots.org/ , visited at 30th November 2011.
[11] I. Niles and A. Pease.Towards a Standard Upper Ontology. In Proceedings of the 2nd International Conference on Formal Ontology in Information Systems (FOIS-2001), Chris Welty and Barry Smith, eds, Ogunquit, Maine, October 17-19, 2001.
[12] G. Guizzardi. Ontological Foundations for Structural Conceptual Models, PhD Thesis, University of Twente, The Netherlands, 2005.
[13] D. Russomanno, C. Kothari and O. Thomas. Building a Sensor Ontology: A Practical Approach Leveraging ISO and OGC Models.The 2005 International Conference on Artificial Intelligence, Las Vegas, NV.2005.
[14] A. Chella, M. Cossentino, R. Pirrone and A. Ruisi. Modeling ontologies for robotic environments. International Conference on Software Engineering & Knowledge Engineering, p.77-80, 2002.
[15] M. Fernandez-Lopez, A. Gomez-Perez and N. Juristo. METHONTOLOGY: From Ontological Art Towards Ontological Engineering. In: AAAI-97 Spring Symposium Series, 24-26 March 1997.
[16] J. Euzenat. Building consensual knowledge bases: context and architecture, in Mars, N. (Ed.), Building and sharing large knowledge bases, pp143-155, Amsterdam (NL): IOS press, 1995.
[17] A. Gomez-Perez. Evaluation of Ontologies International Journal of Intelligent Systems. Special Issue: Verification and Validation Issues in Databases, Knowledge-Based Systems, and Ontologies. Volume 16, Issue 3, pages 391-409, March 2001
[18] N. Guarino and C. Welty. An Overview of OntoClean. In Steffen Staab and Rudi Studer, eds., The Handbook on Ontologies. Pp. 151-172. Berlin:Springer-Verlag, 2004.
[19] M. Tenorth, A. Perzylo, R. Lafrenz and M. Beetz. The RoboEarth language: Representing and Exchanging Knowledge about Actions, Objects and Environments. In International Conference on Robotics and Automation (ICRA), 2012.

[20] L. Kunze, T. Roehm, M. Beetz. Towards Semantic Robot Description Languages. In IEEE International Conference on Robotics and Automation (ICRA), 2011.
[21] M. Genereseth and R. Fikes. "Knowledge Interchange Format" Stanford Logic Report Logic-91-1University. Stanford University, 1992.
[22] D. Gessler, G. Schultz, G. May, S. Avraham, C. Town, D. Grant, R. Nelson. SSWAP: A Simple Semantic Web Architecture and Protocol for semantic web services. BMC Bioinformatics 10:309. 2009.