



# **Formalization and Runtime Verification of Invariants for Robotic Systems**

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*"Dreams breathe life into men, and can cage them in suffering. Men live and die by their dreams, but long after they've been abandoned, they still smolder deep in men's hearts. Some see nothing more than life and death. They are dead! For they have no dreams."*

*Kentaro Miura in Berserk*



## Resumo

A Robótica tem uma grande influência na sociedade atual, ao ponto que a falha em algum sistema robótico que seja crucial pode impactar o modo em como nós vivemos, se, por exemplo, um carro autônomo provocar a morte de algum passageiro devido a um defeito, futuros e atuais utilizadores deste modelo irão certamente ficar apreensivos em relação à sua utilização. Assegurar que robôs reproduzam um comportamento correto pode assim salvar bastante dinheiro em estragos ou até mesmo as nossas vidas.

As práticas atuais em relação a testes de sistemas robóticos são vastas e envolvem métodos como simulações, verificação de “logs”, ou testagem em campo, frequentemente, um denominador comum entre estas práticas é a necessidade de um humano pessoalmente analisar e determinar se o comportamento de um sistema robótico é o correto. A automatização deste tipo de análise poderia não só aliviar o trabalho de técnicos especializados, facilitando assim a realização de testes, mas também possivelmente permitir a execução massiva de testes em paralelo que podem potencialmente detetar falhas no comportamento do sistema robótico que de outra maneira não seriam identificados devido a erros humanos ou à falta de tempo.

Apesar de existir alguma literatura relacionada com esta investigação, de uma maneira geral a automatização no campo da deteção de erros ou criação de invariantes continua a não ser adotada, pelo que o estudo apresentado nesta tese é justificado.

Esta dissertação visa assim explorar o problema da automatização na deteção de erros comportamentais em robôs num ambiente de simulação, introduzindo uma linguagem de domínio específico direcionada a especificar as propriedades de sistemas robóticos em relação ao seu ambiente, assim como a geração de “software” de monitorização capaz de detetar a transgressão destas propriedades.

A linguagem de domínio específico necessita de expressar requisitos de determinados estados ou eventos durante a simulação, desta maneira precisa de apresentar determinadas características. Palavras-chave para representar relações temporais de ou entre objetos, como, por exemplo, o robô “nunca”, ou “eventualmente” o robô. Referências a estados anteriores da simulação, como, por exemplo, a velocidade do robô está sempre a aumentar, ou seja, é sempre maior que no estado anterior. Atalhos para ser possível referir certas características de ou entre objetos, como, por exemplo, a “posição”, “velocidade” ou “distância” de ou entre robôs.

A linguagem de domínio específico também assume que o sistema robótico irá ser executado por meio da framework ROS (Robot Operating System), que é amplamente utilizada para investigação e na indústria da robótica. A arquitetura do ROS engloba características como

“publish-subscribe” entre “tópicos” e tipos de mensagem, estas características são tidas em conta e foram integradas no desenvolvimento da linguagem.

O “software” de monitorização gerado refere-se a um ficheiro python que correrá sobre a framework ROS. A geração deste ficheiro assume também que a monitorização será feita no simulador Gazebo, isto porque para obter dados como a posição ou velocidade absoluta de um robô durante a simulação é necessário aceder a “tópicos” ROS específicos que na geração do ficheiro de monitorização estão “hardcoded”. A geração de um ficheiro capaz de executar a monitorização significa que esta pode ser executada independente de um sistema robótico, permitindo assim a automatização da monitorização a respeito de vários objetos e as suas relações.

Resultados mostram que é possível expressar propriedades temporais e posicionais de e entre robôs e o seu ambiente com o suporte da linguagem de domínio específico. O trabalho mostra também que é possível automatizar a monitorização da violação de alguns tipos de comportamentos esperados de robôs em relação ao seu estado ou determinados eventos que ocorrem durante uma simulação.

\*Evaluation ?\*

\*possíveis problemas, e futuro\* - proof of language or that it works - better information on the errors - frequency of checking the properties can be modified in some circumstances to not check at every iteration - alargar a outros simuladores - integration with other tools like scenario generation

**Palavras-chave:** Robótica, Linguagem de domínio, Detecção de erros, Automação, Monitorização



## Abstract

Robotics has a big influence in today's society, so much that a potential failure in a robot may have extraordinary costs, not only financial but can also cost lives.

Current practices in robot testing are vast and involve such methods as simulations, log checking, or field tests. The frequent common denominator between these practices is the need for human visualization to determine the correctness of a given behavior. Automating this analysis could not only relieve this burden from a high-skilled engineer but also allow for massive parallel executions of tests, that could potentially detect behavioral faults in the robotic system that would otherwise not be found due to human error or lack of time.

