

Towards a Robotic Intrusion Prevention System: Combining Security and Safety in Cognitive Social Robots

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Abstract

Social Robots need to be safe and reliable to share their space with humans. This paper reports on the first results of a research project that aims to create more safe and reliable, intelligent autonomous robots by investigating the implications and interactions between cybersecurity and safety. We propose creating a robotic intrusion prevention system (RIPS) that follows a novel approach to detect and mitigate intrusions in cognitive social robot systems and other cyber-physical systems. The RIPS detects threats at the robotic communication level and enables mitigation of the cyber-physical threats by using *System Modes* to define what part of the robotic system reduces or limits its functionality while the system is compromised. We demonstrate the validity of our approach by applying it to a cognitive architecture running in a real social robot that preserves the privacy and safety of humans while facing several cyber attack situations.

Keywords: Social Robotics, Safety, Security, Cognitive Robotics

1. Introduction

Cognitive robots augment their autonomy, enabling them to deploy in increasingly open-ended environments [1][2]. These advances offer enormous possibilities for improvements in the human economy and well-being [3]. However, it also poses high risks that are difficult to assess and control by humans[4]. Our group's research aims to create safer and more reliable intelligent autonomous robots by investigating the implications and interactions between cybersecurity, safety, and explainability. Robots are increasingly common in our society: vacuum cleaners, company robots, caregivers, and autonomous vehicles, among others. Robots need to be safe, respectful of privacy, not manipulable by external agents, and capable of explaining their behavior. This paper focuses on the first two components: safety and security.

Safety has been an essential element in robotics since the first industrial robots [5][6][7]. A typical implementation of safety mechanisms is the use of modes of System Modes [8] The presence of people in the work area of a robot changes the operating mode to a different one that limits the damage that can be caused to people, for

example by reducing the speed or power of the motors.

Regarding security, the field of robotics (and more so in mobile robotics) has tended to rule out the use of secure protocols and tools because robots have traditionally been little-exposed systems that functioned in well-controlled research environments. With the increasingly common deployment in organizations and domestic environments, this assumption is no longer valid, requiring the establishment of mechanisms that ensure that a robotic system is not compromised or that this situation is detected and mitigated.

Intrusion Detection Systems (IDS) are tools that detect unauthorized access to a computerized system. In the event of any suspicious activity, they issue alerts. Intrusion Prevention Systems (IPS) are tools that, besides detecting intrusions, also perform actions to mitigate the threats. There are two types of IPS: Network Intrusion Prevention Systems (NIPS) and Host Intrusion Prevention Systems (HIPS). NIPS are network devices that monitor the wireless and wired traffic and mitigate the threats by dropping suspect packets, blocking and resetting connections, etc. HIPS are installed in the endpoints to analyze and filter the nodes' traffic. Those systems apply different detection techniques, such as

rule-based approaches, signature-based analysis (binary patterns in the data), anomaly-based analysis (detection of unexpected or abnormal behavior), policies, and different machine learning approaches (clustering, classification, estimation, association, prediction, statistics, etc.) [9, 10, 11]. NIPS and HIPS are combined and integrated into unified threat management (UTM) solutions to secure conventional distributed systems.

As other authors [12], we state that conventional network IDS and IPS solutions [9, 10, 11] are not suitable for autonomous robotic systems, cognitive social robots, and other kinds of cyber-physical systems (CPS) that comprise interacting digital, analog, physical, and human components engineered to function through integrated physics and logic [13]. In this scenario, traditional IPS solutions can be used to detect and prevent low level communication attacks, but they are not able to inspect the robotic communications properly and apply safety related mitigation measures at the robotic level. For this reason, we propose the creation of a Robotic Intrusion Prevention System (RIPS) for ROS 2 [14] systems.

It is common to use operating modes for safety. The ISO 13482:2014 standard, which covers robots, specially personal care robots, defines various modes of operation in which a robot can operate safely. System Modes [8] are a way of implementing modes of operation in robots since they provide an architectural scheme to separate the management of contingencies and modes of operation independently of the application's logic.

In this work, we will define some modes of operation similar to those proposed in safety, but that can represent the threat level detected by a RIPS system. We are convinced that in this way, it is easy to integrate into any robotic system the principles of safety, privacy, and integrity of the information without affecting the main logic of an application. , the system is reactively reconfigured to adapt to the perceived threat level and the mitigation that can be carried out.

The experimental validation of our approach will present a set of appropriate metrics to validate or reject the hypotheses raised and thus answer the research questions raised. The main contributions of this paper are:

1. The analysis and design of an system to detect intrusions in a social robot.
2. A novel approach to deploy safety in social robots using system modes.
3. A Security/Safety mechanism that combines the previous points in the same robot system.

This paper is structured as follows: In section 2,

we put our approach in context, analyzing the existing works in this area. In section 3, we present our cognitive architecture, which we use as reference to develop our proposal in section 5. We detail out the experimental validation in section 6, which serves to validate or reject our hypotheses. Finally, we answer our research questions in the conclusions presented in section 7.

2. Related Work

2.1. Security in Robots and Autonomous Systems

Different studies focusing on generic cybersecurity aspects for robotic environments (e.g., threats, vulnerabilities, attacks, risks, etc.) can be found in the literature. Cerrudo et al. [15] studied generic security issues in robotics, such as insecure communications, authentication issues, authorization issues, weak cryptography, privacy issues, etc. They also provided some example attack scenarios for different scopes (military, industrial, etc.). Clark et al. [16] published a paper describing real and potential threats to robotics at the hardware, firmware, operating system, and application levels. They also analyzed the impact of such attacks and presented a set of countermeasures for each level. Basan et al. [17] proposed a methodology to analyze the security of a network of mobile robots. They classified the structural and functional characteristics of robotic systems and analyzed potential attackers, their goals, and capabilities.

