A Review of Knowledge Bases for Service Robots in Household Environments

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Abstract. Consider a typical task-solving scenario where a robot is performing a task involving tool use. When a robot is operating in a dynamic environment, it can not be assumed that a tool required in the task will always be available. Our research work concerns the development of a knowledge-based computation system to determine a substitute for the unavailable tool. During the development, we identified the requirements regarding the knowledge base for our scenario and selected 9 existing knowledge bases for review. In this article, we review existing knowledge bases developed for the service robotics and investigate their suitability for this specific application. The knowledge bases are reviewed with respect to various criteria corresponding to the categories *knowledge acquisition*, *knowledge representation*, and *knowledge processing*. Our main contribution is to facilitate the selection of a knowledge base according to one's requirements of a target application for service robots involving household-objects.

Keywords: Service Robotics · Knowledge Base · Knowledge Representation · Reasoning

1 Motivation

It is not uncommon to find a tool needed for a certain task unavailable. However, humans tend to circumvent such hurdle by improvising the usability of a *suitable* existing object in the environment. For a robot who is expected to work alongside humans in the real word is bound to face such obstacles and an effective way to carry on with the task for it in such situations would be to find a substitute. A selection of an appropriate substitute requires a knowledge driven non-invasive deliberation to determine its suitability. Baber in [1] suggested that humans are aided by ontological knowledge about objects during the deliberation process. Our research work aims at developing a computation system to determine a substitute which is aided by ontological knowledge about objects.

For instance, consider a scenario in which a robot has to choose between a plate and a mouse pad as an alternative for a tray. A tray, in general, can be defined as a rigid, rectangular, flat, wooden, brown colored object while a plate can be defined as a rigid, circular, semi-flat, white colored object and a mouse pad as soft, rectangular, flat, leather-based object. Bear in mind, however, that some properties are more relevant than the others with respect to the primary purpose of the tool. For a tray whose primary purpose is *to carry*, rigid and flat are more relevant to *carry* than a material or a color of a tray. Consequently, to find the most appropriate substitute, the relevant properties of the unavailable tool needs to correspond to as large a degree as possible to the properties of the possible choices for a substitute.

The proposed approach performs a knowledge-driven reasoning to identify the relevant properties of the unavailable tool and determines the most similar substitute on the basis of those properties. Since the computation requires an access to the ontological knowledge about properties of a missing tool and of existing objects in the environment, we set out to explore the existing knowledge bases. The primary objective of this exploration was aimed at determining whether the knowledge about objects from the existing knowledge bases can be exploited in our approach.

The demand for such ontological knowledge about objects has been increasing (see Table 2). Especially, for the developers of the reasoning systems such as tool selection, task planning or an action selection aimed at a service robot who is expected to perform household tasks, an unhindered access to a stack of knowledge about objects or the environment is a primary concern. Since there are many knowledge bases developed for service robots, it can be cumbersome to scrutinize each one of them to examine the usefulness to the intended system. The objective of this review article is to provide an overview of the existing knowledge bases which can facilitate the selection of a knowledge base according to one's requirements of a target computation system involving household-objects for service robots.

2 Knowledge Base Selection

There has been an increasing interest in the knowledge-based systems aimed at various applications in robotics such as human-robot interaction [12], action recognition [8], task planning [25], robot navigation [23]. While there are myriad amount of knowledge bases designed for either specific application or for wider range of applications, it is a challenging task to identify the most suitable one for our specific demands. After determining that there is no comparison of knowledge bases containing the relevant information for the robotic applications exists, we executed a systematic investigation of the state of the art into three phases to identify the relevant knowledge bases:

b) Literature Search: In order to find the relevant papers for this review article, we automatically aggregated publications from publication databases by referencing the following combinations of keywords : `knowledge engine robot`, `knowledge database robot`, `knowledge household objects`, `knowledge data household` and `knowledge base robot`. The crawler provided 313 papers after removing the duplicates.

