Universidade do Minho
Escola de Engenharia
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Formalizing ROS2 security configuration with Alloy

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity.

I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

ABSTRACT

Industrial restructuring is becoming highly reliant on automation developments, as they bring more efficient and accurate processes with less associated cost. Consequently, robots are rapidly being deployed in a wide range of scenarios, especially where security is demanded. In such cases, it is critical to employ appropriate procedures to verify both the system's quality, as well as its security.

Following the current growth of cyber-physical system, as well as their usage into various technology domains, the development of software applications is demanding due to the complexity behind the integration of needed services, beyond those provided by the operating system. Hereupon, software middleware is increasingly used, since it offers services that support application development and delivery.

One of the most popular open-source software platforms for building robotic systems is the Robot Operating System (ROS) [50] middleware, where highly configurable robots are usually built by composing third-party modules. A major factor behind its popularity and widespread adoption is its flexibility and interoperability. One drawback of this flexibility, however, lies in the increased security risks that ROS applications face. Alongisde security risks, the arising of performance and scalability issues related to the ROS middleware specification, compelled the development of ROS2.

Robot Operating System 2 (ROS2), which continues to provide a simple, uniform message passing interface to allow components to communicate with each other, is implemented using the Data Distribution Service (DDS) [46] communication protocol, where security guarantees are ensured by DDS-Security specification. Using DDS-Security, it is possible to configure ROS2 to run with security guarantees using the SROS2 toolset [24]. However, improper configuration can still lead security problems.

This dissertation proposes a technique, based on the software verification perspective, to automatically verify system-wide properties related to the security configuration of ROS2-based applications. The intended purpose is to model the ROS architecture, as well as the network communication behaviour, in Alloy [28], a formal specification language and analysis tool supported by a model-finder over which, system-wide properties are subsequently model-checked.

KEYWORDS Robotics, ROS, ROS2, DDS, SROS2, Security, Software Verification, Alloy

RESUMO

A constante implementação da ideia de automização de processos tem motivado a reestruturação nos mais diversos setores industriais, com o obejtivo de aumentar a eficiência e precisão nos processos integrados, consequentemente, reduzindo os custos associados. Além disso, esta ideia impulsiona a integração robótica nos mais amplos domínios tecnológicos, especialmente em domínios onde a segurança é exigida. Nestes casos, é fundamental adotar técnicas apropriadas de forma a verificar tanto a qualidade do sistema, como a segurança do mesmo.

Como resultado do atual crescimento de sistemas ciber-físicos, nomeadamente sistemas robóticos, bem como sua utilização em vários domínios tecnológicos, o desenvolvimento de aplicações é exigente devido à complexidade da integração dos serviços necessários, tipicamente não fornecidos pelo sistema operativo. De forma a acompanhar o aumento da complexidade destes sistemas, *middlewares* têm sido adoptados, pois integram serviços que oferecem suporte ao desenvolvimento de aplicações robóticas.

Uma das plataformas considerada como *standard* no que toca ao desenvolvimento sistemas robóticos é o middleware Robot Operating System (ROS) [50], onde robôs altamente configuráveis são construídos atráves da composição modular de *software* externo, oferencedo características como flexibilidade e interoperabilidade aos sistemas integrados. No entanto, a constante priorização na flexibilidade resulta num aumento de vulnerabilidades de segurança, pondo em causa a integridade das aplicações. Além da falta de segurança apresentada, existem também problemas de desempenho e escalabilidade relacionados com a especificação do *middleware*. Assim, era necessário uma mudança na estruturação do ROS, resultando na criação do Robot Operating System 2 (ROS2).

O Robot Operating System 2 (ROS2) implementa um protocolo de comunicação, de nome Data Distribution Service (DDS) [46], que para além de garantir serviços de comunicação, fornece diversas especificações, onde diversas implementações DDS usufruem de tais especificações. A especificação DDS-Security, que através de uma metodologia de *plugins*, oferece diferentes métodos de adoção de segurança. Através do uso desta especificação, juntamente com o uso do SROS2 *toolset* [24], é possível configurar o ROS2 de forma a adotar estas medidas de segurança.

Esta tese propõe uma técnica para a verificação automática de *system-wide properties* em aplicações ROS. Esta técnica apresentada baseia-se na formalização estrutural de arquiteturas ROS em Alloy [28], com o obejtivo de modelar o comportamento associado à comunicação dentro do sistema, tendo em consideração configurações associadas às propriedades de segurança.

PALAVRAS-CHAVE Robótica, ROS, ROS2, DDS, SROS2, Segurança, Verificação de Software, Alloy

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Part I

INTRODUCTORY MATERIAL

1

INTRODUCTION

The concept behind automation development is being incorporated into the industrial world, through the use of flexible tools to assist in the most various scnearios, as it brings efficiency and accuracy to the industry's processes. Robotics is already the key driver of competitiveness and flexibility in large scale manufacturing industries, as it is significantly reliant on a variety of technologies. Due to the continuous growth of technology in these different domains, robots can be used in a wide range of applications [44], since their usage brings increased productivity, safety and more manufacturing production work back to developed countries. [23, 15]

Despite the advances in technology, dealing with hardware-level applications becomes highly impractical as the system's complexity increases. Thereupon, developing and writing software code for robot applications is demanding, where multiple aspects must be properly considered [49]. Since robots became to be integrated into distributed systems through seperated components, connecting different hardware and software modules raises interoperability and communication issues. To solve this issue, modular architectures, based on message-passing communication patterns, are continually emerging as the architecture's middleware layer. Their primary focus is to offer services to the application layer, consequently easing the development cost, while providing interoperability and communication facilities. [44, 42]. The requirement for a middleware layer that meets different robot's specfication is a novel approach to enable the creation of robot applications over robotic systems, while supporting features such as robustness and modularity.

The Robot Operating System was created by a collaborative open-source community to contribute in the advancement of robots, with the aim of helping build robot applications easily. [22] It enables locomotion, manipulation, navigation, and recognition tasks over complemented software libraries and tools. Concerning the wide range of robotics hardware and software, ROS was designed to be flexible, enabling interpolation with potential added components. However, performance and scalability issues arised due to its middleware specification. [49] Additionally, real-time constraints such as fault-tolerance, deadlines, or process synchronization were not supported by ROS, making it unsuitable for safety-critical and real-time systems. [34]

Besides having no middleware support for distributed real-time systems, security was not prioritized by ROS, which started to be demanding for deployed systems. An increasing number of real-time applications, for instance robotic systems, requires security ensurance for protecting real-time sensive data against unauthorized access. [37]

This lead to the creation of Robot Operating System 2, developed using the Data Distribution Service (DDS) [46] specification protocol as its middleware, leveraging for its messaging architecture. Issues concerning system integration and scalability are mitigated by DDS various implementations, due to the several transport

configurations provided, making it suitable for real-time distributed systems. DDS also provides a security specification, called DDS-Security. ROS2 makes use of this specification, providing security guarantees to the deployed robotic systems. [5]

Due to the widespread usage of robotic systems, software verification, through the use of formal methods, are necessary to prevent potentially catastrophic consequences, mainly related to security matters, as safety guards are gradually implemented into the software domain. [63] Within this context, Alloy [31, 39] framework enables the behaviour expressness of systems with rich configurations, due to the combination of both relational and linear temporal logic (LTL) provided by its specification language, consequently supporting model-checking techniques. Model-checking techniques enable far better levels of coverage and, as a result, more reliability than traditional testing, where the system is abstracted as a conventional model, that is automatically checked over performing property verification on finite-state machines. [6]

The proposal of this dissertation is to develop a novel technique to automatically verify system-wide safety properties using Alloy framework, confining a ROS2 system into an abstract model, in order to obtain a prototype tool that can be used by developers to easily detect security configuration issues on their respective robotic application.

1.1 OBJECTIVES AND CONTRIBUTIONS

The first goal of this thesis rests in introducing concepts around the Robot Operating System, contextualizing the evolution behind its framework towards achieving security, where the former version of ROS lacked due to the focus on flexibility. Since ROS2 has been developed over the DDS framework, as its communication middleware, DDS must be properly understood before considering the security aspects. To do so, simple examples will be previously introduced, in order to provide ROS-based context to the reader. The domain of autonomous systems, where security is of extreme relevance, namely the Autoware [33] ROS2 platform for self-driving vehicles will also be introduced. To understand SROS2 we intend to configure and run a realistic case study related to Autoware with security guarantees.

The DDS Security standard functionality is evaluated, as well as how security is integrated into ROS2. Since security issues, concerning public networks, are recent to the robotics domain, ROS2 security network design should be analysed structurally.

Security configuration related to SROS2 toolset will be provided in this chapter, supported by an example that accounts multiple security features, those being authentication, encryption and, most importantly, access control, applying restriction constraints to the network and its participants, that by default are not controlled.

The second goal is to extend a previously proposed [9] formalization of ROS applications in Alloy/Electrum [28, 39] to also take into consideration the security configuration defined with SROS2. Using this extension, we intend to explore the viability of verifying simple information-flow security properties. For instance, to ensure that no commands to the vehicle motor can be sent via the infotainment system.

The final goal is to automate the extraction of such formal Alloy models from the configuration files of a ROS2 application, in order to obtain a prototype tool that can be used by roboticists to easily detect security configuration issues.

1.2 DOCUMENT STRUCTURE

The current dissertation structure is divided into three different chapters. Chapter (2) introduces all the concepts related to Robot Operating System, and its evolution as robotic development framework towards achieving system security. Chapter (3) introduces the Alloy framework, as its specification language supported by a concrete example case. Chapter (4) presents previous developed work that covers concepts that are also addressed within this dissertation, as well as, expected considerations about the future work.