Three surveys on threats and attacks on robotic systems have been published recently: (i) Archibald et al. [18] published a survey on security in robotic systems in 2017. They divided the robotic system vulnerabilities in different classes: physical, sensor, communication, software, system-level, and user vulnerabilities. They also described potential physical and logical attacks; (ii) In 2019, Jahan et al. [19] published a survey on security modeling of autonomous systems. This work reviewed the historical evolution, approaches and trends, and analyzed the different types of autonomous systems (autonomous vehicles, IoT, swarms, robots, etc.). They also presented a set survey papers regarding the modeling of the systems and possible attacks and a discussion on future research directions and challenges; (iii) In 2021, Yaacoub et al. [20] published a survey on the main security vulnerabilities, threats, risks, and their impacts, for robotics environments. There are also multiple recent surveys on the security of autonomous vehicles (CAVs) [21, 22, 23, 24, 25].

The security of ROS and ROS 2 has been analyzed in multiple studies [26, 27, 28, 29, 30, 31, 32, 33, 34,

35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. As far as we know, there is not any IPS for ROS 2 systems. There are different tools for detect and debug incorrect programs and monitor ROS1 and ROS 2 systems. HAROS [45] is a framework used to detect incorrect code in ROS 2 applications. The static analyzer framework inspects the source code and creates a formal model in a specific language designed for capturing ROS 2 properties (scope, patterns, etc.). Those properties are used for testing.

ARNI [46, 47] is a framework to monitor ROS1 systems. It is used to find configuration errors and bottlenecks in the communications. The framework allows the user to define a reference state for the whole ROS1 system. Then, it continuously compares the reference state to the actual state. If there are deviations, the user is warned through a dashboard. The user can also define countermeasures that are executed by the system.

Drums [48] is a tool for monitoring and debugging ROS1 systems. It permits the user to inspect the node graph, audit services, and communication channels as native processes and network channels. In addition, it allows the user to monitor host resources (CPU, memory, etc.) and store the collected information in a database. Drums provides a dashboard and uses a data-driven anomaly detection software [49], but it does not provide IPS capabilities.

Vulcanexus [50] is a software stack for ROS 2 that provides a set of libraries, tools, simulators, etc. It includes a ROS 2 monitor to track communications performance with the eProsima Fast DDS implementation. It provides real-time information about the communications (packet loss, latency, throughput, etc.), that can be used to detect bottlenecks and other issues.

ROS-FM [51] is a network monitoring framework for ROS1 and ROS 2 systems. It is based on Berkely Packet Filters (eBPF) and eXpress Data Path (XDP). It also includes a security policy enforcement tool and a visualization application. The Berkely Packet Filters (eBPF) [52] is used to run sandboxed programs in the operating system’s kernel. Those programs are compiled to byte-code, which is executed by a BFP virtual machine inside the kernel. eBPF is used to add additional capabilities to the operating system at runtime, usually for packet filtering. The eXpress Data Path (XDP) [53] is a programmable layer in the operating system network stack. The ROS-FM visualization application is based on Vector [54]. Those components form a high-performance monitoring tool for ROS1 and ROS 2. Nevertheless, ROS-FM does not provide mechanisms to detect anomalous ROS 2 traffic or trigger actions to mitigate threats in the robotic system.

ROS-defender [55] integrates three different tools:

a Security Event Management System (SIEM), an anomaly detection system (ROSWatch) plus a intrusion prevention system (ROSDN), and a firewall for ROS1. They are built upon a Software Defined Networking (SDN) framework (OpenFlow v1.3). ROSWatch inspects the network and the logs in order to detect intrusions. It uses a pattern matching model to detect attacks in data flows and logs. The rules use identifiers such as nodes and topics and can be classified into priority classes. ROSDN uses SDN to replace the standard ROS network communication. This way, it is able to filter the communications and ban compromised ROS1 nodes from the network. The main problem of this approach is the dependency on SDN technology. In addition, the performance of this system is criticized by its own authors [51]. ROS-defender is not available for ROS 2. In addition, this system focuses on the conventional IPS procedures (message filtering, etc.).

Different methods have been proposed to detect attacks in robotic environments. Urbina et al. [56] presented a survey on attack detection methods in industrial control systems (ICSs). Vuong et al. [57] presented a method to detect attacks by using the data collected from on-board systems and processes. They used a decision tree-based method for detecting attacks using both cyber and physical features that can be measured by its on-board systems and processes. Guerrero-Higueras et al. [12] conducted an empirical analysis to demonstrate that there are statistically meaningful differences in the data provided by beacon-based Real Time Location Systems (RTLSs) when the robot is under attack. They also described some precedents for detecting attacks through sensor data, by using statistical and Machine Learning techniques. Sabaliauskaitė et al. [58] proposed a method based on a statistical technique named CUSUM [59] to detect stealthy attacks that are designed to avoid detection by using knowledge of the system’s model.

2.2. Safety in Robotics

Safety is defined as the condition of being protected from or unlikely to cause danger, risk, or injury. It is a critical issue in Industrial Robotics, where more than 1.5 million industrial robots are operating in factories worldwide. However, its introduction created other problems, mostly in those Human-Robot collaborative scenarios. One of the main objectives of deploying robots in factories was to prevent the operators engage in hazardous tasks or environments [6].

A complete collection of safety standards has been developed in this field to reduce the risk of accidents when robots interact with humans. The concepts of

robot design, manufacture, installation, operational processes, maintenance and decommission are key when we are planned to deploy a robot in public spaces and standards such as UNE-EN ISO 10218:1 proposes the rules for Industrial Robots. Three different iterations 2006, 2008 until the current 10218:1 2012 ISO covers all type of risks associated to non planned tasks such as start-ups or human interaction as well as definitions for regular operation.