Table 1. List of selected knowledge bases and their names

Knowledge Base	Name
Knowledge processing system for Robots	KNOWROB [19]
Knowledge Base using Markov Logic Network	MLN-KB [26]
Non-Monotonic Knowledge-Base	NMKB [15]
Open Mind Indoor Common Sense	OMICS [7]
Ontology-based Multi-layered Robot Knowledge Framework	OMRKF [18]
OpenRobots Ontology	ORO [11]
Ontology-based Unified Robot Knowledge	OUR-K [13]
Physically Embedded Intelligent Systems	PEIS [3]
Knowledge Engine for Robots	RoboBrain [17]

c) Literature Filtering: In this phase, the paper selection was manually evaluated and assessed. The papers without any relation to the aforementioned required knowledge bases were rejected while the remaining papers were ordered according to the knowledge base. We removed the papers which:

- focused on the development of knowledge bases for non-robotic applications.
- were written from the application perspective, without a discussion of the underlying knowledge base.
- do not cover knowledge about household objects.
- focused primarily on knowledge acquisition without a framework in place to store the acquired knowledge or update the existing knowledge.

As a result, we selected 39 papers covering 9 knowledge bases for evaluation [1]. The involved knowledge bases are summarized in Table 1 along with their acronyms by which they are identified. The plot in Figure 1 illustrates the life span of each knowledge base.

d) Final Literature Selection: In the last step we revised the final list and extracted the most important papers according to:

1. Content - we looked for papers providing detailed descriptions of configurations, content, performance, interfaces, etc. of the knowledge base. This information is necessary to assess the knowledge bases with respect to different criteria.
2. Impact - we examined the impact of each paper on the basis of the number of citations the selected papers have received and how those numbers have evolved over the years as illustrated in 'Impact of the paper' column of table 2. In terms of the number of citations, KNOWROB is so far the most influential knowledge base since its inception while individual papers referencing OMICS and OMRKF are continuously cited.

[1] This complete list is available at `https://essfiles.ivs.cs.ovgu.de/index.php/s/PgdgM19V6GSQ5IW`

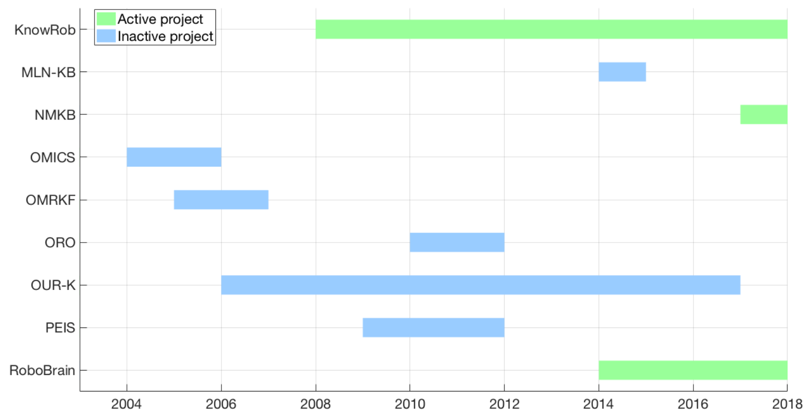

Fig. 1. The plot illustrating the knowledge bases that are still actively researched according to the published work indicating the life span of each knowledge base.

For KNOWROB, however, we have isolated 4 from over 40 papers. For the comprehensive list of the paper, please visit the web page of KnowRob (see Appendix A) As a result, the original list was filtered and eventually 20 research papers were selected covering the 9 knowledge bases (see Table 2).

3 Knowledge Base Review

For reviewing, we focus on three primary components to characterize a knowledge base: how is the knowledge acquired, how is it represented and how is it processed. This section provides an aerial view of the knowledge bases along the same characteristics. For each characteristic: we have selected the following criteria (see Table 3)

The real-world is differently perceived by a robot than its human counterpart due to the limited perception capabilities of the robot. It is, therefore, necessary to distinguish between what knowledge was acquired from the sensory data or from the robotic perspective and what knowledge was acquired from non-sensory sources such as web pages, manually encoded, or from a human perspective. For the proposed approach, the acquisition of knowledge from a robotic perspective is prudent. Note that a substitute selection is a decision relative to an agent's (human or robot) understanding of an object. We believe that a substitute should be chosen based on a robot's understanding of an object instead of human's understanding since it is a robot that is supposed to manipulate the substitute. Thus, when reviewing the 'knowledge acquisition' of the knowledge bases, we focused on the source of the knowledge and what kind of knowledge was acquired from this source. These two aspects inform what knowledge is from human perspective and what knowledge is from robot perspective. For instance,

