Sys-Self, Systems That Know What They Are (Doing): Extended Abstract

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Abstract

Autonomous robots are used in a variety of tasks and context; however, there are still issues with their performance and reliability in real-world scenarios. This research focuses on the use of declarative knowledge to improve the dependability of robots in complex, dynamic environments. We propose to leverage Model-Based Systems Engineering through ontologies so that systems can flexibly respond to unexpected situations while maintaining performance standards. Moreover, to enhance reusability and granularity, we rely on formal conceptualizations based on Category Theory. This integration of knowledge representation and mathematical models seeks to aid decision-making to adapt robot behavior in the presence of contingencies.

Keywords

knowledge representation and reasoning, category theory, model-based systems engineering, robot dependability

1. Introduction

Autonomous robots have revolutionized various domains by performing complex tasks with endless possibilities. However, there are still open issues in dependability and trust. To ensure successful deployment in unstructured, real-world scenarios, robots require a better understanding of their environment and the tools to act and react properly, even in the presence of high uncertainty.

This research focuses on using *declarative knowledge* to represent and reason about the cross-cutting elements of the robot, such as its mission, its design, and its operation in open environments. By exploiting this information at runtime, robots can adapt their structure and replan actions to keep pursuing their goals, even in unexpected situations. Ontologies are used at runtime to ensure mission fulfillment within expected performance, thereby increasing robot flexibility, explainability, and efficacy.

Despite standardization efforts such as IEEE 1872-2015 Standard Ontologies for Robotics and Automation [1] or the Ontology for Autonomous Robotics [2], more complete formalisms are needed to enable operationalization in complex environments. Model-Based Systems Engineering (MBSE) is a promising methodology that utilizes *system representation* throughout the entire system lifecycle, facilitating automated module production and enabling functional

FOIS 2023 Early Career Symposium (ECS), held at FOIS 2023, co-located with 9th Joint Ontology Workshops (JOWO 2023), 19-20 July, 2023, Sherbrooke, Québec, Canada

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reliability and adaptive resilience. This approach has gained traction in robotics engineering due to the critical role that models play in robot design, enabling the achievement of holistic properties such as functional reliability and adaptive resilience while facilitating automated module production. However, to support the deployment of autonomous robots in real-world scenarios, a deeper understanding is needed beyond the engineering phase. We propose the use of formal conceptualizations leveraging *Category Theory* as a mathematical framework to describe abstractions and produce accurate robot models.

The combination of knowledge representation and reasoning with abstract mathematical system models based on Category Theory (CT) can significantly enhance the performance, dependability, and trustworthiness of autonomous robots. Using ontologies at runtime allows the robot to reason about the system, its environment, and its behavior, so it has a better comprehension of the situation it faces. This helps the autonomous robot to make more informed decisions. The categorical theoretical model provides a formal foundation to ensure consistency along the changes that the knowledge base, or the system itself, can suffer during robot operation. This can aid in the accuracy and reliability of the system as it strives for the system to behave as expected.

2. Motivation

Robotics has shown enormous possibilities in a variety of tasks and environments. However, there are still *open issues* that compromise the dependability of autonomous robots. Our motivation stems from the challenges of bridging the reality gap between robots used in controlled environments and their deployment in unstructured, real-world scenarios. To enable successful deployment in such scenarios, it is essential to equip robots with the necessary tools to act and react properly to undesired events with high uncertainty. To overcome these challenges, we shall endow the robot with a better *understanding* about what is happening, what capabilities the robot has and what tools the robot can use to reach its goals. Our research studies the hypothetical benefits of (i) formalizing system models -including both software and hardware- and (ii) exploiting such models at runtime. These models can potentially improve robot awareness, increasing explainability and resiliency towards unexpected contingencies.

3. Research Questions

We aim to use robust models at runtime as a tool to deliver a better understanding of the situation and react properly in unstructured environments. This can be condensed as the research question:

> *"Is it possible to enhance robot's understanding—about itself, its mission and its environment—from a systemic perspective?"*

As our approach is motivated by system models and mathematical abstract formalisms, the following question arises:

> *"Does system models increase robot dependability, i.e., its ability to fulfill user needs, in complex missions and/or in presence of contingencies?"*

Lastly, as we envision knowledge representation and reasoning as a way to leverage explicit engineering knowledge during robot operation, we question its impact on robot performance:

> *"How ontological reasoning about complex system models affect robot decision-making?"*

4. Objectives

The aforementioned research questions can be translated into specific objectives to create a software asset that can be used at runtime and is based on a CT-grounded abstract formalism:

- Analyze existing approaches for system modeling and knowledge-driven robots.
- Explore the relation between self-awareness and models.
- Formally define constituents of robot operation and its relationships in an abstract mathematical model, e.g., mission, design, behavior, perception, actuation, environment, etc.
- Develop a layered ontology based on robot formal models.
- Build reusable software assets that exploit robot ontologies at runtime.
- Demonstrate the validity of the approach at least in three robotic deployments, including simulated and real robots.