2

SOFTWARE DEVELOPMENT IN ROS2

Robotic systems have emerged into several scenarios, where its usage ranges between basic processes automation, up to full performance over critical tasks, consequently causing the complexity increase in these domains. Concerning the complexity behind writting software code, due to the widely variety presented in the robot's hardware as in fields of action [14], Robotic Operation System (ROS) presents itself as a middleware system, created to facilitate robotic systems development.

In ROS, software flexibility was valued above all else, meaning that values like security were not duly valued, so ROS-based applications tend to face increased security risks, exposing the whole robotic network. As ROS became a standard for many robotic systems, and due to the scale and scope of the robotics growth, security ensurance must be addressed as a developing priority. [22, 34]

The upgraded version of ROS, Robot Operating System 2 (ROS2), presents itself as a framework for developing robotic systems, supported by a standard, the Data Distribution Service (DDS), where multiple middleware implementations are built over this standard, providing ROS applications multiple DDS-based specfications, as well as valued Quality of Service (QoS) settings over the transport configuration.

The DDS-Security specification [47], embedded by every DDS implementation supported by ROS, supplies multiple plugins regarding the security domain. As result, ROS2 yields a wider command toolset compared to the former version of ROS, as they bring forth to a toolset, the Secure Robot Operating System 2 (SROS2) toolset, concerning the security functionality that DDS-Security plugins offer.

This chapter introduces necessary background information over the major concepts on which this thesis rests. First, it is presented a detailed introduction to the concepts around Robot Operating System (ROS), as well as the evolution approach that ROS faced towards providing security to its deployed systems. Regarding this goal, Data Distribution Service (DDS) and its integration on Robot Operating System 2 (ROS2) must be contextualized beforehand.

2.1 ARCHITECTURE CONSIDERATIONS

The Robot Operating System was created by a collaborative open-source community, that has undergone rapid development [14], to contribute in the advancement of cyber physical systems, serving as developer enhancer for the world of robotic applications. [22, 49]

Fundamentally, ROS is a middleware, as it provides a custom serialization format, a custom transport protocol as well as a custom central discovery mechanism, presenting itself as a distributed layer between the top application layer and the operating system layer. ROS was designed to provide as much as modularity and composability to the application layer [10] as possible, allowing ROS applications to be built over several software modules, as independent computing processes called *nodes*, that compose together to fulfill the deployment characteristics of the corresponding robot. [42]

2.1.1 *Former Architecture*

The former communication architecture supported by ROS focused on a centralization perspective, as it had a implementation of a *Master node*, that controlled every aspect of the communication establishment. Every information exchange between nodes had to go through this master, as these nodes must also be able to address the ROS Master's location.

Due to the sheer wide capabilities controlled by the master, this centralization approach fits the purposes of a research tool, as it is simpler to monitor and analyse the system behaviour. This communication architecture, however, does not scale well since it is heavily reliant on the master node's availability, making it unsuitable for safety-critical and real-time applications. If the master fails, the entire system fails, representing a single point of failure and a huge performance bottleneck.

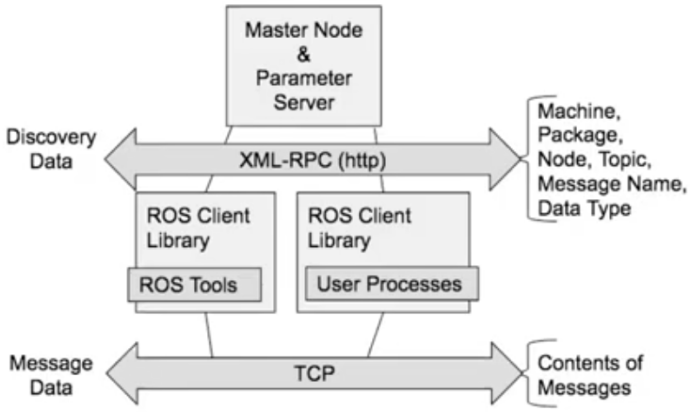

Figure 1: Robot Operating System architecture.

Many research communities tried to fix these real-time issues by proposing potential solutions, while supporting the same architecture design. However, these solutions did not fully accomplished the needs of real-time applications. So, it became clear to the ROS community that the framework had architectural limitations that could not be rearranged using the same design approach. [42]

Robot Operating System 2 comes as a complete refactoring of ROS, with the aim of increase the framework's real-time capabilities, by allowing the development of time-critical control over ROS, as it moves away from the

former architectural design towards the implementation of an external middleware that can support the production needs of the outgrowing robotic systems. [34, 10]

2.1.2 *Data Distribution Service*

The Data Distributed System [46], simply known as DDS, is a Object Management Group (OMG) middleware standard, resulted from the need of better interoperability between different vendors middleware frameworks, directly addressing data communication between nodes that belong to a *publish-subscribe* communication architecture, for real-time and embedded systems.

A middleware, such as DDS, aims to ease the complexity behind creating each sytem's own middleware, by handling relevant aspects like network configuration, communication establishment, data sharing and low-level details. As a result, system developers can mainly focus on their applications purposes, rather than concerning about information moving across levels. [25]

DDS uses the Data-Centric Publish Subscribe (DCPS) model as its communication model approach. DCPS is based on a *publish-subscribe pattern*, where the *data-centric* messaging technique is implemented. It conceptually creates a virtual *global data space*, acessible by any DDS-based application, where data is properly delivered to the applications which quest for it, saving bandwith and processing power. [46, 48] A domain participant enables an application to participate in the global data space, either as a *publisher* or as a *subscriber*, according to their role on data exchange. [42, 1, 17]

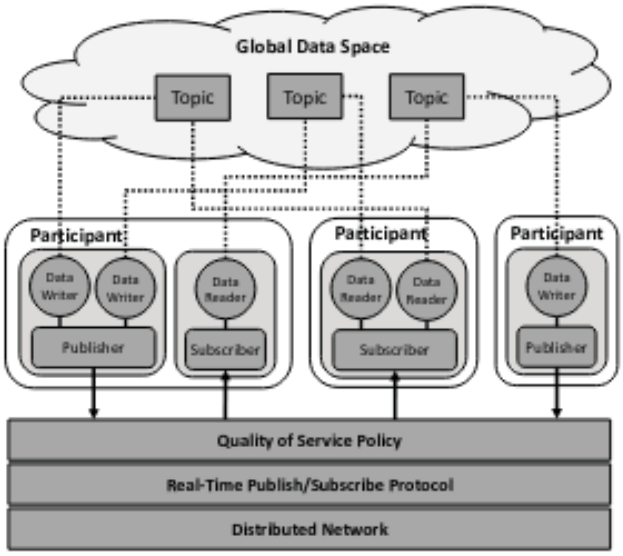

Figure 2: DDS architecture: DCPS model with RTPS. Extracted from [42].

To properly address the data transportation through physical network, DDS offers a wire specification protocol called Real-Time Publish-Subscribe Wire Protocol (RTPS) [55], providing automatic discovery between participants. This protocol also works under a *publish-subscribe* policy over best-effort transports, where data transmission

between endpoints is handled. [64] RTPS allows multiple applications, that could differ on their used DDS implementations, to interoperate with each other as network domain participants. [17, 1]

Furthermore, RTPS was designed to make use of *Quality of Service* profiles, where multiple transport policies can be specified that, by default, DDS does not support. This approach offers flexibility over communication configuration and development versatility, allowing the developer to specify whatever QoS satisfies its system's communication needs. [1, 22, 42]

Briefly speaking, DDS leverages the premise of a transport-independent virtualized Data Bus to address network resources' distribution, in which stateful data is distributed through the network. The involved applications can access this data in motion, representing an architecture with no single point of failure, respectively enabling a realiable way of ensuring data integratity. Consequently, by adopting this approach, the load on the network is independent of the number of applications, making it easily scalable.

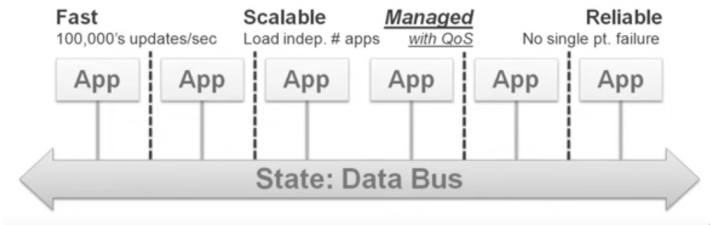

Figure 3: Data Distributed System architecture in a nutshell.

2.1.3 *ROS2-DDS Architecture*

As previously stated, the Robot Operating System 2 was developed to address the lack of support for real-time systems that the former ROS provided, mainly due to its architecture design that relied on their own middleware specification. To address this, ROS2 middleware approach is built upon the DDS framework [42], leveraging DDS for its messaging architecture, where communication and transport configuration are handled.

As far as dependencies are concerned, DDS implementations have light sized dependencies, often related to language implementation libraries, easing the complexity behind installing and running dependencies for ROS developers. [62]

The middleware's on-top layer regards the ROS client library (*rcl*), already implemented in the former ROS architecture. This layer accounts the availability of ROS concepts to the Application layer, as it provides APIs to ease the software implementation by ROS developers. [51] As ROS aims to support different programming languages over the same computing context, each language-specficic API must have its corresponding client library (*rclcpp* regarding *C++* and *rclpy* regarding *Python*). The *rcl* accounts these client libraries by abstracting their specification, reducing code duplication. [56, 10]

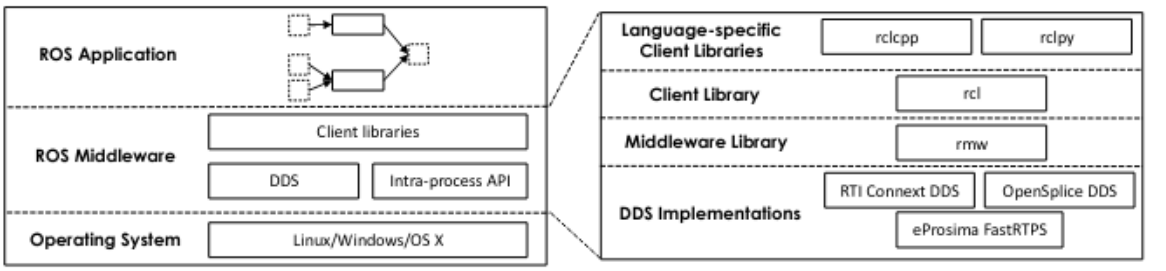

Figure 4: ROS2 framework architecture.

