Universidade do Minho
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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) [36] 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) [31] 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 [18]. However, improper configuration can still lead security problems.

This thesis 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 [20], 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) [36], 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) [31], 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* [18], 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 [20], 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 [30], since their usage brings increased productivity, safety and more manufacturing production work back to developed countries. [17, 8]

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 [35]. 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. [30, 28]. 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. [14] 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. [35] 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. [24]

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. [25]

This lead to the creation of Robot Operating System 2, developed using the Data Distribution Service (DDS) [31] 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. [2]

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. [4] Within this context, Alloy [21, 26] 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. [3]

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 [23] 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 [5] formalization of ROS applications in Alloy/Electrum [20, 26] 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 four different chapters. Chapter (3) introduces all the concepts related to Robot Operating System, and its evolution as robotic development framework towards achieving system security. The current provided work regarding ROS and security in ROS is also presented in this chapter. Chapter (2) introduces the Alloy framework, as its specification language supported by a concrete example case. Chapter (4) presents the approach developed during this work, which allows the automatic verification of system-wide safety properties, considering security in ROS2 applications. Chapter (**??**) evaluates the latter approach supported by a concrete example. Chapter (6) presents the thesis conclusions, alongisde possible future aproaches complementing the current work.

2

ALLOY SPECIFICATION FRAMEWORK

As aforementioned, this thesis 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, as well as previous developed work that has the same or similar goals as this thesis (2.4).

As result of the increased usage of robotics, and with their integration into the human world, security ensurance for robotics software is highly required. The use of formal methods, especially in systems highly reliant on flexibility and reliability, is recommended to avoid security-critical faults. [4] 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* [21], fits within within this context, as it furnishes a declarative specification language, based on the relation concept, used for software modelling, with extended tools supporting analysis over these models. [20] 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 latter is exhaustively checked over property verification. [26, 4]

The framework includes an IDE, as well as an *analyzer* that takes the specified model's restrictions into account, and performs 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. [20]

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.

2.1 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 [26], meaning that it only excel the structural design. However, the lattest Alloy confers the ability to properly deal with expressive temporal properties, 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 consenquently allows large specification development. [4] Before accurately accounting both structural design as modelling technique and structural analysis, it follows the Alloy formal syntax.

```
alloyModule ::= [moduleDecl] import* paragraph*
moduleDecl ::= module qualName [[name,+]]
import ::= open qualName [[qualName,+]] [as name]
paragraph ::= sigDecl | factDecl | predDecl | funDecl
    | assertDecl | cmdDecl
sigDecl ::= [var] [abstract] [mult] sig name,+ [sigExt] { fieldDecl,* } [block]
sigExt ::= extends qualName | in qualName [+ qualName]*
mult ::= lone | some | one
fieldDecl ::= [var] decl
decl ::= [disj] name,+ : [disj] expr
factDecl ::= fact [name] block
predDecl ::= pred [qualName .] name [paraDecls] block
funDecl ::= fun [qualName .] name [paraDecls] : expr { expr }
paraDecls ::= ( decl,* ) | [ decl,* ]
assertDecl ::= assert [name] block
cmdDecl ::= [name :] ( run | check ) ( qualName | block ) [scope]
scope ::= for number [but typescope,+] | for typescope,+
typescope ::= [exactly] number qualName
expr ::= const | qualName | @name | this
    | unOp expr | expr binOp expr | expr arrowOp expr
    | expr [ expr,* ]
    | expr [! | not] compareOp expr
    | expr ( => | implies ) expr else expr
    | let letDecl,+ blockOrBar
    | quant decl,+ blockOrBar
    | { decl,+ blockOrBar }
    | expr '
    | ( expr ) | block
const ::= [-] number | none | univ | iden
unOp ::= ! | not | no | mult | set | # | ~ | * | ^
    | always | eventually | after | before | historically | once
binOp ::= || | or | && | and | <=> | iff | => | implies |
    & | + | - | ++ | <: | :> | . | until | releases | since | triggered | ;
arrowOp ::= [mult | set] -> [mult | set]
compareOp ::= in | = | < | > | =< | =>
letDecl ::= name = expr
block ::= { expr* }
blockOrBar ::= block | bar expr
bar ::= |
```

```
quant ::= all | no | sum | mult
qualName ::= [this/] ( name / )* name
```

Alloy's syntax.

