Engineering Background Knowledge for Social Robots

Luigi Asprino

University of Bologna, Bologna, Italy

1 Motivation and objectives of the research

Social robots are autonomous embodied agents that interact, collaborate, communicate with humans, by following the behavioral norms expected by people with whom robots are intended to interact. In recent years, the field of socially assistive robotics has emerged given the great potential of social robots in supporting people with cognitive impairment or physical disability. In order to show human-like social abilities, robots should be endowed with a background knowledge. This could be informally defined as the knowledge that a robot need in order to operate. This background knowledge includes (but it is not limited to): linguistic, encyclopedic and procedural knowledge as well as knowledge concerning the physical world and social norms.

Providing a framework for engineering robots' knowledge raises several problems like identifying sources and modeling information relevant for robots' activities, integrating knowledge coming from different sources, evolving this knowledge with information learned during robots' activities, grounding perceptions on robots' knowledge, assessing robots' knowledge with respect humans' one and so on. The choice of a knowledge representation framework has an impact on the expressiveness (the breadth of concepts that can be represented), on the ability infer logical consequences form asserted facts in a tractable manner (i.e. tractability) and on the amount of tools and knowledge already available that can be provided to robots for supporting their tasks.

The Semantic Web standards give a good trade-off among the expressiveness, tractability and availability of resources and tools for manipulating such knowledge. The Semantic Web is an extension of the World Wide Web aimed at providing a framework that allows data to be shared with a common syntax and semantics. It based on a language defining the syntax of data to be shared (i.e. XML), a model defining the format of data (i.e. RDF) and a language to formally specify the semantics of data (i.e. OWL). Semantic Web standards provide a good expressive power (equivalent to Description Logics), without compromising decidability and tractability. It is supported by a pletora of off-the-shelf reasoners, knowledge management systems, as well as tools for creating, organizing and integrating knowledge. Another benefit of implementing a framework that relies on Semantic Web technologies is the opportunity of exploiting knowledge available as Linked Open Data (LOD).

The aim of the research can be summarized in the following question.

RQ0: To what extent Semantic Web technologies and Linked Data can be used to create, organize, access to, and evolve robot's background knowledge?

Existing solutions for managing robots' knowledge (e.g. RoboEarth, RoboBrain, ORO) only partially exploit the potential of Semantic Web technologies and Linked Data. In these projects, Semantic Web technologies are mostly employed to address syntactic heterogeneity of data, to define conceptualizations of the robots' knowledge, and, more rarely, to include external datasets within the robots' knowledge base.

We claim that robots' architectures can profoundly benefit of Semantic Web technologies and Linked Data paradigm. *(i)* Semantic Web technologies could enable an incremental and iterative development of the architecture. *(ii)* Semantic Web standards allow to easily integrate data generated by a variety of components, thus enabling robots to make decisions by taking into account knowledge about the physical world, data coming from their operating environment, information about social norms, users' preferences and so on. *(iii)* Semantic Web technologies provide flexible solutions to extend and evolve robots' knowledge over time. *(iv)* Linked (Open) Data paradigm lets to easily reuse (i.e. integrate with robots' knowledge) existing external datasets so to bootstrap knowledge base with relevant information for robots' activities. *(v)* Linked Data also provides a mechanism that allows robots to mutually share knowledge.

The research question RQ0 can be decomposed into the following sub-questions:

RQ1: What kind of knowledge a robot needs to operate in socially assistive context? What exiting ontologies can be used to organize the robot's knowledge? What ontologies need to be advanced? What domains of interest in this context miss of a conceptualization?
RQ2: What Linked Data can provide background knowledge for social robots tasks?
RQ3: How to provide robots with access to knowledge?
RQ4: How to integrate robot's knowledge with data coming from robot's experience?
RQ5: How Semantic Web technologies can be orchestrated to support robot tasks?

2 Description of the approach and the evaluation strategy

The organization of the research activities have followed two complementary paths, though interlinked and interleaved among each other. On the one hand, we approached a case study with an explorative strategy aimed at investigating the needs of a real socially assistive robotic application and highlighting the limits of current solutions. On the other hand, the problems that came from the real setting have been generalized in order to contribute with their solutions to advance the state of the art. The two activity paths are summarized hereafter together with the strategy for evaluating the contributions of the thesis.

Explorative Approach to the Case Study. The work carried out along this path has focused on identifying the needs of a real socially assistive robotic application, highlighting the limits of current solutions, and, designing, developing, deploying and testing working solutions within a concrete robotic application. In line with the overall principles and methodology adopted in the case study (the H2020 MARIO Project), we have followed an incremental and iterative design and development approach, inspired by Agile principles. As a consequence, the implemented approaches and solutions have been: *(i)* designed following a requirements-driven and user-centered approach, taking into account pilot sites' needs and scenarios; *(ii)* incrementally integrated, tested and validated during trial activities; *(iii)* gradually refined and improved on the basis of trials feedback.

Research Activities and Solutions Targeting Open Problems. The work carried out along this path has focused on research activities aimed at identifying solutions targeting open problems in the field of knowledge representation and engineering. These research problems are either inspired by and abstracted from concrete use cases or derived from general challenges that can be specialized in the context of socially assistive robots. These problems have been synthesized in the research questions RQ0-RQ5 outlined in Section 1.

Evaluation strategy. The contributions of the thesis have been evaluated by following two different strategies, one targeting the whole robotic system that was developed and assessed in the context of the MARIO project and the other focusing on individual components of the architecture that were individually evaluated through suitable experiments (meant to assess the accuracy of components) or proof-of-concepts (intended to demonstrate the feasibility of components).

3 Major contributions

This thesis contributes to goals presented in Section 1 as follows.