Towards supplying a wide range of configurations back to application layer, to vastly cover the robotic applications needs, ROS2 aims to support multiple DDS implementations, in which these implementations API specification might differ from each other (currently, *FastRTPS* by *eProsima*, *Connext* by *RTI*, and *Vortex OpenSplice* by *Adlink*). It should be noted that the DDS implementations are low-level of abstraction, strictly defined by its corresponding vendor's API. DDS only defines fundamental procedures at a higher degree of abstraction.

In order to abstract *rcl* from the specifications complexity of these implementations APIs, an DDS-agnostic interface is being introduced, the *rmw* (ROS MiddleWare) interface [10], allowing portability among DDS vendors, which consequently enables ROS developers to interpolate DDS implementations, based on their applications needs during runtime. The information flow through the middleware layer is done over structure mapping between ROS and DDS data models, addressed by the *rmw*, regarding the DDS implementation that is being considered at runtime.

2.1.4 *Computation Graph*

From a logical perspective [10], ROS applications are composed of many software modules that operate as computation nodes, allowing its participation into the ROS global data space. The primarily use of publish-subscribe model approach as communication type, through *message-passing* patterns, confers additional concept complexity to the application architecture, where the latter can be naturally represented as a *computation graph*.

The application's computation graph presents itself as a graphical network, where runtime named entities have their unique role when it comes to data distribution. The mainly used network entities are *Node Instances*, *Topics* and *Interfaces*, which will be covered in this presented section.

Node Instances

The application development is done over package orchestrating, where each logically represents a useful software module. Packages might be compromised by numerous *nodes*, that can be perceived as processes that will likely perform computation over the network. It is worth mentioning that, nodes can be connected within a single package or between multiple packages, as they are built over their corresponding packages.

The network is comprised by many nodes, running simultaneously and exchanging data between them, where each node addresses its corresponding network module purpose. Fault tolerance features are guaranteed as

nodes have their corresponding unique name, allowing communication in an unambiguous manner, which confers a suitable approach when developing a complex robotic system.

The notable usage o callback functions provide great functionality when it comes to manage the node's behaviour in the communication process. Additionally, *timers* can also be used, since they provide a useful way of managing these callbacks, by time-assigning.

Communication

Message-passing is the primary means by which nodes communicate with one another. The *message* definition is a well-typed data structure, which commonly characterizes every data structure concerning the information exchange between nodes. A message is defined by its data type, also known as its *interface*, which can either be primitive (*integer*, *string*, *boolean*, among others), or defined by a complex data structure, where multiple data types are assigned to their corresponding variables.

ROS computation graph provides *3* different ways of establish node communication, those being *Topics*, *Actions* and *Services*, where each one has its different corresponding interface, specified in different folders with unique namespaces.

Topics are perhaps the most common method, naturally perceived as middle-communication buses, over which messages are passed through. As semantic approach, communication through topics is handled by the publishing-subscribing pattern. A node publishes the message to any number of topics, that are then subscribed by nodes that want to get access to that message. Topics provide a multicast routing scheme, where publish data is casted into the multiple nodes that are subscribed to the topic.

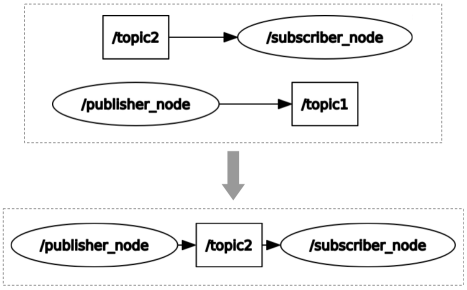

Figure 5: ROS2 communication behaviour over *topics*.

A specific *topic* is created upon specifying its entity name over either a publisher or a subscriber callback instance. Whenever a node creates a publisher, intentionally instantiated to publish a message through a specified topic, *roscore* is used to advertise the latter, enabling message passing to the corresponding topic subscribers. Message processing is done via the node's callback functions, which are activated upon message receipt, as it can also be utilized for publishing purposes. [10]

Even though *topics* are the most conventional way of communication, due to its multicast scheme, subscribers can not be identified by the publishers, so logging and synchronization becomes rather difficult.

The use of *services* enables a client node, that can also be seen as a topic subscriber, to request data from a server, that likewise a topic publisher, furnish data through a service. The data is only provided when the client

node makes a request. Each service is always linked to just one server node, and does not maintain active connections. To address the service stalling that the former ROS issued due to the service's synchronization nature, ROS2 services are asynchronous, since it is possible to specify a callback function that is triggered when the service server responds back to the client.

Other notable way of exchanging data is by setting goals through *Actions*. Actions, likewise services, also uses a client-server model, but they were design for other purposes rather than only processing a request and sending back a response. Actions are intended to process long-running tasks, where the client sends a goal request to the server node, that confirms the receiving of this goal. Before returning a response back to the client, the server can send feedback back to the client.

Launch Files

A conventional way of deploying a ROS application is through the use of *launch files*, enabling the multi-configuration over entire robotic applications, where network involved nodes can be individually pre-configurated. Therefore, ROS makes use of the *roslaunch* to automatically initialize the whole network, simultaneously launching each node. This provides a simpler way of monitoring the system nodes. In the Figure **??** is depicted a launch file example regarding an application composed by *4* nodes.

Additional node configuration, such as name remapping and parameter adjustments, can be specified under the *args* tag, which offers great functionality to the launching process.

Distinctive namespaces allow the system to start the nodes, without any name nor topic name conflicts. However, this technique has some flaws attached, since it does not furnish a way of launching nodes in a separated terminal, often needed for user interaction purposes, like input reading.

Parameters

Another relevant concept behind ROS is the existence of nodes *parameters*, that allows individual configuration of the network nodes. In the former version of ROS, the node parameters were controlled by a global *parameter server*, managed by its corresponding ROS Master. However, in ROS2 each node declares and manages its own parameters, by using the predefined commands *get* and *set*. Additionally, using a parameter function callback, the node's parameters can easily be edited.

Node Composition

Usually a node is attached to a single process, but it is possible to combine multiple nodes into a single process, structurally abstracting some network parts, while improving the network's performance. However, there is a slight difference about how ROS and ROS2 approaches the node composition. In the former version of ROS, node composition was done over the combination of *nodelets*, intentionally designed to ease the cost of overusing TCP for message-passing between nodes. Supported by the former idea of *nodelets*, ROS2 introduces the *components* as software code compiled into shared libraries, that can be loaded into a *component container* process at runtime in the network, ensuring node composition. Node composition could also be applied for security matters. Suppose

a scenario where multiple nodes respect the same security policies. By combining them into a single process, the mapping into this set of rules would be direct, easing the usage of security enclaves.

2.2 SECURITY

The deployment of real-time systems implies critical concerning about safety and security [42], resulting of the demanding time-critical scenarios. Robotic systems fall under the umbrella of this broad system definition, as they feature unique cyber vulnerabilities related to its integration over highly networked environments, that confers great importance on exposing critical time-reliant scenarios. [43, 20]

The network security evaluation in a system is done over applying several analyzing techniques. Generally, these techniques do not cover every security aspect, as new vulnerabilities arise from the technology evolution. [32] The appliance of security countermeasures techniques upon configuring the system's network confers a critical step when aiming towards achieving security.

Within this vast topic, several avenues of endeavor come to mind, each deserving of a substantial study. Network security entails pre-exploration of the system's network through practical networking security techniques, such as intrusion detection and traffic analysis. [41] However, due to the high non-linearity and complexity of real-time systems, implementing such a thorough analysis method in near real-time remains a significant difficulty task. [19]

2.2.1 *Security Integration in ROS2*

As aforementioned, ROS middleware faces known vulnerabilities due to its architecture model nature. The former ROS communication is built around TCP ports, allowing robots to be built as network distributed modules. As a result, techniques such as port scanning is usually used to expose the data itself. Due to the ROS master role in the communication architecture, and its ability to connect to other nodes, exposing this node poses a critical threat over the whole network. [18]

There was also worries regarding how ROS handled node communication. Network security may be jeopardized, as a result of the publish-subscribe pattern transparency, where node-to-node communications are settled in plain text, making data content vulnerable to unauthorized usage. [34]

As result of the *Data Distribution Service* (DDS) implementation as a flexible middleware interface in the ROS2 architecture, issues regarding security is no longer mainly ROS-dependent. Thus, when it comes to addressing security over communication, and subsequently data protection enhancment, ROS2 is heavily reliant on how the DDS standard is able to manage security. [34, 18]

The *Object Management Group* (OMG) [46], the already mentioned organization who is responsible for maintaining the DDS standard, accounts security integration by supplying an in-depth security specification, consequently adding features to the already developed DDS standard. The *DDS-Security* is a specification that serves as a security extension to the DDS protocol, defined by a set of plugins (Authentication, Access Control, Cryptographic, Logging, Data Tagging), combined in a *Service Plugin Interface (SPI)* architecture. [5, 24]

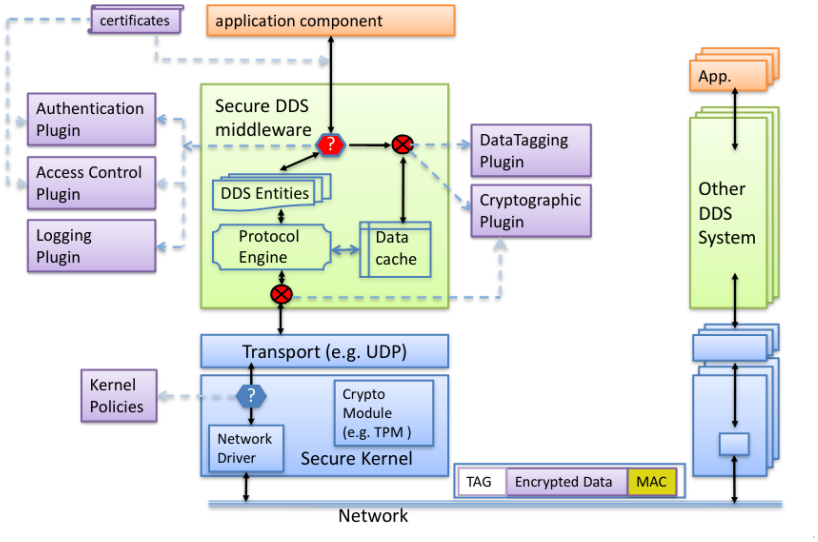

Figure 6: DDS-Security Architecture. Extracted from [47].