2.1.1 *System 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.

2.2 STRUCTURAL ANALYSIS

2.2.1 *System Analysis*

2.2.2 *Alloy Analyzer*

2.2.3 *Model Checking*

2.3 RELATED WORK

3

SOFTWARE DEVELOPMENT IN ROS

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 [7], 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, compromising 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. [14, 24]

The upgraded version of ROS, Robot Operating System 2 (ROS), 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 [32], 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. Thereafter, it will be presented a section dedicated to related work regarding the study of security in ROS based systems. (3.3)

3.1 ARCHITECTURE CONSIDERATIONS

The Robot Operating System was created by a collaborative open-source community, that has undergone rapid development [7], to contribute in the advancement of cyber physical systems, serving as developer enhancer for the world of robotic applications. [14, 35]

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 [6] 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. [28]

3.1.1 *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.

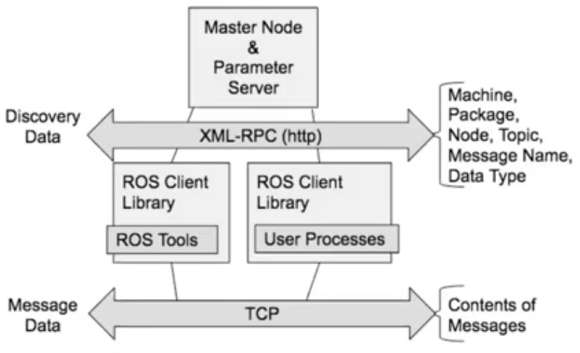

Figure 1: Robot Operating System architecture.

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. [28]

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. [24, 6]

3.1.2 *Data Distribution Service*

The Data Distributed System [31], 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. [19]

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. [31, 33] 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. [28, 1, 10]

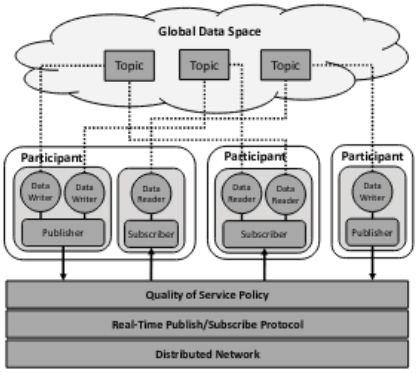

Figure 2: DDS architecture: DCPS model with RTPS. Extracted from [28].

To properly adress the data transportation through physical network, DDS offers a wire specfication protocol called Real-Time Publish-Subscribe Wire Protocol (RTPS) [38], 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. [42] RTPS allows multiple applications, that could differ on their used DDS implementations, to interoperate with each other as network domain participants. [10, 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, 14, 28]

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 acess 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.

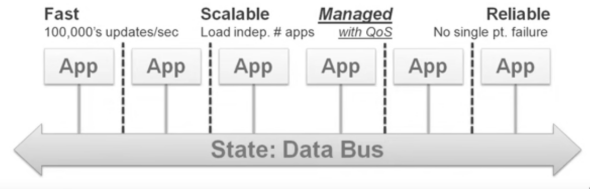

Figure 3: Data Distributed System architecture in a nutshell.