The thesis proposes a set of interconnected and modularised ontologies, i.e. the MARIO Ontology Network (MON), which are meant to model all *knowledge areas* that are relevant for robots' activities in socially assistive contexts (cf. **RQ1**). MON reuses and integrates state-of-the-art ontologies in various domains (such those related to personal information, social and multimedia contents), and, proposes novel solutions in medical domain (e.g. CGA Ontology) and in robotic domain (i.e. Affordance Ontology Design Pattern).

The knowledge base is originally populated with lexical, linguistic and factual knowledge retrieved from Linked Open Data. The thesis presents a novel process for generating, integrating and assessing this knowledge (cf. **RQ2**). Moreover, it proposes a novel empirical method for assessing foundational distinctions over Linked Open Data entities from a common sense perspective (e.g. deciding if an entity inherently represents a class or an instance from a common sense perspective). This method realizes the preliminary step of a more general procedure meant to automatically generate common sense knowledge from Linked Open

Data (cf. **RQ2**). These methods advance state-of-the-art in Semantic Web by proposing standardized techniques for creating an integrated repository of linguistic, factual, encyclopedic, ontological and common sense knowledge. The benefits of these techniques as well as the resulting datasets are not limited to robotic domain, but also extend to every application domain that requires a rich knowledge base to operate.

The thesis presents an object-RDF mapper (called *Lizard*) that facilitates software components to interact with an RDF knowledge base (cf. **RQ3**). In particular, given an RDF knowledge base and an OWL ontology describing its structure, Lizard provides applications with an API for accessing RDF facts stored in a knowledge base following the object-oriented paradigm. The API reflects the semantics of the input ontology and allows transparent access to the knowledge base, Differently from existing systems, Lizard exposes the API following the REST architectural style over HTTP. This tool is aimed at easing the software development of knowledge-aware systems by filling the gap between Semantic Web technologies and Object-Oriented applications. The benefits of Lizard are not to be intended only for robotic domain, but every application that need to access to a knowledge base compliant with Semantic Web standards could potentially use Lizard's APIs.

The thesis describes a novel approach for automatically integrating knowledge coming from different ontologies with a frame-driven approach (cf. **RQ4**). This method aimed at finding complex correspondences between ontology entities according the intensional meaning of their models, hence abstracting from their logical types. In this proposal, frames are considered as "unit of meaning" for ontologies and are used as a mean for representing intentional meaning of ontology entities.

The thesis introduces a component-based architecture relying on Semantic Web standards for supporting knowledge-intensive tasks performed by social robots, and whose design has been guided by requirements coming from a real socially assistive robotic application. The ultimate goal aim of the architecture is to create a platform for easing the development of robotic applications by providing developers with off-the-shelf software artifacts, models and data. The strategy to pursue this goal is to massively reuse Semantic Web technologies due to their intrinsic availability and interoperability. Moreover, we present a prototype which is aimed at demonstrating feasibility and benefits of such a architecture and two applications running on top of the architecture prototype. This framework could potentially be integrated, with appropriate adaptions, with every autonomous agents (not limited to embodied systems).

4 Ongoing and Future Work

Approaching other Domains. Although trials in different healthcare settings confirm the validity of the approach, large part of the future activities shall be put in analyzing, adapting, deploying and evaluating the overall framework for other scenarios different from the healthcare context (e.g. education or entertainment).

New modeling requirements for the architecture (e.g. new components to be integrated) and for the ontology network (e.g. new modules to be designed) could emerge from new scenarios. Novel information shall be possibly integrated within the knowledge base for supporting robot's activities in the new scenarios.

Pattern-based Interaction with Knowledge Base. Lizard, like other tools for programmatically accessing knowledge bases, enables a triple-based interaction with triple stores, i.e. generated Java methods deal with a single triple at time. Instead, a valuable direction for improving the usability of the API and the interaction with the knowledge base could be enabling a pattern-based interaction.

Extending Framester. Ongoing work is about integrating and linking Framester's linguistic information with other kinds of knowledge, so to provide robots with a richer human-like knowledge base. The following types of knowledge could be valuable for the robot activities: procedural knowledge (e.g.The Web of Know-How), physical knowledge, and open-domain common sense knowledge (such that produced in projects like ConceptNet and NELL). Another line of research is on improving linguistic coverage of Framester's frames in cataloging and describing situations.

Common Sense Knowledge. This thesis reports a set of experiments for assessing whether the Web, and in particular Linked Open Data, provides an empirical basis to extract foundational distinctions, and if they match common sense. For both questions we observed promising results and define a method that can be generalised to investigate additional distinctions. We plan experiments on other foundational distinctions (e.g. types of locations, objects that can serve as locations or containers, etc.) and with additional methods. The good precision of alignment-based methods ($\sim$90% for both classifications) allows to hypothesize that output of this method could provide valuable examples for training Machine Learning methods. Our ultimate goal is to advance the state of the art of AI tasks requiring common sense reasoning by designing a methodological framework that enables mass-production of common sense knowledge, and its injection into LOD. To this end effort should be payed on knowledge representation languages and (meta-)models to encode common sense. Challenges for knowledge representation filed come from the need of having suitable languages and models for encoding: *(i) agreement on*, *(ii) evidence of*, and *(iii) validity of* common sense facts. This information is essential for autonomous agents to take decision. Agreement (i.e. the number of people that agree with a stated fact) and evidence (i.e. other facts that support a given fact) of facts guarantee the trustworthiness of data and the reliability of its decisions. The validity (i.e. where and when a fact is true) guarantees the suitability of context in which the fact is used. Validity and evidence together could enable an agent to assess: if a certain fact apply for the context at a hand, and the degree of similarity between a situation an agent should face and other situations where the fact has proven to be true. Future work shall focus on investigating to what extent available languages and models are suitable to these purposes.