5. Research Methodology

Given the multidisciplinary approach in this work and the desire to obtain generality without losing sight of the engineering application, we follow a mixed methodology between the scientific method and the engineering process. First, we follow a preliminary analysis phase to characterize the problem, identify existing approaches, and identify key issues, research areas, and technologies of potential relevance. This study allows us to establish the design principles for *Formal System Model*. This model shall be refined into several applications to prove its applicability to different robot contexts and its reusability. We shall use testbeds to validate the research conducted in both simulated and real robot deployments.

As this research focuses on several fields, there is no common solid mainstream ground to depart from. To guarantee a steady progress, we follow the *snowflake methodology*, in which we start with a simplistic approach to the analysis-development-validation process and iterate over it to add complexity and generality. Some important milestones in our approach upon which we iterate are (i) the formalization of robot concepts in an abstract mathematical framework, (ii) the grounding of models in ontologies to exploit them at runtime, and (iii) the evaluation of how runtime reasoning impacts robot performance, fault tolerance, and explainability.

6. Research Results to Date

This section aims to provide a clear and concise summary of the research conducted. In a broad sense, it establishes a landscape on how ontologies can be formalized by category theory to provide reusable software assets to increase robot dependability.

We conducted a systematic review of ontology-enabled processes for trustworthy robot autonomy [3]. From it, we determined that conceptualization provides robots with a powerful tool towards achieving robustness and resiliency. However, most frameworks that use ontologies at runtime do not include full explicit engineering knowledge about the robot or its mission (information about robot components and their interaction, design requirements, and alternatives that the robot can use to explain its decisions or adapt to the situation). Robots are far from meeting user and owner expectations, especially in terms of dependability, efficiency, and efficacy. For example, robot models could include user phenomenological aspects, required safety levels, or energy thresholds that make a task unprofitable.

Following the ontological approach, we extended the Teleological and Ontological Model for Autonomous Systems (TOMASys) framework, a meta-model developed to provide concepts for modeling the functional knowledge of autonomous systems. This work aims to reuse system models on a variety of deployments. In particular, we applied this approach to an underwater robot [4], a miner robot [5], and a mobile robot in a university setting [6, 7]. We measured its impact in robot performance but found some limitations on OWL description logic's expressiveness and scalability.

To overcome these issues, we propose the use of *Category Theory* (CT), a framework to support system modeling and behavioral analysis for complex Systems of Systems (SoS). CT is a general theory of mathematical structures. It was invented in the 1940s to unify and synthesize different areas in mathematics [8]. It can be seen as a set of tools to describe general structures and maintain control over which aspects are preserved when performing abstractions. This can be especially useful in the context of robotics, where there may be many different components that need to work together to achieve desired behavior. Using CT, we can represent the different components and their relationships in a formal way, which can help us reason about the system as a whole. As described by Schweiker in [9], it is a natural framework for modeling and analysis of systems.

In conclusion, we believe that explicit formal knowledge can support autonomous robot operation in unstructured environments and the necessary engineering processes. There are still many open issues with respect to the reliability, safety, and explainability of meeting the expectations of researchers and industry. However, the steps taken towards enhancing robot autonomy using ontologies have proved how promising this approach is. Category theory provides a neutral, universal framework to formally depict structure and behavior; to represent and reason about complex systems with many interconnected components in an abstract sense. Such formalization can increase ontological soundness and reusability, taking a further step towards convergence and harmonization.

Acknowledgments

This work was partially supported by the ROBOMINERS project with funding from the European Union's Horizon 2020 Research and Innovation Programme (Grant Agreement No. 820971), by the CORESENSE project with funding from the European Union's Horizon Europe Research and Innovation Programme (Grant Agreement No. 101070254), and by a grant from *Programa Propio* of Universidad Politécnica de Madrid.

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