Table 2. The selected knowledge bases, along with the pointers to the papers about and an overview about their impact (overall count of references on this paper(s), year of publication, distribution of the references between 2004 and 2018)

Knowledge Base	**Pointers**	**Impact of selected papers**
KNOWROB	[19], [22], [20], [21]	761
MLN-KB	[26]	95
NMKB	[15]	0
OMICS	[7], [5], [6]	98
OMRKF	[24], [9], [18]	91
ORO	[11], [10], [16]	105
OUR-K	[13], [4]	88
PEIS	[3], [2]	80
RoboBrain	[17]	57

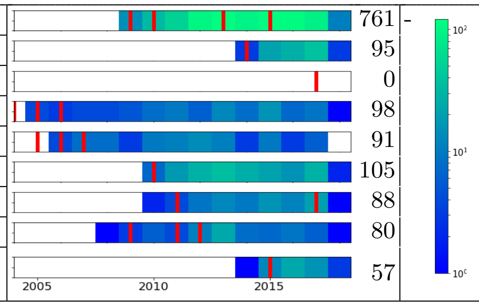

Table 3. The list of criteria corresponding to the characteristics Knowledge Acquisition, Knowledge Representation and Knowledge Processing used to review the knowledge bases

Characteristic	**Criteria**
Knowledge Acquisition	Knowledge Source Knowledge Type
Knowledge Representation	Representation Formalism Modeling of Uncertainty Symbol Grounding
Knowledge Processing	Inference or Query Mechanism

some knowledge bases have extracted common sense knowledge about objects from WordNet or OpenCyc and geometric data about an object, spatial relation between objects or metric map of an environment are acquired using vision sensors such as a camera or laser scanner.

The knowledge acquired from various resources needs to be accumulated and encoded in a formal language such that it provides meaningful description of the world and can be processed smoothly. The 'representation formalism' criteria examines the different formalisms used to represent the knowledge in the knowledge bases (see Table 5). Since the proposed approach deliberates on a possible substitute non-invasively, we are interested in a logic-based representation of the world that will allow a reasoning-based computation.

On one hand our proposed approach requires the understanding of the environment and the objects in it from the robotic perspective; on the other hand, the knowledge about the objects need to be represented in a logic-based formalism. These two requirements can co-exist when knowledge is grounded in the sensory data. The grounding of knowledge is popularly known as symbol grounding or symbol anchoring. For a developer who wishes to use knowledge representation and reasoning techniques for a robotic application, it is recommended that knowledge is grounded into the robot's reality of the world. There-

Table 4. Comparison of the selected knowledge bases with respect to knowledge acquisition: what is the source of knowledge and what kind of knowledge was acquired using the source.

Knowledge Base	Contents: Object	Appearance	Properties of Objects	Spatial Relations	Temporal Relations	Uses of Objects	Topological Relations	Map of the Environment	Actions	How to Perform Task	Other	Source of knowledge
KNOWROB	●	●		●	●		●	●	●			Multi-Modal Sensor Systems
	●	●	●	●		●	●				A	OpenCyc, WordNet, OMICS
	●	●										Online Shops
										●		Observation of Human Activities or Shared by Other Robots
										●		Web Instructions
MLN-KB	●	●										ImageNet
	●	●	●									Freebase, Amazon, Ebay
	●		●									WordNet
	●					●						Manually Encoded
											B	Standford 40 Action Dataset
NMKB	●	●	●	●		●	●		●	●		An Interaction-Oriented Cognitive Architecture [14]
OMICS	●	●	●	●	●	●	●	●	●	●	A	non-expert users, WordNet
OMRKF	●	●	●	●			●	●				Multi-modal Sensors
	●		●	●	●	●	●					Manually Hand-coded
ORO	●	●	●	●					●			OpenCyc
	●	●	●	●			●					Multi-modal sensor system
	●	●	●	●			●					Human Interaction
OUR-K	●	●	●	●			●	●				Multi-modal sensor system
	●		●	●	●	●	●		●			Manually Hand-coded
PEIS	●		●	●		●	●					Cyc
	●		●	●		●	●					Vision and Localization System
RoboBrain	●		●			●			●	●		Robot Interaction
	●		●								A	WordNet, OpenCyc, Freebase
	●		●									ImageNet

A = Common Sense Knowledge about the objects and the environment
B = Human-poses and human-object relative position during object manipulation

Table 5. Comparison of the selected knowledge bases with respect to Representation Formalism

Knowledge Base	**Formalism**
KNOWROB	OWL-RDF
MLN-KB	Markov logic network
NMKB	Prolog - Horn Clause
OMICS	Relational Database
OMRKF	OWL-RDF
ORO	OWL-RDF
OUR-K	OWL-RDF
PEIS	Second Order Predicate Logic
RoboBrain	Graph Database

fore, the selected knowledge bases are reviewed to examine what knowledge in the knowledge base is grounded (see Table 6).

