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UNDERGRADUATE COURSE IN CONTROL AND AUTOMATION ENGINEERING

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Runtime verification in low level software in the ProVANT project

Florianópolis
2024

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Final report of the subject DAS5511 (Course Final Project) as a Concluding Dissertation of the Undergraduate Course in Control and Automation Engineering of the Federal University of Santa Catarina. Supervisor: Prof. Leandro Buss Becker, Dr.

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2024

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This work is dedicated to my classmates and my dear
parents.

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ABSTRACT

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Keywords: Keyword 1. Keyword 2. Keyword 3. *[essas palavras-chave devem obrigatoriamente ser utilizadas no Abstract]*

RESUMO

Resumo traduzido para outros idiomas, neste caso, português. Segue o mesmo formato do Abstract.

Palavras-chave: Palavra-chave 1. Palavra-chave 2. Palavra-chave 3.

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LIST OF ABBREVIATIONS AND ACRONYMS

AADL	Architecture Analysis & Design Language
CPS	Cyber-Physical Systems
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
FPGA	Field Programmable Gate Array
GPU	Graphics Processing Unit
HLH	High Level Hardware
LLH	Low Level Hardware
PWM	Pulse Width Modulation
RM	Runtime Monitoring
RV	Runtime Verification
SCS	Safety-Critical Systems
TCP	Transmission Control Protocol
TL	Temporal Logic
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UML	Unified Modeling Language

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1 INTRODUCTION

Over the last 20 year, a plentiful of studies dealt with the Runtime Verification (RV) for Safety-Critical Systems (SCS), researching ways of sustaining the desired behavior of Cyber-Physical Systems (CPS) and a avoiding critical faults.

2 TECHNOLOGICAL BACKGROUND

2.1 RUNTIME VERIFICATION

RV or Runtime Monitoring (RM) is the observance of system behavior during deployment, in order to check or even try to enforce some specification. (Falcone *et al.*, 2021; Sánchez *et al.*, 2019) It's normally attempting a formal verification, but restricted to a single trace (the trace that actually got executed in the monitored execution) not being able to verify alternative executions like in Model Checking.

It's normally used in SCS, where faults can cause catastrophic consequences. Said systems should be designed with safety in mind, methodically developed by systematical approaches and verified by model checking techniques. The most famous modeling language is the Unified Modeling Language (UML), but there are other options for embedded system modeling like the Architecture Analysis & Design Language (AADL) (Feiler; Gluch, 2013), which can be used for model checking. However, the model may not be a one to one representation of the system, which can lead to unexpected faults, to avoid and/or detect those RV is used.

The system responsible to verify the specification in a RV application are generally called monitors. The idea is similar to oracle-based testing, where an observer called oracle is implemented to verify properties of a given test execution. However, as noticed by Bauer, Leucker, and Schallhart (2011), tests typically attempt to be exhaustive, to validate the system during test, while RV is only concerned with the current execution. They also count as a difference the fact that RV is normally done by synthesize a higher level Temporal Logic (TL) language.

RV monitors can be run either online (i.e. together with the application, in real time) or offline (i.e. processing a recorded trace). (Bauer; Leucker; Schallhart, 2011; Broering, 2023) For online verification, it's desirable that the monitor be very lightweight so to not interfere with the systems time constraints, or better yet be run in a different processor, core or even in a separate board. In some cases, unobtrusiveness is a required characteristic, for instance to not violate flight certificates, which lead to approaches where the monitor only listens to a existing bus line, being implemented on a dedicated controller or Field Programmable Gate Array (FPGA). (Rozier; Schumann, 2024)

2.2 TEMPORAL LOGIC

Some authors use the concept of *bad* and *good prefix* as defined by Kupferman and Vardi (2001), where a *bad prefix* is a sequence of events that never leads to the fulfillment of the requirements, while the *good prefix* is when any continuation of the trace will be within the specification. In *three-valued logic*, as soon as identified by a RV

monitor, *bad prefix* should return *False*, *good prefix* should return *True*, and any other prefix, yields inconclusive. (Bauer; Leucker; Schallhart, 2011)

and, because of these definition, it is continuously verified, which wouldn't need to be if it used the classic definition, but would be less expressive.