For my thesis, I have developed a domain-specific language to specify the properties of robotic systems in ROS. Specifications written by developers in this language can be compiled to a monitor ROS module, that will detect violations of those properties. I have used this language to express the temporal and positional properties of robots, and we have automated the monitoring of some behavioral violations of robots in relation to their state or events during a simulation.

\*Evaluation ?\*

**Keywords:** Robotics, Domain-specific language, Error detection, Automation, Monitoring



# Contents

<b>List of Figures</b>	<b>xiii</b>
<b>List of Tables</b>	<b>xv</b>
<b>Listings</b>	<b>xvii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	1
1.2 Problem Statement . . . . .	2
1.3 Objectives . . . . .	2
1.4 Contributions . . . . .	2
1.5 Structure of the document . . . . .	2
<b>2 Background &amp; Related Work</b>	<b>5</b>
2.1 Robot Testing . . . . .	5
2.1.1 Challenges . . . . .	5
2.1.2 Invariants . . . . .	5
2.2 Robot Operating System . . . . .	5
2.3 Gazebo . . . . .	5
2.4 Property Specification . . . . .	5
<b>3 Proposed Approach</b>	<b>7</b>
<b>References</b>	<b>11</b>



# List of Figures

3.1 Tool for monitoring robot properties. . . . .	8
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# List of Tables





# Listings



# Chapter 1

## Introduction

Robot arms in car assembly lines, autonomous vacuum cleaners, or cat-like robots to carry food in a restaurant, robotics already have a great impact on our current society. Due to their broad practicality, the quality of software used by robots should be of extreme importance to us.

Robot software as well as the techniques used to test their quality are very field-specific and different from the techniques employed in traditional Software Engineering, mainly because robots are meant to interact with the real world. Automatic tests are barely used in robotics due to multiple factors: cost, complexity, and hardware integration, among others [4].

The goal of this thesis is to remove the need for humans to manually inspect the correctness of robot behavior based on visual inspection, through the study of a possible solution for automation in the testing of robotic systems.

### 1.1 Motivation

Today, robots are vastly used industrially (medicine, agriculture, etc.) or leisurely (contests, personal use, etc.). The tendency is for robot usage to keep growing at a global level. Robot tasks tend to be repetitive or rather specific, but the robot software tends to be quite different from conventional software. The Cyber-Physical systems of robots are non-deterministic and unreliable, mainly because robots interact directly with the real world. A sensor can return imprecise values since the environment itself can be very hard to predict. As a result, verifying whether a task or movement is correct can be hard for a system to conceive.

Current practices in testing robot software involve, field testing, simulation testing, logs checking, among others. The common denominator among these is that they require a human to analyze the behavior of the robot to determine whether the behavior is correct. Studying possible options for viable automation of tests in robotic systems could lead to an opening on its usage in research and the industry. Allowing for multiple parallel executions of tests not depending on human visualization could improve the quality of current and future robot software.

## 1.2 Problem Statement

The multiple challenges in robot testing have an influence on planning how to test a robot because there are tradeoffs among choices. While simulation-based tests are a promising approach for automation there is still distrust in the precision and validity of the results. This means that, despite being dangerous and sometimes expensive, real-life robot testing is still the main choice. Both in real-world testing or simulations, human supervising will most likely be used. This is because identifying if a robot fulfills an expected behavior is very hard for the robot system itself. For this reason, automatic tests in the robotics field are hardly reliable and hard to implement. The resulting product is a lack of quality in the software across projects.

In the case of simulators, we can use the real value of objects' attributes in a simulation to compare with what the robot system perceives, but even so problems like what components to monitor and how to express them arise. Having a domain-specific language to specify a robotic system's properties can be useful or a burden depending on its complexity and accessibility.

## 1.3 Objectives

This work has the objective of showing how a domain-specific language can be used to specify temporal and positional properties of robotic systems and monitor the simulation components associated with these properties.

The language should allow describing a robotic system's properties in a simple and intuitive way, while at the same time still being able to express relevant temporal and positional arguments between robots and objects in the simulation.

The language will need to be supported by a compiler. The compiler should translate the language to a monitoring mechanism. In this way, if a robotic system doesn't follow the properties defined by the user writing in the language, during execution, the compiler should detect an anomaly and make the analysis that the behavior of the robot is not consistent.

## 1.4 Contributions

The expected contributions of this thesis are below enumerated.