Table 6. Comparison of the selected knowledge bases with respect to Symbol Grounding.

	Grounded Knowledge								
Knowledge Base	Object	Properties of Objects	Spatial Relations	Location	Affordances	Topological Relations	Actions	Task	Other
KNOWROB	●	●	●	●	●	●	●	●	
MLN-KB	●	●	●	●	●		●		A
NMKB	●		●				●		
OMICS									B
OMRKF	●	●	●			●			B
ORO	●	●	●			●			
OUR-K	●	●	●			●			
PEIS	●	●	●		●	●			
RoboBrain	●	●							

A = Weights of the objects
B = Knowledge is not grounded

Understanding the environment or objects in it from a robot perspective has its own share of difficulties. For instance, the knowledge that is acquired from the sensors carries a baggage of uncertainty. The uncertainty can be due to the

Table 7. Comparison of the selected knowledge bases with respect to Modeling of Uncertainty: what knowledge is modeled and what mechanism is used

Knowledge Base	**Mechanism**	**Knowledge Content**
KNOWROB	Probabilistic Model Statistical Relational Models	Noisy sensor information Relations between objects, types of objects
MLN-KB	Median-based	Noise in the web data
NMKB	Principle of Specificity	Incomplete Knowledge
OMICS	-	Uncertainty not considered
OMRKF	-	Uncertainty not separately modeled
ORO	Validation by Users	Unknown objects and its properties
OUR-K	Bayesian Inference	Unknown objects, action selection, context recognition
PEIS	Validation by Users	Disambiguate multiple groundings of a symbol
RoboBrain	Validation by Users	Inconsistencies due to knowledge coming from different resources, Disambiguate due to the same word having different meaning

noisy data or partial observability and can manifest into various forms such as incompleteness, inconsistency, ambiguities that can affect the overall quality of the knowledge. One way to deal with the uncertainty is, for instance, by representing the uncertain knowledge probabilistically. In order to do that, one needs to identify what knowledge is uncertain. The 'modeling of uncertainty' criteria focuses on these two issues: what kind of knowledge is modeled for uncertainty and what mechanism is used for modeling (see Table 7).

Not all knowledge can be perceived using the sensory sources, for instance, typical topological relations between objects and places such as cups are usually in the kitchen or the similarity relations between objects which can not perceived visually in its entirety. The possible source for such type of knowledge would be by reasoning about the existing knowledge and drawing inferences from it or by querying the knowledge base. The knowledge processing criteria looks into both the aspects of processing: what knowledge in the knowledge base is inferred or can be queried and what inference or query mechanism is used to achieve that (see Table 8).

So far, we have discussed the characteristics of the knowledge bases with respect to knowledge acquisition, representation and processing. For a knowledge base to be useful, size of the knowledge base is a critical piece of information. The size of the knowledge base can be measured in terms of quantities in which different kind of knowledge is available, for instance, number of objects, properties, relations etc. In table 9, we have provided the information on the size of each knowledge base as reported in the respective literature.

Accessibility is the quality of being easily available to use. The knowledge bases should be developed such that they can be used by the developers around

Table 8. Comparison of the selected knowledge bases with respect to Inference/Query Mechanism: what kind of knowledge is inferred and what mechanism is used.