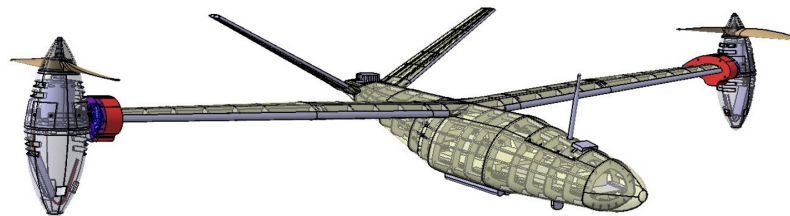
Similar past-time operands variations are defined by (Reinbacher; Függer; Brauer, 2014), called

3 PROJECT OVERVIEW

3.1 VANT ARCHITECTURE

ProVANT Emergencia is a Unmanned Aerial Vehicle (UAV) prototype built in 70% of it's designed size in Belo Horizonte, Brazil¹, comprised of a fuselage, which houses the electronic components, a V-Tail and wide wings with flaps, ailerons and wingtip nacelles, where the propeller lies. The propellers can rotate 180° to allow for a helicopter like flight and take-off, as can be seen in Figure 1. (Merchán, 2021)

Figure 1 – ProVANT Emergencia general mechanical structure view



Source: Merchán (2021).

The embedded electronics, as described both by Lara (2019) and Merchán (2021) is developed around two types of embedded processors, called Low Level Hardware (LLH) and High Level Hardware (HLH). The LLH is responsible for directly interfacing with the actuators and simple sensors. It is implemented by two redundant STM32 Nucleo-F767zi.

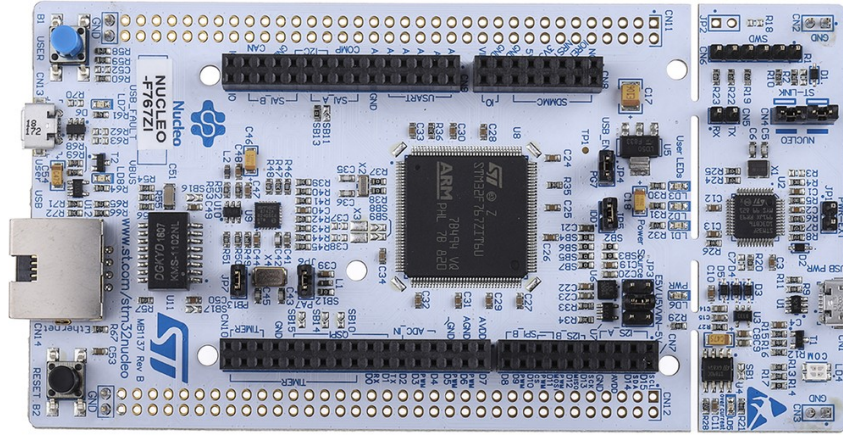
The importance of having redundancy in these boards is that they are the only boards in the system with access to the actuators, therefore, in case of a failure in them the system would be incapable of controlling it self. With two Low Level boards, the chances of both failing is much smaller.

The main HLH is the Jetson Tx2 board, aimed to run the main control loop and chosen by the capability of running neural network, because of it's Graphics Processing Unit (GPU) that allows for parallelization of the computing operations. It also interfaces with precise sensors with low latency reading requirements, like the IMU and GPS. (Lara, 2019; Merchán, 2021)

Since both aforementioned thesis, a new board was added along the Jetson in the High Level system to interface with the Navio 2 board and a telemetry radio. This board is a Raspberry Pi 4, it facilitates the communication with the Navio 2 board, which implements multiple useful sensors for drones and can generate Pulse Width

¹ A 100% scale version is planned to be build in Universidad de Sevilla

Figure 2 – ProVANT Emergencia LLH board (Nucleo-F767zi)



Source: From an advertisement in Chipdip

Modulation (PWM) for controlling of actuators. Navio 2 is made to be used with a Raspberry Pi, so using it was the easiest solution.

Both Nucleos, the Jetson and Raspberry Pi are connected together in a communication network that implements standards internet protocols, with User Datagram Protocol (UDP) transport layer protocol instead of Transmission Control Protocol (TCP), for it's performance; and Ethernet as physical and link layer protocols. To avoid the non-deterministic characteristics of the standard Carrier Sense Multiple Access with Collision Detection (CSMA/CD) medium access control protocol, a token ring protocol² is implemented to avoid collisions.

3.2 FAULT MODELS FOR PROVANT

When started up, Jetson controls the UAV and the primary Nucleo controls the actuators according to the data received from the Jetson. The primary Nucleo should take control if the Jetson enters into a faulty state, likewise the secondary Nucleo has to get the control if both the Jetson and the primary Nucleo fails.