This specification enables its integration by furnishing a *Security Model* supplied to the DDS standard, whereas the *Service Plugin Interface* architecture is responsible for granting plugin enhancment for compliant DDS implementations. Moreover, depending on the security requirements needed for a particular application, these plugins might be adjusted by the latter's runtime DDS implementation. [47]

Every DDS implementation supported by ROS2 makes use of the DDS-Security specification, enabling security over ROS's application environment. Even though ROS2 is deployed without security mechanisms by default [24], ROS2 provides a toolset, the *Secure Robot Operating System 2* (SROS2) toolset, extending ROS2's functionality to make use of the DDS-Security functionality.

The control over these tools are done by *rcl*, providing security over the Application layer, while DDS is capable of providing security over the communication architecture. [34] The SROS2 configuration is done over applying a set of security files to each ROS2 participant, considering the assignment approach (strict or permissive) that is being used.

Since this security integrity on ROS2 is consider a recent technology implementation [24], the developer must be aware of improper configuration, that can still lead to security problems. However, the variety of capabilities in SROS2 toolset attempts to aid with security configuration across environments.

2.2.2 *SROS2 Configuration*

To properly introduce the set of tools that SROS2 provides, it follows an application example that will now account the security features, as to provide authentication and encryption over the network communication, as well as access control policies over the application nodes.

The TurtleSim Application

For instance, consider a well-known example called *TurtleSim*, which is a simulator typically used for learning ROS, mainly composed by *two nodes*, that perform together towards moving a turtle. Additional nodes were implemented, in order to add complexity to the current network, as to later support security as a proper example.

For understanding reasons, the reader may want to see how the network architecture is organized. ROS2 provides a GUI tool called *rqt*, that assists developers in manipulating the network elements, in a more user-friendly manner. The *rqt* visualizer, *rqt_graph*, allows the developer to perform analysis over a graphical visualization of the network computation graph.

Figure 7: *TurtleSim*'s network graph presented by *rqt_graph*.

The *multiplexer* node handles commands related to turtle's movement, acting as a topic selector between two different subscribed topics, each of them was respectively associated with a priority value. Based on the priority valued, the *multiplexer* node forwards the commands, related to the selected topic, into the *turtlesim* node, triggering the turtle's movement.

However, *multiplexer* is not exclusive to the *turtlesim* node, as it is still possible to directly publish commands to the topic that handles the turtle's movement, since security policies are yet to be implemented.

Configuration

In technically terms, a *keystore* must be initiated beforehand, to provide a secured environment over the network. SROS2 yields a command that permits its creation. A keystore is a created directory where files regarding security are stored. By generating a keystore directory, it may then be sourced and utilized by *rcl* features towards applying security to the application. The *security* additional keyword-flag enables features regarding security matters, concerning the DDS-security artifacts.

```
ros2 security create_keystore demo
```

Keystore creation using the proper SROS2 command.

Upon the creation of the *demo* keystore, three respective subdirectories are created, where each has their own role when it comes to security enhancement over the network.

• The *enclaves* directory contains the security tools related to each enclave created. An *enclave* is a group of ROS nodes, controlled by the same set of security rules, defined in its corresponding enclave directory.

• The *public* directory contains material that is permissible as public. A Certificate Authority certificate is stored in this directory, related to the CA *public key*. It is used to validate the identity and permissions of each ROS network node by the CA.

• The *private* directory contains material that is considered private. A Certificate Authority certificate is stored in this directory, related to the CA *private key*. It is used to modify the network policies, such as access permissions, and to add new participants. Similar to the public directory, the CA key corresponding to its identity and permissions can be stored in their corresponding individual directories.

The following exports need to be sourced to force SROS2 security features, as they concern relevant environment variables. The first sourced variable points to the directory root of the keystore, allowing ROS2 to identify where the security artifacts are kept. The second serves as the security enabler. The last variable sets which security strategy will be used when dealing with security files.

```
export ROS_SECURITY_KEYSTORE=/demo
export ROS_SECURITY_ENABLE=true
export ROS_SECURITY_STRATEGY=Enforce
```

SROS2 environment variables.

Understanding Security Enclaves

Once the keystore has been created, the respective enclaves can be implemented. As mentioned, an enclave is a group of nodes that follow the same security policy. Enclaves usage are specified upon execution time, implying that their security artifacts are actually used by running processes.

Typically, a node is perceived as an abstraction of a DDS *participant*. However, by considering node composition, as a reliable way for matching multiple nodes simultaneously to the same enclave, this node perception as participants can not be taken into account, due to causing non-negligible overhead. There is also not convenient to compose nodes as individual participants, as far as operating system's security is concerned, where permission distribution and memory becomes rather difficult to handle.

To address this, each participant must be matched to a node shared context, instead of being directly related to a specific node. Thereby, the initial given definition of an enclave is not totally correct, since a participant can either be perceived as single node or as multiple node shared context. So, each enclave security artifacts are used by its respective DDS participant.

As long as security is enabled, the whole network must be properly authenticated. Thus, every node within the network must be authenticated, using an enclave as their identifier. Node composition can not be considered in this network, as it is not intended to share topic privileges. Note that, if an enclave was shared by multiple nodes, each node policy would be considered as common policy within the enclave.

```
ros2 security create_key demo /turtlesim
ros2 security create_key demo /multiplexer
ros2 security create_key demo /keyboard
ros2 security create_key demo /random
```

TurtleSim enclave creation.

The keystore creation, alongside with their respective enclaves, only ensures security over the network communication, in which node authentication and data encryption are concerned. With the proper use of port scanning tools, data encryption can be easily verified. Authentication is ensured upon the enclave's creation. However, to properly apply security over the *TurtleSim* application, access control policies must be appropriately covered.

Access Control

To accurately achieve topic exclusivity, in which the turtle's movement is uniquely concerned by the *multiplexer* node, *access control* policies must be applied. The remaining nodes should be considered untrustworthy, denying any potential undesired turtle's movement.

In order to provide access control, each permission file needs to be modified, accounting the network policies restrictions. This is ensured by adding security permissions to these files, with the mandatory signature of the Certificate Authority. A suitable way of editing the permission file, *permissions.xml* (file that dictates how the enclave manages the permissions within the network) is by creating a policy file, that explicitly specifies the set of permissions of each enclave.

Following the *ConArmor* policy language [61], the *SROS2 policy file* confers a restrict *XML schema*, where security policies bind profiles to access permissions for network objects, granting privileges back to a certain profile. *Profiles* are implemented under the *enclave* declaration, to duly support the node composition into a single process, enabling the possibility of combining multiple profiles, respectively addressing its corresponding node. Typically, each *enclave* declaration is linked to a corresponding ROS node, naturally perceived as a DDS participant.

Objects are classified over a subsystem type, structurally characterized by permissions tags. Then *object privileges* are controlled over access values, either *allow* or *deny*, attributed to their corresponding permissions tags. For instance, consider the *topics* domain, where a profile can either publish or subscribe to that topic. To properly address the allowance of a profile privilege over a topic, the permission tag (either subscribe or publish) must be followed with the *allow* tag.

The policy design approach works under the *Mandatory Access Control* (MAC), that denies any privilege by default. The only way of allowing access to any object, is by explicitly specifying the subject's privilege access.

```
ros2 security create_permission demo /turtlesim policies.xml
ros2 security create_permission demo /multiplexer policies.xml
ros2 security create_permission demo /keyboard policies.xml
ros2 security create_permission demo /random policies.xml
```

Setting permissions into each enclave.

As it follows, security is enabled within this network as well as policy control over topic's permissions. The network can be easily configured and automatically launched through the execution of a launch file, where *roslaunch* uses this files to perform overall initialization.

```
<launch>
    <node name="turtlesim" pkg="default" exec="turtlesim" output="screen" args="
        --ros-args --enclave /turtlesim" />
    <node name="keyboard" pkg="default" exec="keyboard" output="screen" args="--
        ros-args --enclave /keyboard" />
    <node name="random" pkg="random" exec="random" args="--ros-args --enclave /
        random" />
    <node name="multiplexer" pkg="multiplexer" exec="multiplexer" args="--ros-
        args --enclave /multiplexer" />
</launch>
```

Figure 8: *TurtleSim* launch file.

The network is now sucessfully running as a secured environment, where nodes within this network can not be perceived from outside, neither their topic list. To prove that access control is properly employed, the user may want to try to enhance the turtle movement directly from the random controller, by forcing the remapping of the *low_topic* to the *main_topic*. Thus, by attempting to remap the *low_topic* topic prevents the node from launching, since the random node is only allowed to publish through the *low_topic*.

```
<node name="random" pkg="turtle_random" exec="random" args="--ros-args --enclave
    /random -r /low_topic:=/main_topic"/>
```

Attempting the *low_topic* remap.