1. Definition of a domain-specific language to specify robotic systems' properties.
2. Implementation of a compiler for the language that can generate software capable of monitoring relevant components while in a simulation.
3. Evaluation of the expressive capabilities of the solution.

## 1.5 Structure of the document

The document is organized as follows:

- Chapter 2 - Background & Related Work:

- Chapter 3 - Proposed Approach:
- Chapter 4 -



## Chapter 2

# Background & Related Work

In this chapter as a background to the work, the Robot Operating System (ROS) is introduced. Has for related work, Gazebo is introduced as the simulation software to be used and GzScenic as a language that allows to specify testing scenarios.

### 2.1 Robot Testing

#### 2.1.1 Challenges

#### 2.1.2 Invariants

### 2.2 Robot Operating System

### 2.3 Gazebo

### 2.4 Property Specification

ROS is an open-source framework with a vast collection of libraries and tools that help build robot software. ROS runs on Linux Ubuntu and provides an abstraction between hardware and software. ROS was built with the purpose of cross-collaboration, there are packages for almost everything and no need to reinvent the wheel. ROS is the most widely used tool for writing robot software. Companies like Sony, LG, Rapyuta Robotics, etc., rely on ROS to deliver their products [2].

Robot simulation is an essential tool for testing robots behavior. Gazebo started with the idea of a high-fidelity simulator to simulate robots in outdoor environments under varied conditions. Today it offers the ability to simulate numerous robots in complex distinct environments. Gazebo is an open-source 3D simulator that supports sensors simulation and actuators control under different physics engines [1].

Scenic is a domain-specific language used to describe scenarios. It is a probabilistic programming language and it helps design the cyber-physical systems used in a simulation. Scenic big potential is allowing the randomization of specific scenarios delimited by the language. Although this is true Scenic as a problem, it is designed to support only a specific number of simulators, mainly vehicle simulation [5].

With this in mind, GzScenic was built. The GzScenic tool allows the generation of this type of scenarios in the Gazebo simulator, which is the most popular general-purpose simulator [\[3\]](#).



## Chapter 3

# Proposed Approach

The proposed approach consists initially in creating a domain-specific language. The language will serve as a way to describe the properties of a robot. For instance, if our robot is an autonomous car navigating on the road, one property could be that the robot stops at stop signs. To describe robot properties, we also need the description of the testing scenario. In the above example, the "road" and "stop sign" should be defined in the language as part of the testing scenario, without it there would be no way to describe the above property effectively. To describe the scenario itself we can use GzScenic [3] in order to take advantage of the arbitrary creation of multiple scenario possibilities. This language will then be composed of a new domain-specific language in association with the already established GzScenic language.

Next in the approach, there is a need to build a compiler for the proposed language. The compiler should be able to interpret a property in the language and be able to identify the components of the robot necessary to monitor the said property. The monitorization could take place either during runtime or after using log files. Taking the above example into account, our compiler should have the information of which component of the robot is responsible for the car position as well as the position of the stop sign, it can then monitor the component and check if the property has been broken.

The language should be of high level in the sense that it should be intuitive to the writer. With this approach, the person doing the robot testing shouldn't need so much in-depth knowledge about the robot to perform a test. This is because of the writing simplicity of the language and the removal of the manual labor side of personally monitoring the robot.

The final scheme of the tool proposed is represented in the below diagram.

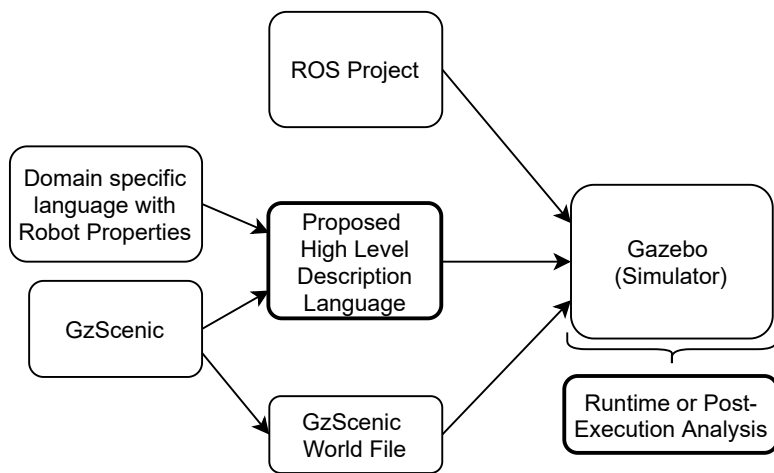


Figure 3.1: Tool for monitoring robot properties.

# Appendix A



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