The state of liveness of each board could be modeled as the Figure 6. The composition of this automata for each of the modules is equivalent of the state diagram proposed by Benicá (2024) and shown in Figure 7, where colors are assigned to represent the severeness of the situation.

These status should be monitored by each of the modules in order to verify the safeties requirements and for the correct operation of the token ring protocol, as the

² This means that only one of the machines will have the permission to use the network hardware. It's said that this board has the "token", and once the permission is given to other board, that the "token was handed" to the other computer.

Figure 3 – ProVANT Emergencia main HLH board (Jetson Tx2)



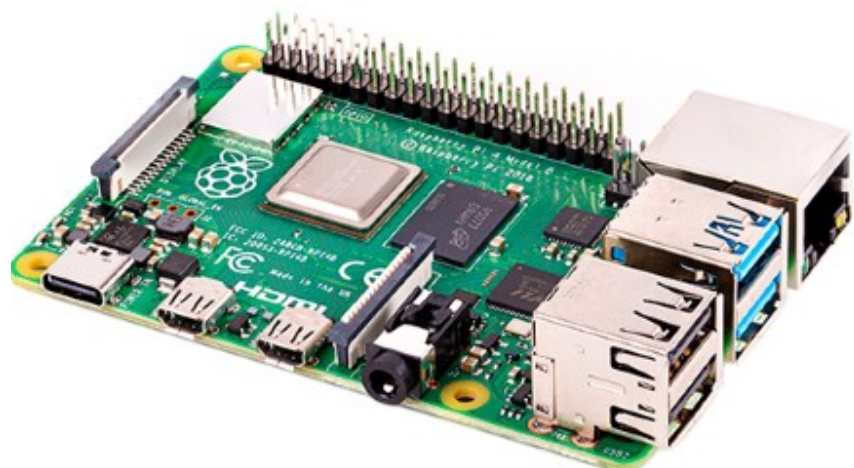
Source: From Nvidia's website

tokens shouldn't be given to an unresponsive board. A possible implementation could be adding a flag at the Module class, or *struct* in case of the c code used in the Nucleos.

To do so, it is necessary to implement techniques to identify faulty boards in the system. As boards should continuously monitor their own behavior with RV, it could be the case that a faulty board inform the others about it's faults prior to trying to recover, for example by a reset. However this scenario cannot be considered always possible, unforeseen faults may cause the board to reset or shutdown without warning, or even be unable to communicate.

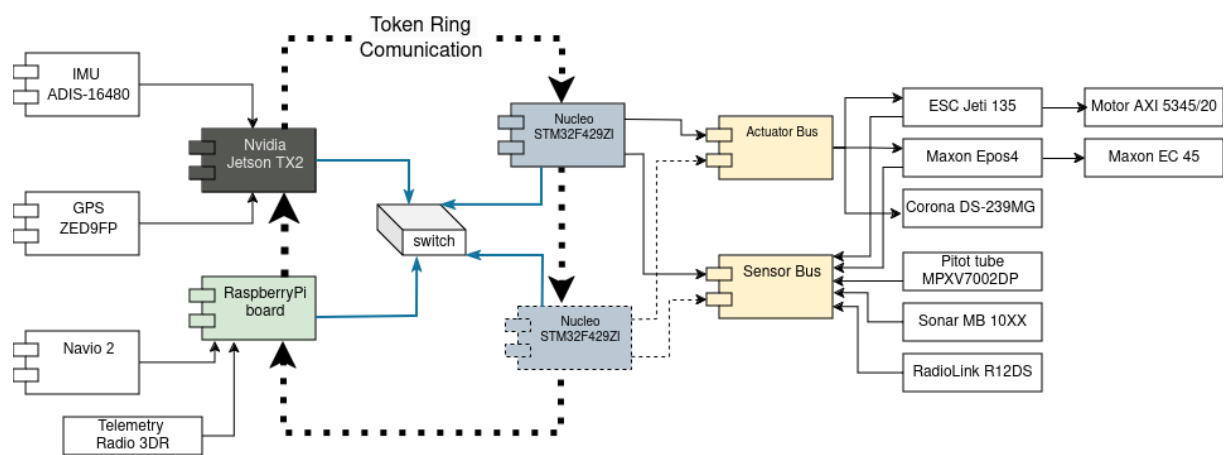
Benicá (2024) proposes methods to identify faults in the system. These methods being: heartbeat, watchdog, network monitoring and exception notification. Heartbeat means periodic messages, called heartbeats, sent by each of the boards inform the normal behavior, missing heartbeats inform a disconnection, this can help to identify a fault on a board that couldn't have communicated it. The watchdog is a timer that needs to be periodically reset by code, allowing the watchdog to overflow could mean the code is not executing or is in a deadlock. Network monitoring is simply calculating the latency of the network and the occurrence of missing messages. Exceptions notification is the common implementation of exceptions in code which can be catch by a catch