3

ALLOY SPECIFICATION FRAMEWORK

As aforementioned, this dissertation aims to tackle the security vulnerabilities resulted from the miss-configuration over ROS files. In this chapter, it is intended to explore the Alloy framework that is relevant to overcome the above-mentioned challenge.

The increasingly usage of robotics onto safety-critical systems results in demanding considerations over ensuring the proper correctness of both software and hardware, as failures mainly regarding the security domain might lead to fatal consequences. Thus, the use of formal methods and verification techniques, especially in systems highly reliant on flexibility and reliability, is recommended to avoid security-critical faults. [12] Software frameworks designed for this purpose must provide methods to perform structural design over systems with rich structures, abstracting their behaviour as a conventional model. Additionally, these frameworks must support features to enable automate analysis, in which property evaluation over these designed models is used as technique.

The *Alloy Framework* [31], fits within within this context, as it furnishes a declarative relation-based language, used for software modelling, complemented with extended tools supporting analysis over these models. [28] The language combination of both relational and linear temporal logic (LTL) enables the ability to model both systems with rich structures and complex behaviour. To address the correctness over the specified model, Alloy performs model-checking techniques over these logic languages, where the model M is exhaustively checked over property verification. [39]

The framework *analyzer* takes the specified model's restrictions into account, performing bounded and unbounded model checking to find instances that satisfy those implied restrictions. It can be also be useful for checking model properties, where the analyzer will try to return a counterexample instance. Instances are displayed by the framework Visualizer, alongside with the modelling process steps, regarding a trace representation. Instances appearance can be customized, using the *theme*'s extension. [28]

This chapter will go through these principles in further depth, to give the reader a proper review on how Alloy is structured, as its importance as a model checker to the computation domain, supported by a previously configured example where ROS communication architecture is structurally modelled. Since system analysis rely on the reasonable implementation of Model-Checking techniques, the follwing section within this subject intends to cover a clear contextualization on this matter.

3.1 MODEL CHECKING

Performing software testing has been regarded as the established assessment procedure in which functional and non-functional specifications are evaluated. The conventional approach on software verification is based on testing the system with different inputs, to achieve quality assurance over several intended specifications. [6, 7] As this technique demands exhaustively evaluation over pre-selected test data, it is commonly explored over automated tools, since manual testing is time-consuming and prone to errors. [13, 26]

Model Checking presents itself as a novel technique with the purpose of verifying temporal properties over the system finite-state, with the latter being duly represented as a conclusive model. Additionally, it enables *model-based testing* by automatically interpreting counterexamples as test cases, resulting in significantly greater degrees of coverage than conventional testing. [26, 6] This technique is becoming highly used due to its importance as an early phase approach upon developing systems [39], as it confers the most valued functionality over model-checking frameworks, in which concrete models, regarding the software architecture, is exhaustively checked over behavioural properties.

It provides highly automatic verification procedures, where other techniques, such as theorem provers fails to address, due to its deductive reasoning nature. The representation of not satisfied specifications over counterexamples, confers great functionality to this technique, often required for debugging matters. However, the system's inevitable state expansion consequently causes the complexity increase on verification. This is referred to as the *state explosion problem*, in which model-checking is unable to handle the size of the state space, failing as system verifying technique. [12, 11]

3.1.1 *Model Checking in Alloy*

3.2 STRUCTURAL DESIGN

The *Alloy framework* presents itself as a formal modelling language, conceived to properly address model-checking techniques over their specification language, where both structural design and temporal behaviour, naturally specified over properties, can easily be defined. Formerly, Alloy was inherently static [39], meaning that it only excel the structural design, where its language was based on first-order logic. The analysis process relied on a bounded model checking technique with no support for temporal behaviour. Notwithstanding, the latest realease of Alloy confers the ability to properly deal with expressive temporal properties, as well as trace evaluation over time, while employing the former structural approach.

As intentionally design to formally abstract both system's configuration and behaviour, Alloy successfully incorporates a set of features, within a well-documented and wide-ranged syntax that consequently allows large specification development. [39] The following subsection 3.2.1 addresses the Alloy concepts required for understanding how system modelling is covered.

3.2.1 *Structural Modelling*

Alloy aims to address the complexity behind richly structured systems, that require critical control over their intended behaviour, by presenting a novel approach for abstracting these systems as conventional models. System's structures can be specified over time-evolving states, where its behaviour clearly identifies the states' inbetween transitions. Thus, the conception of system transitioning offers a great formal approach when it comes to reason about the system's design.

The Alloy structural definition relies on a relation way of connecting system's elements, where the latter is abstracted in terms of relations. In Alloy, unary relations, commonly known as sets, are labelled as *signatures*, that are inhabited by a set of *atoms*, from a finite universe of discourse. Atoms are perceived as the lowest-grain elements, with no particular semantics attached. A signature, identified by the keyword sig, might include multiple *field* declarations enclosed between braces, addressing relation between the signature's atoms and a set or other relation. Fields are inhabited by tuples of atoms from the universe, that must meet the same arity.

Signatures can either be perceived as a top-level signature, or as other signature's subset. Signature hierarchy is conceivable through disjoint extensions ($extends$), or by set inclusion (in). The $abstract$ keyword declares a signature that contains no atoms beyond those within its extensions.

To address default configuration over the universe's multiplicity, both signatures and fields can be specified under a multiplicity constraint. The former constrains the number of signature atoms, where it is commonly used to express singleton sets, over the constraint keyword $one\ sig$. Fields, however, makes great use of multiplicities, offering behaviour expressness over relations between atoms. Additionally to these model constraints, explicitly specified over the course of the modelling process, system assumptions can be defined over axioms, expressed as $facts$, where multiple constraints can be incorporated. [27]

Moreover, the lattest Alloy version enables evaluation changing throughout the trace evolution, consequently allowing the consideration of both signatures and fields as time mutable declarations, through the usage of the keyword var.

Throughout the sections that follow, it will be presented an illustrive example over which graph theory rests, this being the study of *Eulerian Circuits*. This example will be used to duly contextualize both modelling and verification process in Alloy. *Eulerian Circuits* must meet several behaviour constraints over the classic graph definition, that must be addressed over model constraints. However, the structural modelling must be provided beforehand.

Model Structure

With regard to the presented example, as it falls under the study of graphs theory [59], it follows an abstract representation of the graph mathematical structure. In this sense, a graph is made up of nodes which are connected by edges.

Considering the Alloy's abstract ability to reduce complexity over model designing, at a high degree of abstraction, graphs can be represented as a set of *nodes*, that connect together over relations, with no need to address edges as a separated structure declaration.

```
sig Node {
```

```
    adj : set Node,
    var visited : set Node
}
```

Graph representation over a sigle Node declaration.

As depicted above, the sig keyword followed by the corresponding *Node* signature declaration, represents the state of our intended example. The *Node* signature is defined by a static set of node *atoms*, that combined denotes the finite universe of discourse.

Then, *fields* are enclosed between braces upon the *Node* signature declaration. The *adj* concerns the graph edges, where each node can be connected to a set of nodes. As it is identified as an immutable *field*, the corresponding relation between atoms is static. Moreover, addressing additional graph functionality, it is desirable to concern about the visited nodes. The latter represents a mutable relation, identified by the keyword var, meaning that its evaluation may change during the course of the trace's evolution, as opposed to the static ones.

Relation multiplicity constraints are explicitly defined in the field declaration through the use of multiplicity operators, with those being one, $lone$, $some$ and set.

Multiplicity constraints in declarations

Set declarations with multiplicities 76	
e is a expression producing a set (arity 1)	
x: **set** e	x a subset of e
x: **lone** e	x empty or a singleton subset of e
x: **some** e	x a nonempty subset of e
x: **one** e	x a singleton subset of e (i.e. a scalar)
x: e	x a singleton subset of e (equivalent to **one**)

Figure 9: Alloy Multiplicity constraints. Extracted from [3].

Structural constraints can be entailed over explicitly signature declaration. These are often referred as *signature facts*, universally quantified over the signature's set. [3] Suppose a hypothetical design scenario, where the relation *adj* is labelled as mutable. To ensure that the graph architecture consistency, in which, edges are structurally fixed, the following constraint can be specified. Additionally, consider the following *graph* property, where it is desirable to express the following axiom: *The graph contains no self-loops.*

```
sig Node {
    var adj : set Node,
    var visited : set Node
} {
    always adj' = adj
    this not in adj
}
```

Node hypothetical constraints over the signature definition.

As stated, the former poses a model incoherence within the *Node* signature declaration, as *adj* field is formerly labelled as mutable, that is later refuted by specifying $always\ adj' = adj$. This latter introduces the Alloy language's ability to express temporal behaviour through these *two linear temporal logic* operators, $'$ and $always$ respectively.

The $always$ operator expresses an universal quantifier over time, imposing a constraint throughout the trace. The $'$ operator evaluates the *adj* relation in the next state. So, the formula specifies that the evaluation of *adj* in the next state is always the same of the current state. Alloy integrates LTL into the standard relational logic, therefore, supporting both linear temporal logic unary and binary modal operator.

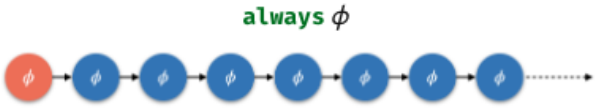

Figure 10: $always$ behavioural representation.

Whereas the latter expresses the *no self-loop* graph property. Even though *adj* is introduced as a relation between *Nodes*, it is perceived as a set of *Nodes* due to specification with the signature declaration. The keyword $this$ addresses each *Node* atom, as self representation of the considered atom. The remaining specifies the intended behaviour, as it specifies the non-inclusion ($not\ in$) over the set of its adjacent nodes.