This research goes outside industrial robot, consequently, it is necessary to explore alternative standards such as ISO 13482:2014 which cover robots and robotic devices, particularly safety requirements for personal care robots. This standard does not cover robots moving faster than 20 km/h, robot toys, water-borne and flying robots, military robots or medical devices such as DaVinci robot. This standard do define four different Operational Modes for care robots: the Autonomous mode; Semi-autonomous mode; Manual mode Maintenance mode. These modes should not be confused with the system modes proposed in this research here, but should be used as a generalization of robots deployed in public spaces.

Previous standards do need to cover current Human-Robot Interaction scenarios [7] and it is necessary to explore collaborative safety features presented in research literature [60]. Thus, it is necessary to do a detailed overview in the field and review current research works in the field as the works proposed in working group IEEE7009 [61]. Privacy is considered a recommendation [62], although the concerns on this matter are nowadays beyond all doubt.

There are no references in the scientific literature about implementable models for all these issues for robotic systems. Only models for physical safety can be found. For instance, in [3] the model Care Robot Impact Assessment (CRIA), based on the ISO 13482:2014, is proposed. This standard is devoted to safety in physical interaction between humans and robots. The European Task Force [63] on Artificial Intelligence spent most of its recommendations on the need for this modelization, from the discovery phase, using honeypots for the cybersecurity dimension, to the accuracy, soundness, and reproducibility of the systems based on machine learning, that is, an explainability model that takes also into account the possible cybersecurity implications. In another work [64] a safety framework based on operational modes is proposed to deal with human-robot interaction.

The modes of operation are used in robotics for safety and error handling. Modeling languages such as AADL [65] or MARTE [66] consider modes of operation one

of the primary mechanisms to address this issue, and they have been successfully used in safety in several works [67][68]. Safety cares about the possible damage a robot may cause in its environment, while security aims at ensuring that the domain does not disturb the robot's operation [69].

2.3. Safety and Security

Lera et al. [70] published a study on attacks associated with service robots, presenting a risk taxonomy for this kind of robotic applications. This work distinguishes between security and safety threats.

In [71, 72], the authors examined how feedback given by a robot agent influences the various facets of participant experience in robot-assisted training: robot acceptance, sense of safety and security, attitude towards robots and task performance. The results suggested that the robot with flattering and positive feedback was appreciated by older people in general, even if the feedback did not necessarily correspond to objective measures such as performance. Participants in these groups felt better about the interaction and the robot.

In [4] addresses the interplay between robots, cybersecurity, and safety from a European legal perspective, a topic under-explored by current technical and legal literature. The authors illustrate cybersecurity challenges and their subsequent safety implications with the concrete example of care robots.

In [73] shows an overview of the ImPACT Tough Robotics Challenge and Strategy for Disruptive Innovation in Safety and Security (ImPACT-TRC), which is a national project of the Japan Cabinet Office that focuses on tough robotic technologies to provide solutions to disaster response, recovery, and preparedness.

Another brief overview, the so-called Industry 4.0, is shown in [5, 74], where authors describe how collaborative robots can be used to support human workers in Industry 4.0 manufacturing environments and how human-robot interaction might also have some risks if human factors considerations are not taken into account in the process.

3. Cognitive Architecture for Social Robots

Moving the robots from industrial cages to public spaces arises interesting research questions surrounding the field of social and assistive robots. When a robot faces a daily life task in a supermarket or in a day care center it has to accomplish new goals. These scenarios present non-stationary elements that have interaction with it and the humans surrounding in non-repetitive

manner. Thus, it becomes necessary to define and bound the set of constraints at decision making level for managing long-term task planning and immediate behavioral approaches.

To achieve that, it is necessary to build and implement those models of cognition that reassemble some aspects of mind as such, knowledge, motivations, generality, and completeness. Thus, cognitive architectures [75] from an artificial intelligence should provide not only the mechanisms to develop robot behaviors but also how each decision affects their actions and behavior as well as those individuals in their surrounding.

Vernon[1]'s research in RockEU2 presents the eleven functional abilities that a robot should achieve successfully in order to provide those cognitive process that will allow it. However, roboticist researchers [2] usually present a cognitive architecture as the technical mechanisms that provides the autonomy to set long-term and short-term intermediate goals to achieve those tasks required by users or robot needs.

The functional abilities of the robot and the pipeline to accomplish tasks is solved in various different ways. The classic one is the sense-plan-act approach. In this approach, a high level system is providing decision making using knowledge declared in formalized descriptive files and afterwards applying it to general-purpose planning systems. ROS 2 Planning System (aka Plansys2) [76] is a ROS 2 solution whose aim is to provide a reliable, simple, and efficient PDDL-based planning system for robots.

For more specific action scheduling, behavior trees (BTs) have been adapted from software video-games scenarios for its use in robotics. Different researchers [77, 78] present them as a generalization for different classic control approaches in robotics such as hybrid control Systems, finite state machines, generalize sequential behavior compositions, subsumption architecture and decision trees. Thus, current behavior generation is deployed using BTs.

Both, planning and behavioral approaches are usually presented in a single architecture. It is common to articulate a hybrid architecture for controlling and managing the behavior of a robot. Examples such as LAAIR [79], Aura [80], or MERLIN2 [81] illustrated in Figure 1, are composed of a deliberative system, which is responsible for making decisions and creating plans, and a behavioral system, which has the actions and skills that the robot can take. These systems consist of layers that are built on top of each other. The deliberative system is composed of a Mission layer and a Planning layer. The behavioral system is composed of the Executive layer (robot actions) and the Reactive layer (robot skills such

as Nav2 or speech generation).