3.1.3 *ROS-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 [28], 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. [41]

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. [37] 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. [39, 6]

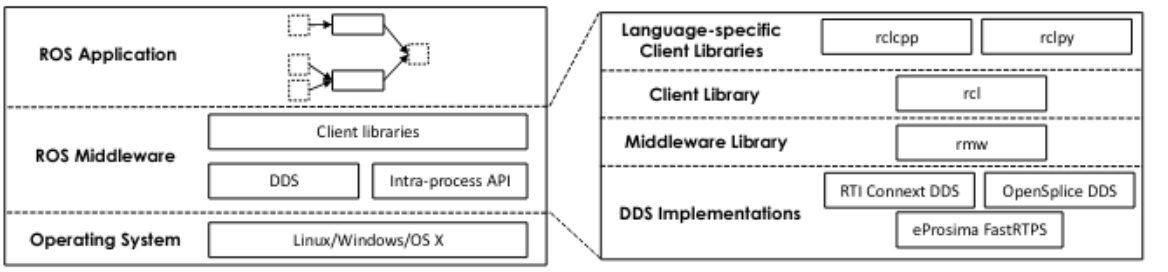

Figure 4: ROS2 framework architecture.

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 implementation's API specification might differ from each other (currently, FastRTPS by eProsima, Connext by RTI, and Vortex Open-

Splice 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 [6], allowing portability among DDS vendores, 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.

3.1.4 *Computation Graph*

From a logical perspective [6], 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 of 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.

For instance, lets considered 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. The ROS2 command toolset allows node launching using the *run* keyword, in which both the node's namespace and its corresponding package must be passed as arguments.

```
/multiplexer
/random
/turtle_teleop_key
/turtlesim_node
```

The `TurtleSim` node list.

Communication

Message-passing models 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), or defined by a complex data structure, where multiple data types are assigned to their corresponding variables.

ROS computation graph provides *three* 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.

Considering the `TurtleSim` example, the main message that is used to trigger the turtle movement, is composed by multiple data movement variables regarding the linear and circular movement of the turtle. The interface is called *Twist* and it is a ROS predefined geometry message.

```
Vector3   linear
Vector3   angular
```

`Twist.msg` interface file that is used to trigger the turtle movement.

Topics are perhaps the most common method, naturally perceived as middle-communication buses, over which messages is 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.

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. [6]

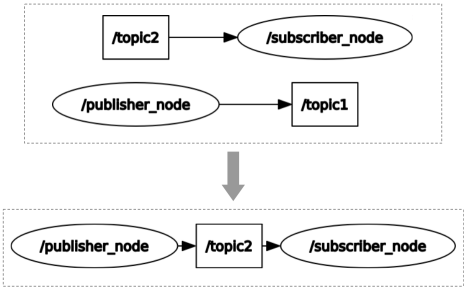

Figure 5: ROS2 communication behaviour over *topics*.

Addressing data exchange over nodes implemented with no associated namespace, the configuration is straightforward, in which their respective subscriber and publisher instances must have the same topic's name

instantiated. Whereas, if the nodes are specified over different namespaces, their topic's name will differ, so a technique of *remapping* must be used.

```
/high_topic
/low_topic
/main_topic
```

The `TurtleSim` topic list.

Launch Files

A conventional way of deploying a ROS appliaction is through the use of *launch files*, enabling the multi-configuration over entire robotic applications, where relevant nodes can be individually pre-configurated. Therefore, ROS makes use of the *roslaunch* to automatically initialize the whole newtork, simultaneously launching each node. This provides a simpler way of monitoring the system 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.

```
<launch>
    <node name="turtlesim" pkg="turtlesim" exec="turtlesim_node" output="screen"
        args="-r /turtle1/cmd_vel:=/main_topic"/>
    <node name="keyboard" pkg="turtlesim" exec="turtle_teleop_key" args="--ros-
        args -r /turtle1/cmd_vel:=/high_topic"/>
    <node name="random" pkg="turtle_random" exec="random"/>
    <node name="multiplexer" pkg="turtle_multiplexer" exec="multiplexer"/>
</launch>
```

`TurtleSim` launch file. Note that topic remap is used to properly address the transmission of movement commands from both publishers.

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 6: `TurtleSim` network graph presented by *rqt_graph*.

The multiplexer has two different active subscriptions, managing two different turtle movement values. Therefore, it must keep both subscriptions synchronized with each other. This is achieved by setting different priorities to each subscription. *Timers* are also used, since they provide a useful way of managing these topics, by time-assigning, alternately changing the priority after the timer runs out, through its corresponding callback function.