Aside from the structural constraints implied within signature's declaration, multiplicity over fields 9 and signatures also narrows the model's universe. The field multiplicity operators could be used to limit the number of signature atoms. Despite this, signature multiplicity is frequently used to represent singleton $one\ sig$ sets.

```
one sig Init extends Node {}
var one sig Euler in Node {}
```

Node signature hierarchy.

The above signatures accurately support the *Eurelian* circuit concept. An *Eurelian* path denotes a trail in a finite graph where every edge is visited exactly once. Additionally, an *Eurelian* circuit implies that the path must start and end at the same node, denoted as *Init*. As this latter differs from the remaining *Node* atoms, the $extends$ keyword must be used to imply hierarchy disjointness. The *Euler* node is an abstract representation of the current node that is being visited. As this impose a mutable state (var) over nodes, hierarchy disjointness is not appropriate. Hence, to properly model that the *Euler* node can be included in an arbitrary atom, signature inclusion (in) should be used.

Both signatures are preceded by the one keyword, imposing a multiplicity constraint over each signature declaration. Setting the multiplicity to one means that each assessed model instance must have precisely one *Init* atom and one *Euler* atom. It should be noted that, since the *Node* declaration is not preceded by the $abstract$ keyword, its atoms do not solely belong to the *Init* signature.

Additional modelling constraints can be specified by making use of the $fact$ declaration. The formula specified inside each $fact$ declaration denotes a model axiom, that holds a truth model assumption, to serve as a premise for further reasoning.

The *Eulerian* path denotes a trail within a finite graph, with each graph edge being visited precisely once. Thus, this already implies that the graph must be connected, where each node must be reachable, and undirected, where edges are non-oriented.

```
fact eulerian_considerations {
    adj = ~adj
    no iden & adj
    Node->Node in *(adj + ~adj)
}
```

Graph restrictions through $fact$ declaration.

These expressions, above specified, makes use of some valued Alloy operators, consequently identified either as a set-theory operator or as a relational operator. Despite the extensive number of operators supplied by Alloy's language, every expression, through the usage of *FOL* quantifiers and *LTL* operators, is later translated to boolean-based expressions.

Alloy	Math
Φ in Ψ	$\Phi \subseteq \Psi$
Φ = Ψ	$\Phi = \Psi$
lone Φ	$\lvert\Phi\rvert \leq 1$
some Φ	$\lvert\Phi\rvert \geq 1$
no Φ	$\lvert\Phi\rvert = 0$
one Φ	$\lvert\Phi\rvert = 1$

Alloy	Math
iden	id
Φ + Ψ	$\Phi \cup \Psi$
Φ & Ψ	$\Phi \cap \Psi$
Φ - Ψ	$\Phi \setminus \Psi$
Φ -> Ψ	$\Phi \times \Psi$
Φ . Ψ	$\Phi \,.\, \Psi$
A <: Φ	$A \lhd \Psi$
Φ :> A	$\Phi \rhd A$
~ Φ	Φ°
^ Φ	Φ^{+}
* Φ	$\Phi^{\star}$
{ x : A | φ }	$\{x \mid x \in A \wedge \phi\}$

Figure 11: Relational Logic Syntax.

Regarding set-theory, set intersection (denoted by &) and set conjunction (denoted by $+$) are introduced. The remaining are relational based operators. The $\sim adj$ denotes the converse relation of *adj*, and the $\rightarrow$ represents the Cartesian product operator. The reflexive transitive closure operator ($*$) confers the smallest transitive $*(adj + adj)$ relation containing all the identifiers, reachable in zero or more steps, through the implicit use of the set composition operator ($\cdot$). The other transitive closure ^ is defined as $\hat{}rel = *rel - iden$.

$$\hat{}rel = rel + rel \cdot rel + rel \cdot rel \cdot rel + ...$$

Figure 12: Reflexive transitive closure operator.

In order to prevent unwanted model structural scenarios, the intended model can be visualized over the *Alloy Visualizer*, upon executing the run analyzing command. In the Figure 13 is depicted an instance of an acceptable configuration of the *Eulerian* circuit with *5 Node* atoms, since every model constraint was duly specified.

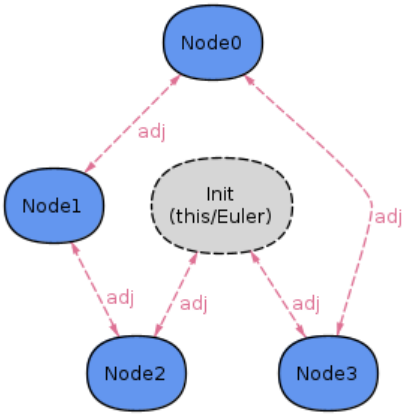

Figure 13: Acceptable *Eulerian* graph model design.

Everything is a Relation

As previously stated, Alloy emphasizes the mathematical relation concept to describe systems as a conventional designed model, through conceiving a set R of relations. Moreover, Alloy confers the ability to express their relations as *variable*. [39] An Alloy relation presents itself as a set of tuples of *atoms* drawn from the same universe context. Subsequently, each relation tuple must meet the same arity of the relation. [8]

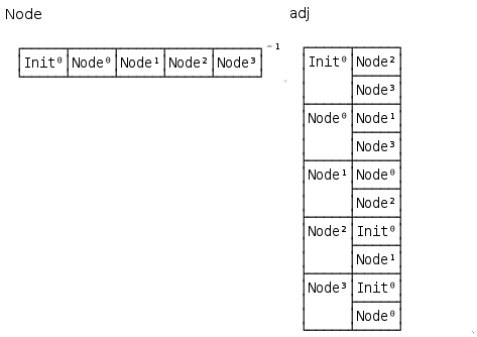

Figure 14: *Node* and *adj* relations.

The *Alloy Evaluator* [28] confers additional functionality to the *Visualizer*. It allows the user to type Alloy-based expressions against the existing model, used to gather structure information about the existing model. [8] In the Figure 14 is presented both *Node* signature and *adj* relation, regarding the model depicted in the Figure 13.

Additionally, the use of the relational based operators $<:$ and $:>$ denote explicit restriction over relations, with the former restricting its domain, and the latter restricting its range.

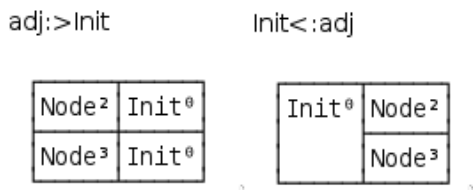

Figure 15: *Init* adjacent nodes.

3.2.2 *Structural Behaviour*

Model's behaviour representation represents the ability to express what is intended to happen during state transitions over the valid traces of a system. A *trace* is represented as an infinite chain of states that completely describes a system's potential behaviour. Valid traces are constrained by explicit specification of axioms, identified using the $fact$ keyword, alongside with the explicit model assumptions covered by each sig declaration, also constrains the system's behaviour. [27]

Despite the usefulness in restricting the system's traces, it is not ideal to express every property as a model assumption. Alloy high level of expressiveness enables the behaviour representation over multiple forms through an event idiom. [39]

System transitions are declared over events, where each event is conveniently specified in separate *predicates*. The latter, denoted as $pred$, enables Alloy to express boolean formulas that only hold their value when invoked.

Generally, events are specified with their respective event *guards* and event *effects*. A guard specifies a formula that must be true prior to the occurrence of the related event. Oppositely, an effect regards how the system evolves through the next state, providing a valid outcome of its event. The effect must account the mutable variables of the model through the usage of the $'$ operator, to guarantee the non-occurrence of unexpected behaviour. In addition, the temporal operator $after$ can be used to hold the truth of a formula in the next state.

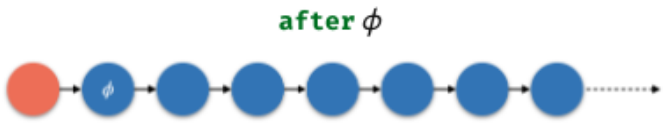

Figure 16: $after$ behavioural representation.

In order to provide a proper contextualization over these concepts, it is desirable to recall the *Eulerian* circuit example. The process of visiting nodes must be specified as it confers the main functionality within the graph theory. It follows the *traverse* predicate to effectively express the latter process.

```
pred traverse {
    some adjn : Euler.adj {
```

```
        adjn not in Euler.visited
        visited' = visited + Euler->adjn + adjn->Euler
        Euler' = adjn
    }
}
```

Eulerian visiting event.

The first guard states the existence of some node *adjn*, that must be related to the *Euler* node ($Euler \cdot adj$). Another guard is specified to cover the *Eulerian* condition where each edge must be visited exactly once ($adjn\ not\ in\ Euler \cdot visited$). It is followed by *2* effects, where the *visited* relation must account the latest visited edge, and the *Euler* node must be incorporated in the respective adjacent node, within the next state.

```
pred stutter {
    visited' = visited
    Euler' = Euler
}
```

Eulerian stutter event.

Unexpected behavior can occur if no constraints are set on how the system grows through such mutable expressions. Constraints imposed on mutable expressions that should remain unchanged in the next state are referred as *frame conditions*, a formula with primes ($'$) stating the "no change" effect. [8]

It is advisable to consider the "nothing changes" possibility in the evaluation of the trace evolution. The *stutter* predicate captures the "no effect" reasoning approach about the behaviour of the system, where frame conditions formulas are enclosed between braces.

Every conceivable trace inside the system must be a permutation of these event handlers performed on a well-defined initial state. When used consistently, this approach constitutes a model design pattern called as Implicit Operation Idiom. [27]

```
pred _init {
    Euler = Init
    no visited
}
```

Eulerian Initial State.

The *_init* states valid conditions valid in the first state. Thus, to properly specify the initial behaviour of our intended model, every edge must start unvisited ($no\ visited$) and the *Euler* node should start in the *Init* node.

As previously claimed, to reason about state transition, the notion of an execution trace should be duly introduced. The system's permissible behavior will be thoroughly specified by restricting the set of valid operations. As it already been specified every acceptable operation, it is presented the following $fact$ axiom.

```
fact traces {
    _init
```

```
    always (move or stutter)
}
```

Trace constraint through the use of an axiom.