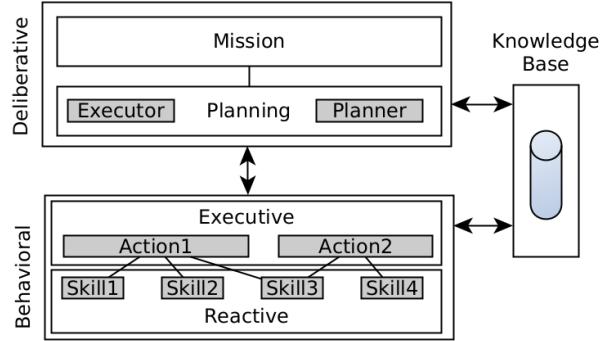


Figure 1: Funcional components of MERLIN2 [81].

4. Intrusion Detection in ROS 2 Systems

This section is a formal abstract description of the set of features that can meet the minimum requirements of a RIPS for ROS 2 systems. ROS 2 is based on the DDS (Data Distribution Service) middleware [82]. ROS 2 components, or nodes, usually communicate following the publisher/subscriber model by using topics¹. We will focus on this communication model.

The RIPS will run as a ROS 2 node that monitors the interactions of the rest of nodes. It includes an engine that evaluates rules defined by the user. Those rules tell RIPS how to process the ROS 2 traffic and how to react for each monitored message.

Basically, a rule is composed by these parts:

- Name: The identifier of the rule, as a string of characters.
- Expression: A boolean expression.
- Actions: A set of actions that will be executed when the boolean expression evaluates to true.

The abstract types used by the rules are:

- `integer`
- `floating point number`
- `string of characters`
- `boolean`
- `set of basic-type`

¹ROS 2 also provides other mechanisms for client/server interactions (i.e., *services*).

4.1. Alert levels

The RIPS defines an ordered set of *levels*, each with a string identifier. The alert level describes the current security state of the system (i.e., how compromised may be the robotic system). This will define the set of permitted actions for the robot (i.e., the privilege limiting which operations can be performed).

The system always starts at a defined level. By default, it only can transition to a more restrictive (lower privileged) level. Conversely, the alert level cannot be decreased autonomously by default, it requires human intervention. Nevertheless, the user can define explicit transitions to lower restrictive levels by using a keyword (*soft*). For example, we can define four levels:

- DEFAULT
- soft ALERT
- COMPROMISED
- HALT

In this case, if the current system level is ALERT, it can de-escalate and switch to the DEFAULT level autonomously. On the other hand, if the system is in the COMPROMISED level, it can not switch to the ALERT level autonomously. That requires human intervention.

When the current alert level is changed by the RIPS, two procedures are executed: The one needed to leave the current level and the one needed to enter the new level. This mechanism follows the traditional Unix run-level approach. This mechanism is flexible: In the case of using System Modes (the proposal of this work), the alert levels can be directly mapped to System Modes. In another case, it permits the definition of generic procedures (e.g., Python or shell scripts) to launch the selected countermeasures or mitigation actions. Both approaches can be combined together.

For example, suppose that the current alert level is DEFAULT and the RIPS changes it to the ALERT level. Then, two procedures are executed: The one to leave the DEFAULT level and the one to enter the ALERT level. Then, these procedures order the System Mode framework to change the robot's System Mode from the DEFAULT mode to the ALERT mode.

4.2. Predefined Global Variables

The RIPS maintains a set of global predefined variables. Those variables can be used in the rules' expressions. For example, the predefined global variables include:

- Time: Integer with the current time.
- Level: String with the current level.
- Uptime: Integer with the uptime of the system.
- ...

4.3. Actions

Rules are reactive to *events*. Each time an *event* is detected by the RIPS, the related rules are evaluated. If a rule's expression evaluates to `true`, its actions will be executed. There are three classes of events:

- Message: Messages delivered to a topic.
- Graph: Changes in the ROS 2 computation graph.
- External: External events.

We identify four types of actions:

- alert: An alert event is generated and logged by the system.
- set: This action defines or modifies variables of the system. The user can define new variables to maintain the context of the rules. Simple arithmetic or string expressions are allowed. For example, the user can define a counter which is incremented each time some specific rules evaluate to `true`. This variable, together with the current time, can be used to write a rule for detecting flooding attacks.
- exec: This action just executes an external program with arguments. For example, the rule can execute a simple Python script to configure a new filter in a firewall in order to drop some types of messages.
- trigger: This action changes the current alert level, triggering a transition. The procedure to exit the current alert level and the procedure to enter the new level is executed. It has one argument, the new alert level (that must be a lower privileged level if the current level is not marked as *soft*).

A rule can execute more than one action sequentially. Actions are executed in chains. In a chain, the result of each action is evaluated to consider if the next action is executed depending on the operator chaining them. These operators can be used to execute actions depending on the the result of the previous action in the chain:

- → executes the right action only if the left action is successful.
- ↛ executes the right action only if the left action is not successful.
- , executes the right action after the left action without considering if it is successful or not (but the chain of actions has to be executed up to that point to even consider the execution).
- □ terminates the chain of actions.

More than one chain can be executed when a rule is triggered.

For example, a rule R can execute the following three chains of actions:

```
alert("info : rule R activated")□
exec(usb_alarm) ↛ alert("warning : usb_alarm failed")□
trigger(HALT)□
```

Therefore:

1. A message is logged in the system to inform of the rule activation.
2. An external program named `usb_alarm` is executed. This program commands the system to activate a physical alarm (e.g. a USB alarm with sound and lights) connected to the computer.
3. If the program `usb_alarm` fails, a new warning message about the failure is logged in the system. Else, that warning message is not logged.
4. The HALT alert level is triggered and the corresponding procedures are executed.

4.4. Expressions

Expressions should not have lateral effects. Note that, even though an external the program can be executed as a consequence of the evaluation of a subexpression, the evaluation of the whole expression should be idempotent.

In this abstract description, we represent the subexpressions as boolean functions. The evaluation precedence is from right to left. The boolean operators `and`, `or`, and `not` are available to create the expression. It applies a shortcut evaluation of such expressions.