Based on the priority settled, the *multiplexer* node forwards the commands through the *main_topic*, enabling the turtle movement. Every aspect related to the publisher-subscriber pattern, in this ROS2 system, is treated over topic's namespace remapping.

Additional ROS network elements

The `TurtleSim` application given as example above, does not address all the existing ways of data-exchanging between nodes. 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.

SERVICES *Services* allows a client, 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.

ACTIONS 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. Unlike services, actions can be cancelled, so the return response could not be acknowledge. A worth mentioned example, commonly used in robotic systems for navigation, is the intent of moving a robot to a position, previously requested by a client. While its traveling, it can send information about the transition state. When the robot reaches the predefined position, the server acknowledges the client by sending a result message.

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.

3.2 SECURITY INTEGRATION

The concerns about security take on particular importance, since robots are becoming more frequently used and can directly affect the physical world. *Cyber-physical* systems, commonly related to the arising of the automation concept of robots, feature unique vulnerabilities that exploit both cyber and physical nature of these devices. [29]

Generally, when considering the deployment of a robotic system, the following information security pillars, over which attacking counter measures should be measured, are hopefully concerned: Confidentiality, Integrity and Availability. [**?**]

3.2.1 *Security Analysis*

As aforementioned, ROS middleware faces known vulnerabilities due to its architecture and model nature. ROS internal 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 compromise the data itself. Due to the ROS master role in the communication architecture, and its ability to connect to other nodes, exposing this node using port scanning poses a threat over the whole network. [11]

There is also worries regarding how ROS controls 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. [24]

Aside from ensuring a well-structured communication architecture, DDS integration over ROS2 also guarantees security properties, where ROS's flexibility is preserved despite this increase on security. The *DDS-Security* [32] is a specification that serves as an add-on 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. The provided specification ensures protection against unauthorized access to data, considering the publish-subscribe pattern, as well as data manipulation and replay attacks. [2, 18]

Depending on the security requirements needed for a particular application, the usage of these plugins may be adjusted. The existence of a *Standardized Plugin API* enables this customization, serving as an interface between modules and DDS security protocols, while also incorporating all features of secure communications.

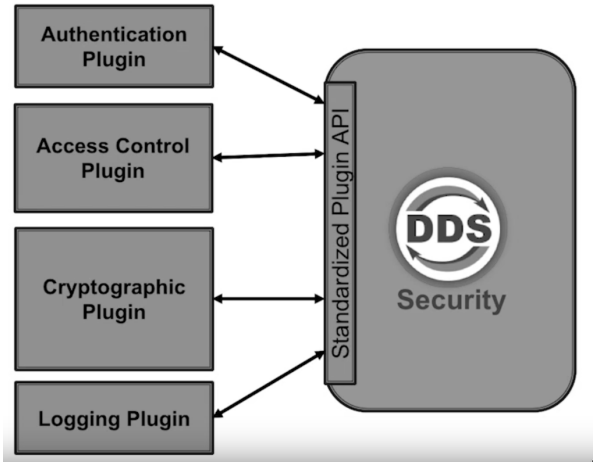

Figure 7: DDS-Security API with their respective security plugins.

Every DDS implementation supported by ROS2 makes use of the DDS-Security specification, enabling security over the ROS application environment. Even though ROS2 is deployed without security mechanisms by default [18], ROS2 provides a toolset, the *Secure Robot Operating System 2* (SROS2) toolset, concerning 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. 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 [18], 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.

3.2.2 *Security Configuration*

To properly introduce the set of tools that SROS2 provides, the `TurtleSim` application already presented 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 *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.

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.

```
ros2 security create_keystore demo
```

Keystore creation using the proper SROS2 command.

The *security* additional keyword-flag enables features regarding security matters, concerning the DDS-security artifacts.