Knowledge Base	Contents										Mechanism
	Object	Properties of Objects	Spatial Relations	Localization	Affordances	Topological Relations	Context	Actions	Task	Other	
KNOWROB	●	●	●	●	●	●	●	●	●	A	Prolog Query
	●	●	●	●		●		●	●	A	Probabilistic Inference
MLN-KB	●				●						ImageNet
NMKB										B	Prolog Query and Logic Inference
OMICS	●	●			●	●	●	●	●	A	SQL query
OMRKF	●	●	●			●	●	●			Logical Inference
ORO	●	●	●	●							Pellet
OUR-K	●	●	●			●	●	●			Bayesian Inference
PEIS			●	●	●	●	●	●	●		OWL Query
RoboBrain										A	RoboBrain Query Library

A = Retrieve knowledge from the knowledge base
B = Conceptual Inferences

Table 9. This table comprises the information about the size of knowledge bases reviewed in this paper. The size of knowledge bases is mainly quantified based on the number of objects, number of classes, instances etc.

Knowledge Base	**Quantification of size of KB**
KnowRob	Around 8000 classes that describe events, actions, objects, mathematical concepts and so on
MLN-KB	40 objects comprise 100 images and on average 4.25 affordance for each objects
NMKB	Not available
OMICS	As of 2004, 400 users with 26,000 accepted submissions, 400 images of indoor objects (current number of images unknown) comprising a total of 100000 entries in the form of objects, actions, senses.
OMRKF	Knowledge about approximately 300 objects as per 2005
ORO	56 object classes and 60 predicates that states relation with objects
OUR-K	Knowledge about approximately 300 objects as per 2005
PEIS	15 objects that comprise 2 to 5 images for each object
RoboBrain	44347 concepts and 98465 relations

the world in various applications.The knowledge base accessibility criteria examines the ways in which each knowledge base is made accessible to the developers.In the accessibility, we have examined, if the knowledge bases are available to download or install, if there are tutorials or any other documentation available to get the user started and if there is information on API available. Additionally, we also check what kind of licensing is made available. The Table 10 summarizes the accessibility of each knowledge base. Since for OMICS, OMRKF, OUR-K and PEIS, we were not able to find the required information, we have indicated NA (Not Applicable) in the table. Additionally, we have provided the available web pages for the knowledge bases in appendix A.

Table 10. Compendium of Knowledge bases accessibility features.

Knowledge Base	**Download?**	**Install?**	**License**	**Documentation**	**API**
KnowRob	yes	yes	Apache License	yes	yes
MLN-KB	yes	no	Open source	no	yes
NMKB	yes	yes	Golem Group License	yes	yes
OMICS	NA	NA	NA	NA	NA
OMRKF	NA	NA	NA	NA	NA
ORO	yes	yes	GNU General Public License	yes	yes
OUR-K	NA	NA	NA	NA	NA
PEIS	NA	NA	NA	NA	NA
RoboBrain	yes	yes	Creative Commons license	Yes	yes

4 Conclusion

In this article, we have investigated the existing knowledge base approaches for service robot applications and evaluated their capabilities related to a specific research project. For this purpose we searched for knowledge bases that are developed for household robots and contain knowledge about household objects and we identified 9 existing knowledge bases. In addition to the life span of each knowledge base, the information concerning which knowledge bases have made impact in the community was measured in the form of a number of citations the literature related to each knowledge base has received. The knowledge bases were reviewed with respect to the amount of knowledge it holds. Each knowledge base was further examined with respect to the following criteria: acquisition of knowledge (what knowledge is acquired and what is the source), representation formalism, symbol grounding, modeling of uncertainty (what knowledge is modeled and what mechanism is used) and lastly, inference mechanism (what knowledge was inferred or queried and what mechanism was used?). We concluded our review by evaluating the accessibility of each knowledge base to the users.

For our approach, we are interested in the knowledge base that has ontological knowledge about household objects, especially knowledge about the properties and uses of the objects. It is also prudent that the required knowledge is grounded and the uncertainty caused by the partial observability of the environment due to the noisy sensor is modeled using probability or fuzzy logic. Based on our investigation, we have concluded that the knowledge bases KnowRob and MLN-KB seems suitable to our purpose. In the future work, we will conduct the experiments where the knowledge extracted from them will be used to evaluate the performance of our approach.

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A Appendix

1. `http://www.aass.oru.se/Research/Robots/projects.html` (PEIS)
2. `https://www.openrobots.org/wiki/oro-server` (ORO)
3. `https://web.stanford.edu/~yukez/eccv2014.html` (MLNKB)
4. `http://robobrain.me/about.html` (Robobrain)
5. `https://github.com/RoboBrainCode` (Robobrain)
6. `https://tinyurl.com/y9uboh62` (NMKB)