Figure 4 – ProVANT Emergencia HLH auxiliary board (Raspberry Pi 4)



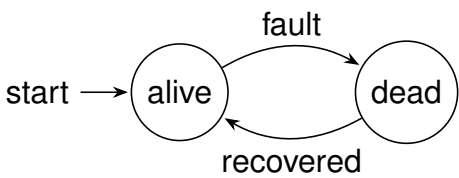
Source: From Raspberry Pi’s website

Figure 5 – ProVANT Emergencia general electrical structure view



Source: Personal archive

Figure 6 – Per module liveliness status automata

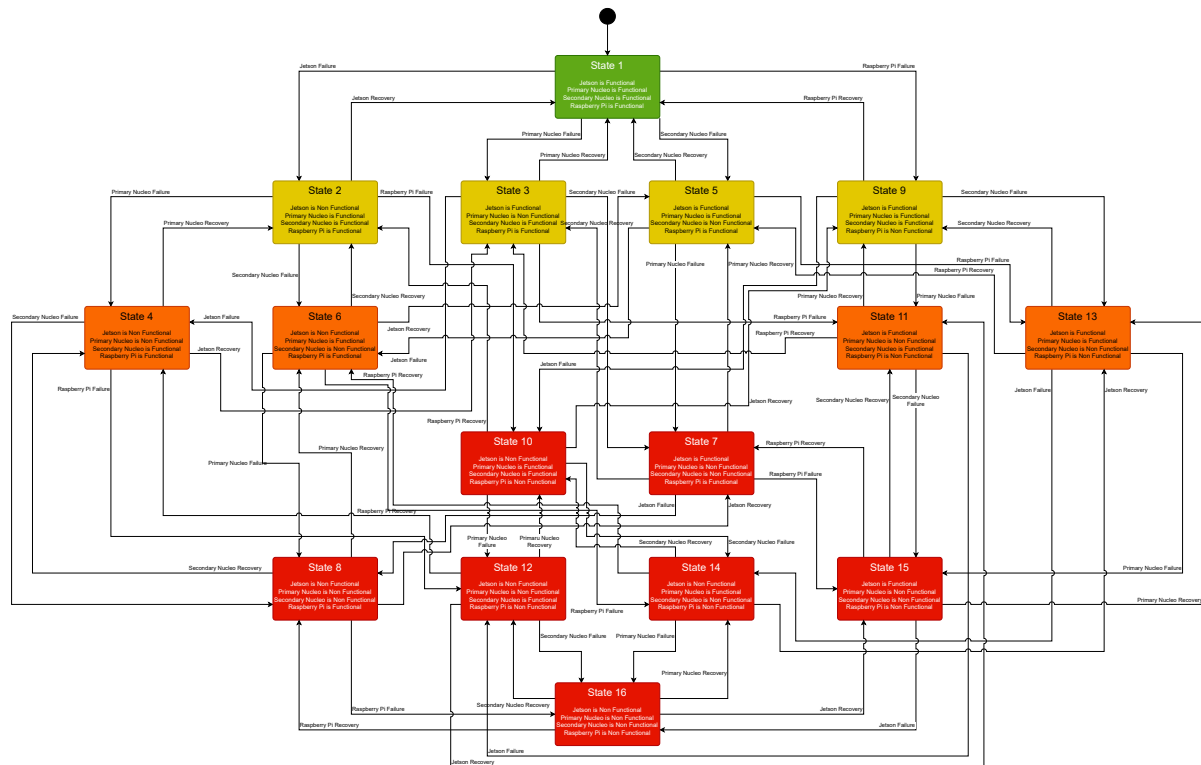


Source: Own elaboration



statement and dealt with in code, one of the proposed ways of dealing with exception was the communication through the network.