Keystore's Directory Architecture

Upon the creation of the *demo keystore*, three respective subdirectories are created, where each has their own role when it comes to security enhancment 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. Each enclave includes files needed to enable security, such as CA certificates and their own private key (`key.pem`).
- The *public* directory contains material that is permissible as public. A Certificate Authority certificate, `ca.cert.pem` 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. DDS supports the separation of identity and permission chains, however ROS usually uses the former `ca.cert.perm` file, meaning that only a CA is used for both these processes.
- The *private* directory contains material that is considered private. A Certificate Authority certificate, `ca.cert.pem` 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 keystore's root, 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 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 adress 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 networt 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 consider 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, acess 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 restrictly specify the set of permissions of each enclave.

Following the *ConArmor* policy language [**?**], 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 denys 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="turtlesim" exec="turtlesim_node" output="screen"
        args="--ros-args --enclave /turtlesim -r /turtle1/cmd_vel:=/main_topic" />
    <node name="keyboard" pkg="turtlesim" exec="turtle_teleop_key" output="screen
        " args="--ros-args --enclave /keyboard -r /turtle1/cmd_vel:=/high_topic" /
        >
    <node name="random" pkg="turtle_random" exec="random" args="--ros-args --
        enclave /random" />
    <node name="multiplexer" pkg="turtle_multiplexer" exec="multiplexer" args="--
        ros-args --enclave /multiplexer" />
</launch>
```

`TurtleSim` launch file. Note that topic remap is used to properly address the transmission of movement commands from both publishers.

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 random 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.

However, if the user forces the inverted remap, it is possible to control the turtle movement directly from the random controller, since no policie has been compromised. Although, the random controller is still publishing to the *low_topic*, the main_topic in which the turtle movement is concerned is remapped towards the *low_topic*. This concerns a problem that is not been duly address by the ROS community. It is unreasonable to expect this flexibility in a secured network, since policies initially settled can be easily compromised.

3.3 RELATED WORK

3.3.1 *Security Analysis*

This section aims to present previous works that attended security matters related to the deployment of robotic systems using Robot Operating System as its application enhancer. When developing real-time systems, safety matters are often referred as critical, because of the overall integration with the real world. Security however, it is measured by evaluating different security issues by properly analysing the system model. However, due to the high nonlinearity and complexity of real-time systems, implementing such a thorough analysis method in near real-time remains a significant difficulty. [12]

The deployment of real-time systems results in the importance of concerning about safety in a performance point of view, resulting of the demanding time-critical scenarios. Many studies were made regarding the performance in both ROS and ROS2 (also regarding DDS Quality of Service policies [28]), by analysing using performance measurement approaches, providing a guided and supported review on how performance can directly affect time critical situations, where safety is envolved. [28, 6]

System security concerning network exposure, often explored by unauthorized acess and data leaking, can be treacherous and it is considered a complex subject, due to the abundance of different network security technologies that do not cover every security aspect, since absolute security does not exist, as new vulnerabilites arise from the tecnology evolution.[22] The creation and deployment of security countermeasures are essential upon configurating the network towards achieving security. Within this vast topic, several different avenues of endeavor come to mind, each deserving of a substantial study. Network security means exploring the network beforehand by computer intrusion detection, traffic analysis, network monitoring, alongside many other practical networking security aspects. [27]

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* [11], 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. The performed scans furnished information about hosts that could either be a sensor, an actuator or even a simulator. Topics were also identified since they provide evidence of what is likely to be available to an attacker. This study is rather relevant because of how easily can attackers gather information about potential robots, and control them further on, through the public Internet, making it unavoidable to develop mechanisms concerning security.

A different approach was previously presented [13] when it comes to protecting the ROS network, which primarily focused on applying security measures on the application layer, treating ROS architecture as a black-box, 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 the message data can not be perceived, unauthorized nodes can still collect information about the flow of the data, since ROS architecture is responsible for the publish-subscribe interaction, meaning that security issues still persist which cannot be handled on the application level alone.

Secure Robot Operating System (SROS) [40] 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 [9], 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.

3.3.2 *Static Analysis*

3.3.3 *Property Verification*

4

VERIFICATION OF INFORMATION-FLOW SECURITY PROPERTIES

5

EVALUATION

6

CONCLUSION

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