Subexpressions of different classes of events cannot be combined. Thus, the rule has an implicit *type* (i.e., *message*, *graph* or *external*), which is inferred from its expression.

We consider that the following set of subexpressions provide enough expressivity to properly model the rules to detect threats in the ROS 2 publisher/subscriber communication scheme.

4.4.1. Subexpressions for message events

- `topicin(topics:set of string)`: This function returns `true` if the topic name of the message is included in the specified set of topic names.
- `topicmatches(regex:string)`: The function's parameter is a regular expression. The function returns `true` if the topic name (the whole name, including the namespace) of a message matches the regular expression.
- `publishercount(min:int, max:int)`: The function returns `true` if the number of participants publishing to the topic of this message are in the range defined by the interval `[min..max]`.
- `subscribercount(min:int, max:int)`: The function returns `true` if the number of participants subscribed to the topic of this message are in the range defined by the interval `[min..max]`.
- `publishersinclude(pubs:set of string)`: The parameter is a set of strings with the names of participants (nodes). The function returns `true` if all the participants of the set are publishers for the topic of the message.
- `subscribersinclude(subs:set of string)`: The parameter is a set of strings with the names of participants (nodes). The function returns `true` if all the participants of the set are subscribers of the topic of the message.
- `publishers(pubs: set of string)`: The parameter is a set of strings with the names of participants (nodes). The function returns `true` if the participants of the set are exactly the publishers for the topic of the message.
- `subscribers(subs: set of string)`: The parameter is a set of strings with the names of participants (nodes). The function returns `true` if the participants of the array are exactly the subscribers of the topic of the message.
- `msgtypein(msgs: set of string)`: The parameter is a set of strings with the names of ROS 2 message types ("std_msgs", "sensor_msgs", "diagnostic_msgs", "geometry_msgs", "nav_msgs", "shape_msgs", "stereo_msgs", "trajectory_msgs", and "visualization_msgs"). The function returns `true` if the message type of the message is included in the set.

- `msgsubtype(msg:string, submsg:string)`: The first parameter is the type of the message, the second one is the subtype of the message. For example, if the type is "std_msgs", the subtype can be "ColorRGBA", "Empty", or "Header". The function returns true if the message has the specified type and subtype.
- `plugin(id:string)`: The plugin specified by the parameter is invoked. A plugin is a program that is able to inspect and analyze the ROS 2 message. Plugins permit the user to create extensions for custom analysis. For example, the user can create a plugin that analyzes the frames sent by a camera component in order to detect a *camera blinding* attack [83, 84].
- `payload(path:string)`: This function invokes YARA to find patterns in the payload of the message. YARA [85] is the de facto standard for textual and binary pattern matching in malware analysis. It is widely used to detect malware *signatures*. The RIPS must be able to inspect the payload of the robotic messages, because they can be used to inject malicious code in the components. This function executes the YARA engine over the payload of the message to find the patterns specified by the YARA rules stored in the file passed as argument. If any of these YARA rules matches, the function returns true.
- `eval(var:string, operator:string, value:string)`: This function is used to check the values of the variables. The second parameter is the textual representation of an operator. The following operators are defined for all the basic types: ==, !=, <, >, <=, >=. The third parameter is the textual representation of the value for the corresponding basic type.

4.4.2. Subexpressions for graph events

The ROS 2 computation graph is defined as the network elements processing data together at one time. It includes the nodes and their connections (topics, services, actions, or parameters). The following subexpressions can be used for this kind of event:

- `nodes(n: set of string)`: This function returns true if the current nodes of the graph are just the ones defined by the set passed as argument.
- `nodesinclude(n: set of string)`: This function returns true if the current nodes of the graph are included in the set passed as argument.

- `nodecount(min:int, max:int)`: If the current number of nodes is in the interval [min..max], the function returns true.
- `eval(varname:string, operator:string, value:string)`: Its the same function explained in Section 4.4.1, used to check the values of variables.

The semantics of the following functions are similar to the semantics of the previous ones (i.e., `nodes`, `nodeinclude`, and `nodecount`), but they are oriented to topics, services, topic's subscribers, and topic's publishers:

- `topics(nodes:set of string)`
- `topicsinclude(nondes:set of string)`
- `topiccount(min:int, max:int)`
- `services(node string, s:set of string)`
- `servicesinclude(node string, s:set of string)`
- `servicecount(node string, min:int, max:int)`
- `topicsubscribers(topic:string, nodes:set of string)`
- `topicsubscribersinclude(topic:string, nodes:set of string)`
- `topicsubscribercount(topic:string, min:int, max:int)`
- `topicpublishers(topic:string, nodes:set of string)`
- `topicpublishersinclude(topic:string, nodes:set of string)`
- `topicpublishercount(topic:string, min:int, max:int)`

4.4.3. Subexpressions for external events

The following subexpressions cannot be combined in a rule:

- `idsalert(alert:string)`: The RIPS can use a conventional IDS/NIPS/HIPS to detect low-level network threats (e.g., to detect suspect messages at network or transport levels). A special expression can be used to react to a low level detection: This function returns true when the alert specified

in the parameter is triggered by the underlying detection system. In our prototype, we use Snort [86] as a low-level IDS.

- `signal(sig:string)`: It can be used to react to user-defined Unix signals. It may be useful to trigger emergency actions from a system shell if necessary. This function returns true when the RIPS process receives a SIGUSR1 or SIGUSR2 signal.

5. Implementing Safety with System Modes

The system modes framework used in our work [8] allows the separation of the system runtime configuration and the system error and contingency diagnosis, reducing the effort for the application developer to design and implement the task, contingency, and error handling.