The temporal operator $always$ followed by the desired formula is used to impose a state constraint, that must hold one of the *2* events, over the full trace evaluation. This axiom, as explained, must account the initial state (*_init*) conditions.

The notion of reusable expressions (fun) and model assertions ($assert$), are also conceptually included in the Alloy's event idiom. This idiom flexibility allows the developer to define action hierarchy, alongside with sharing atoms passed as parameters, resulting in simpler way of managing specifications. [39, 8]

3.3 STRUCTURAL ANALYSIS

Structural modelling only confers a conventional way of formally expressing the intended behaviour over a software component. To perform verification over the specified behaviour, it is advisable to implement analysis techniques, while supporting an illustrative way of exploring the behaviour through simulations.

This section aims to explain how Alloy conducts system analysis, with further explanations over the corresponding analysis commands, along with an overview on the Alloy Analyzer interactive exploration over a system's design.

3.3.1 *Analysis and Verification*

Alloy specification process does not establish a clear process separation over the model design and model analysis. This implies that analysis over model checking also accounts the model itself as a combination of properties specification.

The specification language holds *two* analyzing commands, run and $check$ respectively, as shown above in *Alloy's syntax*. A *Linear Temporal Logic (LTL) formula* is enclosed between braces, to be checked over. Upon executing, both commands accounts the enclosed formula ψ_f, as well as the model declaration M. Likewise in $fact$ declaration, several logic constraints can be combined into the formula ψ_f. Due to Alloy's implicit abstraction, both commands addresses the relational model specification as truth holder, with the latter being consisted by declarations over $fact$ and sig.

Briefly speaking, run instruct the model-checker to present an example that satisfies the considered formula ψ_f over the model definition. This means that the following formula ($M \wedge \psi_f$) is expected to hold. The consistency of the *facts* and *signatures* is consequently verified since the model declaration M is also considered.

Alloy makes use of the $check$ command to perform automatic verification over an $assertion$ declaration. The assertion ψ_f verification is done over proving if the following satisfiability formula $M \models \psi_f$ is valid within the defined scopes.

As result of the first-order logic's undecidability problem, the consistency proofness over satisfiability formulas is not possible. [57] To ensure decidability, the Alloy Analyzer performs analysis over *scopes*, assigned to each signature declaration. By default, if no scope is provided, the model-checker will account at most *three* atoms for each signature, upon trying to provide an *instance* that satisfies the former formula, consequently proving the behaviour specification (*facts* considerations) consistency. Also, as scopes imposes a limit on the state space of an Alloy model, if no run instance is returned, the formula can not be perceived as inconsistent, as scopes can not be properly set to satisfy the latter.

check { ϕ } **for** ... **but** k **steps**

Figure 17: LTL formula ψ verification using *check*, accounting the *Bounded* model checking technique.

Being SAT-based [39], the Alloy Analyzer tries to search for a *lasso trace* instance that satistfies the formula $M \models \psi_f$ over the *check* command, it performs the latter refutation ($(M \wedge \neg\psi_p)$ by applying *De Morgan's laws*), yielding a counter-example if the latter is satisfied. This technique is called *Proof by Refutation*: M entails ψ_p, denoted by $M \models \psi_f$, *if and only if* $(M \wedge \neg\psi_p)$ is unsatisfiable, reducing validity to unsatisfiability.

run { **not** ϕ } **for** ... **but exactly** 1 **steps**
run { **not** ϕ } **for** ... **but exactly** 2 **steps**
...
run { **not** ϕ } **for** ... **but exactly** k **steps**

Figure 18: Reducing Validity to Unsatisfiability.

Moreover, Alloy yields a command to specify the finite number of different steps, related to the expected instance's evaluation trace. This is due to the *bounded* nature of the Alloy transitions between states, where the *Bounded Model Checking* technique is considered as model-checking technique. The number of steps is set to *10* by default, although this may be adjusted using the keyword $steps$, alongside with the bounded scopes specification.

The following run example makes use of both scopes and steps definitions. Moreover, the formula specified in the run states the expected behavioural representation of an *Eulerian* circuit. The $eventually$ (Figure 20) operator is considered to specify the desired final state, where every edge is visited and the *Euler* node finishes where it started.

```
run example {
    eventually (adj in visited and Euler in Init)
} for exactly 5 Node, exactly 5 steps
```

Bounded Model Checking: Eventually the graph will represent an *Eulerian* circuit.

This particular run yields no instance, so its corresponding formula $M \wedge \psi_p$ does not hold, since imposing *5* steps is not sufficient to provide an instance where the desired state, defined by the latter formula, is reached.

Behavioural Properties

The verification process over *Model Checking*, needs to account the formal specification of properties that are relevant to reason about the system's temporal behaviour. [4]

Alloy makes use of the relational logic (Figure 11) to ensure the well-formedness of the system, which falls short when it comes to supplying support over temporal behaviour. Thereby, Alloy includes temporal connectives from *Linear Temporal Logic* (LTL), that acknowledges the system's states along the trace evolution. [39, 28, 9]

Ensuring the correctness of a system's behaviour relies on verifying properties regarding the latter's *Safety* and *Liveness*. Its verification technique is motivated by distinct approaches. [35] The former requires an invariance argument, where the latter requires a well-foundedness argument to prove its system satisfiability. [2]

A *safety property* asserts that "nothing bad should happen" during the system execution, meaning that, every trace state is expected. Consequently, if a trace that jeoperdizes a safety property is found, it can be assumed that the latter has a "bad" property prefix.

```
assert safety_visited {
    always visited in visited'
}
```

Safety Property: The relation visited can only evolve through time.

```
assert safety_euler {
    always (all n :  Node | n in Node.visited implies once Euler = n)
}
```

Safety Property: If a node is visited, then once *Euler* was 'inside' it.

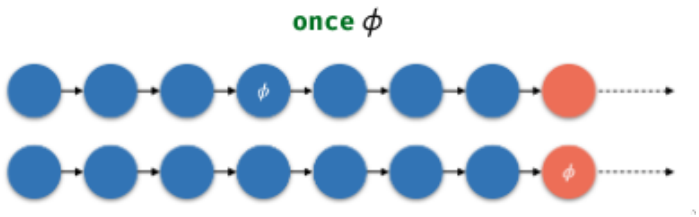

Figure 19: *once* behavioural representation.

Whereas, a *liveness property* expresses that "something good will happen", implying the eventual occurrence of a state during the course of the system's execution. [36]

```
assert liveness_euler {
    eventually (adj in visited and Euler in Init)
}
```

Liveness Property: Eventually the graph will represent an *Eulerian* circuit.

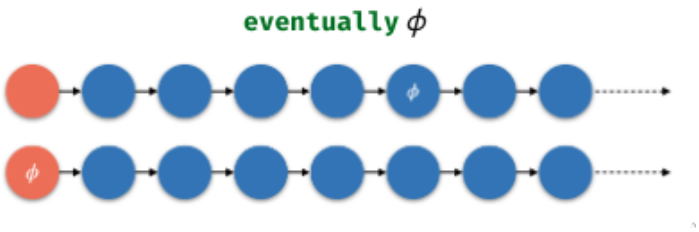

Figure 20: *eventually* behavioural representation.

The above-mentioned properties make use of *2* relevant over time quantifiers. The *once* operator expresses the past validation of a given formula. The *eventually* operator expresses an existence quantifier, imposing the formula verification somewhere along the trace evolution. [8]

Moreover, the liveness property states the expected behavioural representation of an *Eulerian* circuit, where the *eventually* (Figure 20) operator is considered to specify the desired final state. However, its verification, using *check liveness_euler*, yields a counterexample, as it is possible to always perform the *stutter* event, and thus the expected behaviour never happens. This scenario results in an implausible infinite trace behavior, which must be handled by adding fairness to the trace assessment.

Liveness properties evaluation process reasons about states that eventually might reach the wanted scenario, it is advisable to consider *fairness* constraints, intentionally specified to rule out infinite traces with unrealistic behaviour, such as system stuttering. [4] Briefly, a *fairness* constraint imposes fairly considerations on the system's trace evolution. [58]

```
pred fairness {
  (eventually always some Euler.adj) implies (always eventually traverse)
}
```

Fairness predicate: If *Euler* has an adjacent node, it will eventually visit the latter.

The latter imposes a fairness constraint regarding the trace evolution, ensuring that trace stuttering is not possible as long as the *Euler* node has some adjacent node that is not been visited yet. As expected, by instructing the Analyzer to check the asserted property (*check liveness_euler*), it will return no counterexample.

```
assert liveness_euler {
  fairness implies eventually (adj in visited and Euler in Init)
} check liveness_euler
```

Liveness property accounting the fairness constraint. It yields no counterexample.

3.3.2 *Alloy Analyzer*

Normally, the specification process upon abstracting the system as a conventional model is carried out interactively, since considerations about model validation must be preceded by the model specification. The

already mentioned analysis techniques, run and $check$ analysis commands respectively, instruct the Analyzer to check and provide analysis over their implicit formula nature. Moreover, the Analyzer is capable of providing model instances concerning the formula evaluation, depicted graphically as graph-like structures, through the usage of the Alloy *Visualizer*, allowing instance interaction over multiple configuration buttons. Additionally, concerning the user comprehension, the graphical depiction of these instances can be customized using *Themes*, through the Theme toolbar button.

Recall the run example that failed to provide a model instance due to the $steps$ explicit limitation. To find an *Eulerian* circuit instance for n nodes, the minimum of $n + 1$ steps are required.

```
run example {
    eventually (adj in visited and Euler in Init)
} for exactly 5 Node
```

Bounded Model Checking: Eventually the graph will represent an *Eulerian* circuit.