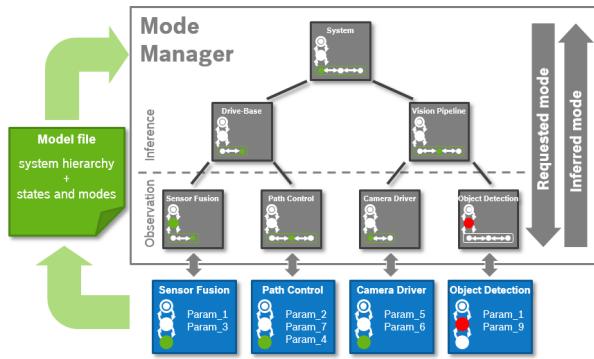


Figure 2: Mode inference and mode management based on the system modes and hierarchy file (SMH) (image from [8]).

Figure 2 shows a system's organization in different subsystems encompassing the components of the robotic system. A top-down flow requests an operation mode, while a down-top flow allows it to be inferred based on configurable rules that observe the real situation of the system. Configuration is simple, specifying in a model file:

1. The structure of systems and subsystems.
2. Which components are active in each subsystem.
3. The value of the parameters for each mode in each of the components.

This framework assumes that the components that make up the cognitive architecture can be activated and deactivated during their operation. In addition, they assume that the operation of each of them depends on a series of configuration parameters that can be changed and taken into account at runtime.

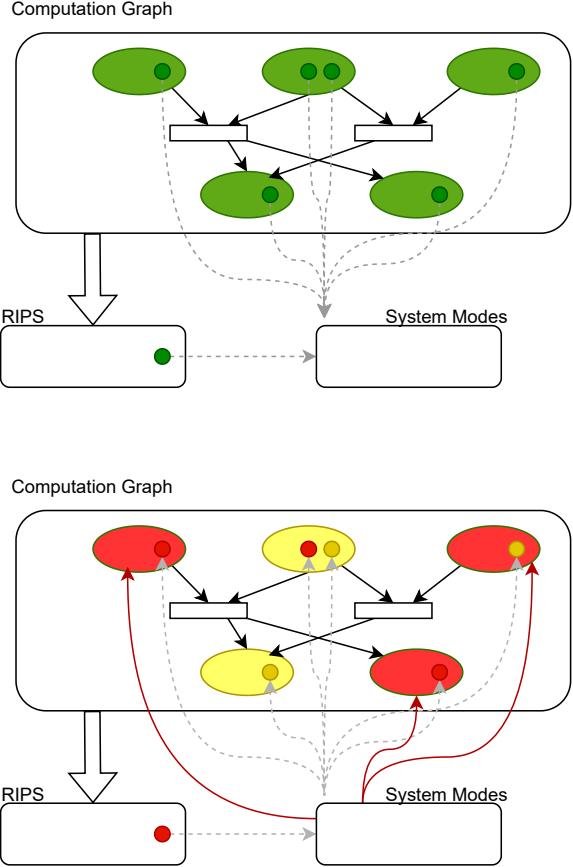


Figure 3: Representation of a robotic application (a computation graph) controlled RIPS and System Modes. Small circles represent parameters with a value represented by a color. Nodes in the computation graph (ellipses) have an operation mode represented by their color. Rectangles are topics to which some nodes publish and others subscribe. The upper part represents a non compromised system (i.e. the DEFAULT alert level in the RIPS) and the bottom part a compromised system (i.e. the COMPROMISED alert level in the RIPS).

Suppose the scenario shown in Figure 3. As explained before, a ROS 2 application is a computation graph. The nodes (ellipses of the computation graph) in this graph are the functional elements that encode the application logic. The nodes have parameters (small circles in the figure) that modulate their operation. These nodes can be active or inactive (green is active, red is inactive, and yellow is reduced operation). During its operation, the operating modes monitor each of the system parameters. If there is a variation in the parameters' value or the nodes' state, the System Modes infer the system's operating mode and establish which nodes should be active in the new mode and their parameters' value. As explained in Section 4, the RIPS watches the computation graph and the messages sent by the appli-

cation's components. Depending on the defined rules, RIPS sets its current alert level. In this scenario, RIPS only has defined four alert levels: DEFAULT, ALERT, COMPROMISED, and HALT. While the level is DEFAULT, all nodes are up and running with their parameters in normal mode (they are green). When RIPS detects some threats (i.e. some RIPS rules are activated and the corresponding actions are performed), it changes its level to COMPROMISED. Then, System Modes reacts to this change and infers a new mode, in which it deactivates some nodes (red arrow and red color on nodes) and sets values for node parameters, causing some to go into a shutdown mode and others to a reduced operation (yellow).

This is an example configuration for the System Operations:

```
safety:
  ros__parameters:
    type: system
  parts:
    image_1_to_2
    imu_1_to_2
    odom_1_to_2
    pc2_1_to_2
    scan_1_to_2
    tf_1_to_2
    tf_static_1_to_2
    twist_2_to_1
  modes:
    __DEFAULT__:
      image_1_to_2: active
      imu_1_to_2: active
      odom_1_to_2: active
      pc2_1_to_2: active
      scan_1_to_2: active
      tf_1_to_2: active
      tf_static_1_to_2: active
      twist_2_to_1: active
      planner_server: active
      filter_mask_server: inactive
      costmap_filter_info_server: inactive
      filter_mask_server_clean: active
      costmap_filter_clean: active
    ALERT:
      image_1_to_2: inactive
      imu_1_to_2: active
      odom_1_to_2: active
      pc2_1_to_2: active
      scan_1_to_2: active
      tf_1_to_2: active
      tf_static_1_to_2: active
      twist_2_to_1: active
      planner_server: active
      filter_mask_server: active
      costmap_filter_info_server: active
      filter_mask_server_clean: inactive
      costmap_filter_clean: inactive
    COMPROMISED:
      image_1_to_2: inactive
      imu_1_to_2: active
      odom_1_to_2: active
      pc2_1_to_2: inactive
      scan_1_to_2: inactive
      tf_1_to_2: active
      tf_static_1_to_2: active
      twist_2_to_1: inactive
      planner_server: active
      filter_mask_server: active
      costmap_filter_info_server: active
```

```
filter_mask_server_clean: inactive
costmap_filter_clean: inactive
HALT:
  image_1_to_2: inactive
  imu_1_to_2: inactive
  odom_1_to_2: inactive
  pc2_1_to_2: inactive
  scan_1_to_2: inactive
  tf_1_to_2: inactive
  tf_static_1_to_2: inactive
  twist_2_to_1: inactive
  planner_server: active
  filter_mask_server: inactive
  costmap_filter_info_server: inactive
  filter_mask_server_clean: inactive
  costmap_filter_clean: inactive
```

6. Experimental Validation

In this section, we experimentally validate the contributions described in this work, focused on the processes involved in security and safety in a real mobile robot. The objective is to show that security issues can be satisfied or enhanced with systems that detect and mitigate intrusion through system modes.

We have validated our contribution implementing onboard a Tiago² robot (left side of Figure 4) the cognitive architecture described in section 3 that uses the system modes described in section 5. In detail, the Tiago robot uses Ubuntu 18.04, ROS1 Melodic, and CycloneDDS. A laptop mounted on top uses Ubuntu 22.04, ROS 2 Humble, and CycloneDDS to command the robot and send the orders simulating the intrusion. To communicate ROS1 and ROS 2, we use bridges available at (https://github.com/fmrico/ros1_bridge). The RIPS core described in Section 4 is emulated in this experiment.

To demonstrate the system in operation, we have devised a scenario on the right-hand side of Figure 4, which emulates an industrial work environment, with three work zones on the edges marked with yellow-black tapes and a central high-security zone marked with red-white tape. The robot must move between these zones to perform specific tasks. If the robot detects an intrusion and is compromised, it should not circulate in the high-security zone, nor should the camera be turned on to prevent sensitive data theft.

To verify the correct functioning of the system, we have shown the evolution over time of two metrics:

- 1. Sending images:** We will show the hertz at which the robot driver publishes images to a topic accessible to the rest of the system and hypothetical intruders.

²<https://pal-robotics.com/es/robots/tiago/>



Figure 4: Robot Tiago (upper) and experimental validation setup (bottom).

2. **Navigable area:** This represents that the central area is not available to be used to navigate through it by being marked as a "forbidden" or "keep-out zone." The map initially consists of 39720 occupied cells and 1662 free ones. Detecting obstacles or activating the keep-out zone reduces free cells and increases occupied cells.

In normal robot operation (DEFAULT mode), it navigates through the scenario from point A to point B and returns to point A (left part of Figure 5), crossing the high-security zone. Once started navigating, at point C (central part of Figure 6), an intrusion is detected by the emulated RIPS and the system changes to ALERT mode, activating the keep-out zone. During this navigation phase, a person crosses in front of the robot to check that camera is disconnected and to avoid mobile obstacles. After that, the COMPROMISED mode is activated in point D (figure 6), and the system stops some devices (twist, camera, laser). Later the robot will return to ALERT mode and continue to point B, where the mode will change to DEFAULT. In the last phase (right part of Figure 7), the robot returns to point A following the shortest path.

The robot calculates the path using Nav2 [87], which will be recalculated after the keep zone activation (point

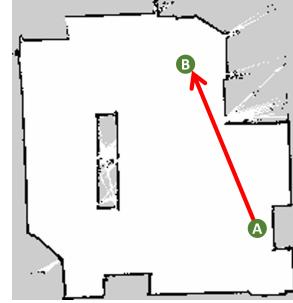


Figure 5: Initial map with start (A) and goal (B) points, and first calculated path.

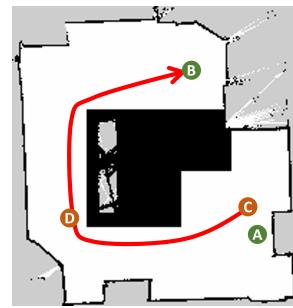


Figure 6: Intrusion points (C and D), and new path.

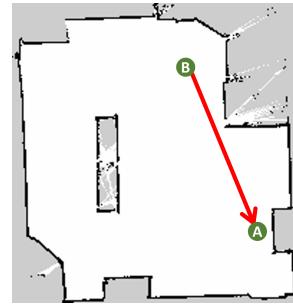


Figure 7: Final map with the new path returning to starting point (A) after the intrusion is remedied.

C in figure 6). We suppose that the area shown in figure 6 should be excluded from navigation due to contains sensitive information that can be vulnerable to digital privacy. At that moment, the robot will calculate a new path avoiding this area to reach point B and complete the task.

Figure 8 shows the behavior of the occupied and free cells of the map, and the hertz at which the graph works after a simulated intrusion.

Figure 8 shows the results for a trial in the scenario with the real robot.

- The robot starts in DEFAULT mode.

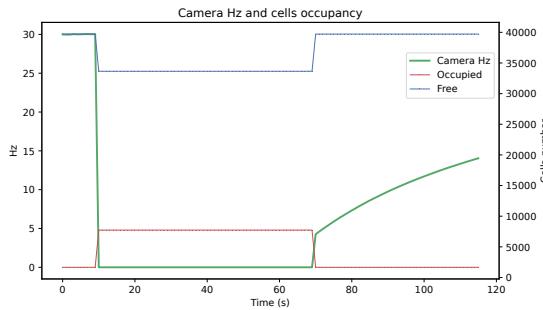


Figure 8: Camera Hz and map cells occupancy

- The robot changes its state when detecting an intrusion at time 12. It goes into a ALERT mode, which disconnects the camera to avoid sending images and activates a security zone through which the robot cannot navigate, maintaining the privacy of the environment and safeguarding a critical area.
- The robot continues with its task to reach point B, calculating a new path and disconnecting the camera. The graph shows how the image publication frequency reduces to 0, which means the camera is paused. The number of occupied and free cells decreases after the keep zone activation to avoid the high-security zone.
- At time 40, the system goes into a COMPROMISED mode, which keeps the camera disconnected until time 47.
- At time 47, the system is changed to ALERT with no apparent changes in behavior mode and finally at time 70 to DEFAULT mode, when the intrusion is mitigated.
- The robot is again allowed to navigate through all the available cells of the map and to reach point A will now follow the shortest path due to the keep zone being deactivated. The number of free cells increases to the totality, and the number of occupied cells corresponding to those of the initial map decreases. In addition, when the camera is activated, it starts publishing images, recovering gradually³ the maximum available hertz.