Producing a concrete instance might be quite helpful throughout the modeling process. The run command presented above is capable of providing a model instance as it performs Bounded Model Checking for at most *10* steps. The Analyzer executes the command and generates an instance regarding the latter, consequently producing a visual graphical (Figure 21) through the usage of the Visualizer.

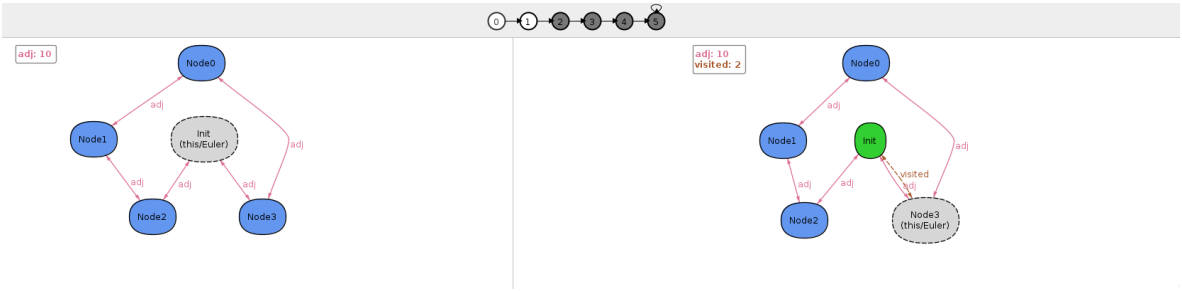

Figure 21: Partial graphical view of the *two* initial states. The *Euler* node starts in the *Init* node, and then moves towards an adjacent node.

The Visualizer furnishes a toolbar with multiple configuration buttons, allowing interactive customization over alternative instances. [8] Traces can also be interactively overviewed through transition buttons ($\rightarrow$ and $\leftarrow$), enabling forward and backward trace navigation.

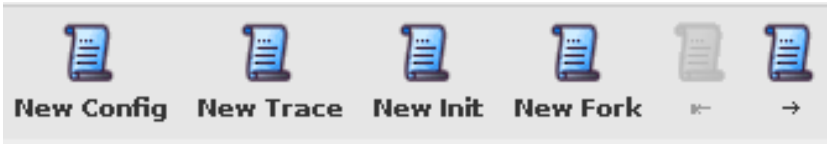

Figure 22: Alloy Visualizer toolbar.

The New Config instructs the Analyzer to provide a new trace configuration, where immutable model expressions (sets and relations) are depicted with new values. Consequently, the Visualizer will present an execution

trace regarding the new model configuration. The New Trace instructs the Analyzer to present a new execution trace, regarding the same model configuration. The New Init requests for a new trace representation, where the initial state is forced to present different model expressions values. At last, the New Fork allows alternative transition behaviour exploration over the same starting state, depicting a new transition post-state. The latter could differ on the result of a given event, or it can display the outcome of a different event. [8]

Alloy forces the property formula translation into an LTL formula, considering the finitude of its universe of comprehension. Due to the emphasis on representing instances over infinite traces, every Alloy instance generated by the Analyzer, captures an infinite trace through *lassos*, where a looping state is reached.

Concerning performance in the evaluation over infinite traces, Alloy considers the Bounded Model Checking technique as the first approach towards the model verification. Here, the corresponding LTL formula is verified for all *lasso* traces of size up to a bounded number of steps. So, the verification is not complete, due to the SAT time-bounded nature. However, it still confers great functionality, as infinite traces can often be represented as finite traces, making verification within small scopes possible. [30]

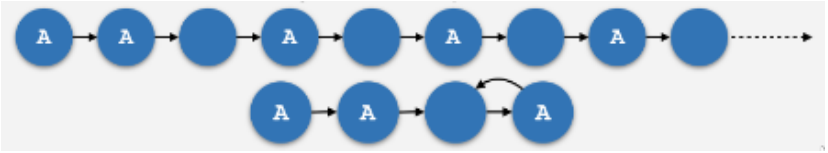

Figure 23: Some infinite traces can be represented by finite lasso traces.

Oppositely, the Analyzer can be instructed to perform Unbounded Model Checking towards achieving consistency over model verification, without bounding traces upfront. [28, 8] This is feasible as the state space is finite due to the Alloy analysis way of bounding signatures, consequently constraining infinite traces as periodic (Figure 23).

To perform complete model-checking, an appropriate solver must be selected in the Options menu, and the time scope must be specified under the following syntax: $for\ 1..\ steps$. Consider, the former run command, now considering the Unbounded Model Checking technique.

```
run example {
    eventually (adj in visited and Euler in Init)
} for exactly 5 Node, 1.. steps
```

Unbounded Model Checking: Eventually the graph will represent an *Eulerian* circuit.

4

STATE OF THE ART

4.1 RELATED WORK

This section intends to present previous developed work regarding the main concepts on what this dissertation rests. The subsection 4.1.1 aims to provide a comprehensive overview over works that attended to prevent security issues related to the deployment of robotic systems using Robot Operating System, as its application enhancer. It is then followed by the subsection 4.1.2 that concerns about previous work addressing property verification and model checking techniques over ROS applications.

4.1.1 *Security Overview*

The literature concerning the network security enhancment that Robot Operating System 2 furnishes, by offering the SROS2 toolset, is quite limited. Most of the existing work is on the exploration of the former version of ROS in terms of port exposure, contextualized in the approach considered to protect the system network.

Many researches were made regarding this issue that ROS faces, one in particular that explored the IPv4 address space of the Internet for instances of ROS, named *Scanning the Internet for ROS: A View of Security in Robotics Research* [18], with the goal of identifying ROS vulnerable hosts, mostly master nodes since they provide information about their related topics and node's parameters, mainly by port scanning, so that developers could be aware of the possibility of exposure of their robots.

Following the need of supplying security assurance over ROS applications, several approaches were presented. A study that is rather relevant because of the similarity between their proposal and the one that SROS2 has to offer is the one presented on the *Application-level security for ROS-based applications* [21]. The approach primarily focused on applying security measures on the application layer, by mainly running an Authentication Server, storing certificates and files related to trusted domain participants, while controlling and providing session keys related to the communication process. Even though encryption and authentication measures are concerned, the protected network is still perceived from the "outside", meaning that security attacks, such as denial of service, still persist which cannot be handled on the application level alone. Secure Robot Operating System (SROS) [60] was initially developed as an experimental tool (later evolved to SROS2 as a supporting tool for ROS2), which supports TLS for all socket transport, node restrictions and chains of trust, guaranteeing publishers authorization

when it comes to publish to a specific topic. Another worth-mentioned tool is Rosbridge [16], which provides a WebSocket interface to ROS and corresponding server to allow interaction between applications and ROS nodes, by using TLS as support and also access control over topics and API calls.

The present works addressing ROS security methods tend to concern solutions to prevent vulnerabilites and issues that might compromise robotic applications deployed, while considering performance as priority. In terms of applying formal methods to verify properties regarding the domain of ROS2 and ROS2 security as models, there are minimal existent works. Despite this, the following section consists of several articles proposed to validate robotic systems, using formal methods as core.

4.1.2 *Analysis and Verification*

Static analysis over ROS represents a major contribution to this domain, in which researchers aim to tackle issues arised from miss configurations or code inconsistencies. The noteworthy *HAROS* framework [54] holds great value thanks to its contribution on improving ROS's software quality. *HAROS* makes use of several analysis techniques to exert quality evaluation of ROS software, followed by ways of feedbacking inconsistencies using predefined code metrics. As this framework seeks to be flexible when it comes to adding functionality, further static analysis works improvements have been proposed as plugins. In both 53 and 52, it is presented additional functionality to the framework, through applying architectural considerations over metamodel designing, where the latter supports the former by supplying property-based specifications. These techniques confers great help back to developers, since static analysis offers advantageable usage over raw review of software code.

The literature concerning property verification over model checking tools is quite extensive. Regarding ROS applications, some approaches were presented that mainly focused on modelling the ROS node-communication, while real-time properties were also considered as support to the target language. In 29, *UPPAAL* model checker is used to model ROS applications, supported by a concrete robot example, that is followed by techniques to verify properties regarding its behaviour. In 9 is presented a notable proposal, where *Electrum* [39], the former version of the current Alloy Analyzer, is used as an additional plug-in to the already mentioned *HAROS* framework. Through ROS launch configurations, the plugin automatically generated models using Electrum and performs verification over these models, to then feedback issues related to their ROS system behaviour.

As ROS2 domain regards the use of DDS communication protocol, a few works on DDS modelling analysis deserve to be mentioned, as they might give important background for property verification over communications protocols. In 1, it is proposed a technique to model the DCPS architectural design that DDS makes use of, alongside with new approaches to the current DDS behaviour. Supported by several modelling techniques for publish-subscribe systems, in 38, DDS in ROS2 is formalized as a timed automata, consequently followed by model verification over property-checking. These works conceive value concepts and procedures useful for this dissertation contextualization.

A few studies on robotics should be recognized in which techniques such as model-checking were performed. Despite the fact that they do not address the domain of ROS, they nonetheless give helpful background for the robotics research over formal approaches. A case study, mentioned in 45, presents a novel approach over

systems that require static analysis based on software assumptions and proper analysis within its environment usage, where user-interaction comes in hand. Concerning this novel idea, a medical system is concerned as a case study, where multiple safety-based considerations are expected, as well as, an end-to-end critical property that must be satisfied over the entire analysis course. Another notable work regarding former analysis using Alloy specification language is presented in 40, where a safety-critical scenario is proposed under the domain of surgical robots. The formal techniques used allows overview over a surgical robot arm, taking into consideration possible violations of important safety properties. Although these studies presents favorable outcomes, their focus lies on a particular area of study. As a result, they lack on providing solutions to a vast majority of situations.

4.2 CURRENT WORK

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NB: place here information about funding, FCT project, etc in which the work is framed. Leave empty otherwise.