³After activation, there is a jump, which gradually increases the frequency. DDS (Data Distribution Service for Real-time Systems) is primarily responsible for this problem because when a UDP packet does not contain at least one IP fragment, the rest of the received

Figure 9 shows another trials with similar behavior. The naveable area is reduced while the threat exists, and the camera stop producing images.

The conclusions of these experiment are that our system correctly reacts to the changes in the security level detected by RIPS. It reconfigures the system as soon as an intrusion is detected, disabling sensible sensors and forbidding the robot navigating in restricted areas. The system also reacts disabling the counter measures when the threat has been mitigated.

7. Conclusions

In this work, we have contributed to the state of the art by combining safety and security through modes of operation applicable to the preservation of privacy and integrity of the environment during an operation of a social, mobile robot controlled by a cognitive architecture. Throughout this work, we have described the cognitive architecture, the operating modes system, and one of our major contributions, the design of a robotic intrusion prevention system (RIPS). We have emphasized technical details to make our system reproducible. This system can detect and mitigate intrusions in cognitive, social robots, and other cyber-physical systems.

Our contributions let to separate the operational logic from the contingency management logic by using a pre-configured set of modes that preserves aspect of safety like privacy or preservation of sensible information. This is carried out by providing a simple but effective collaboration between RIPS and System Modes, convenient for real robot applications.

To experimentally validate our contribution, we have planned a scenario where a robot compromised by an intrusion should not use its camera to avoid data robot, nor should it navigate through high-security zones. Experiments have shown that the system reacts correctly when intrusions are detected during the robot's operation.

Future work includes completing a fully functional RIPS prototype to address all kinds of situations through a scripting language that will provide the system with flexibility in its configuration (including a ROS 2 monitor to intercept communications and computation graph

fragments fill up the kernel buffer. Linux kernels time out after 30 seconds of trying to recombine packet fragments. A full kernel buffer (default size is 256KB) prevents new fragments from coming in at this point, so the connection seems to "hang" for a long time. This issue is generic across all DDS vendors, so the solutions involve adjusting kernel parameters.

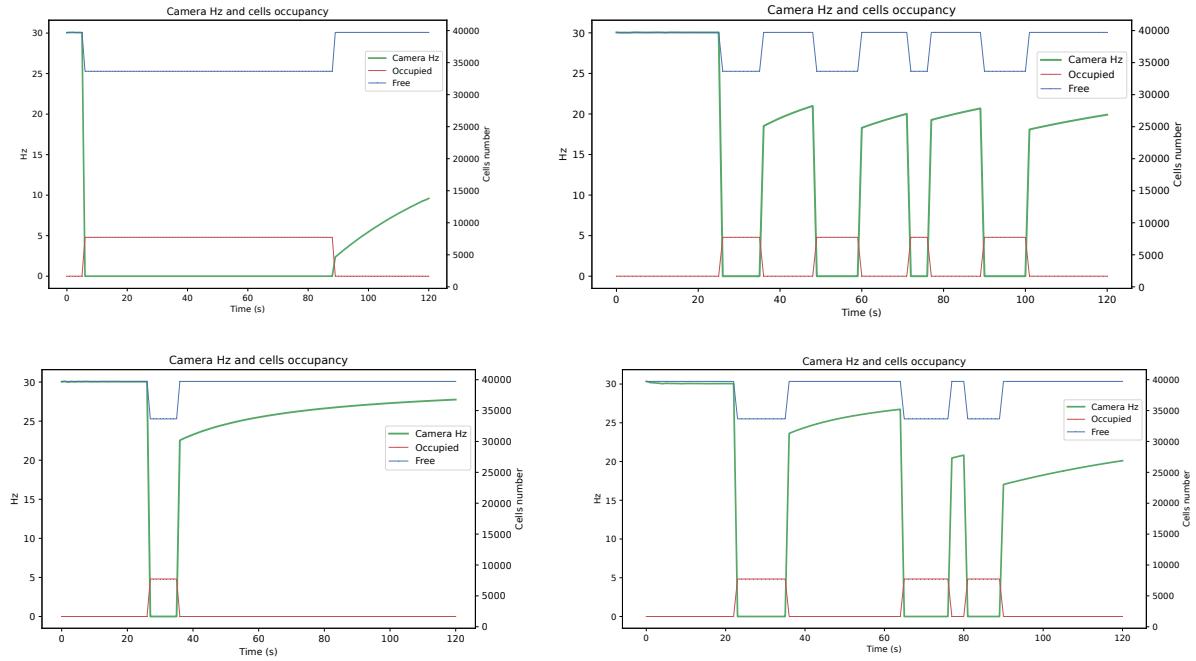


Figure 9: Camera Hz and cells occupancy. (upper left) long camera deactivation. (upper right) camera deactivation multiple. (bottom left) short camera deactivation. (bottom right) camera deactivation multiple with a long activation.

changes, and a custom programming language to specify the rules and actions), creating ROS 2 packages to distribute our prototypes, and integrating the RIPS with a tamper-evident logging system [88] and an explainability subsystem.

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