Benicá (2024) also proposes that the state of each of the boards should follow

Figure 7 – Full system liveliness status automata

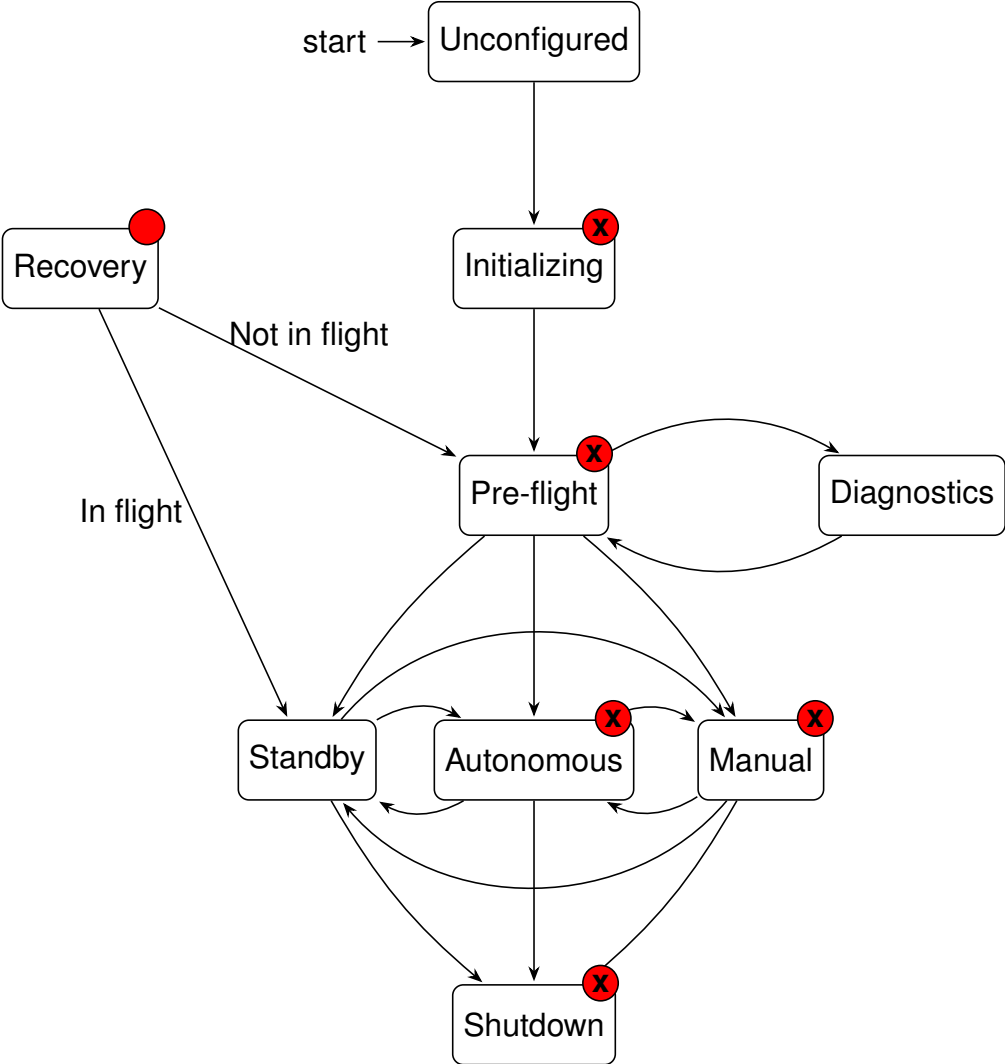


Source: Benicá (2024)

the Figure 8, where the  symbol represents the possibility of occurring a fault in that state, which triggers a transition to the state marked with .

Problems may arise while integrating the heartbeat technique with the token ring protocol, as the designer has decide weither the heartbeat messages should ignore the token, and only data messages have to be send when the board possesses the token, or it should respect the protocol.

Figure 8 – State machine for each board



Source: Benicá (2024) (revised)

4 PROPOSED METHOD

5 TESTS AND RESULTS

5.1 SIMULATION CONFIGURATION

O que tava conectado em quê, como pegamos os dados...

5.2 RESULTS

6 CONCLUSION AND FUTURE WORKS

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APPENDIX A – DESCRIÇÃO 1

Textos elaborados pelo autor, a fim de completar a sua argumentação. Deve ser precedido da palavra APÊNDICE, identificada por letras maiúsculas consecutivas, travessão e pelo respectivo título. Utilizam-se letras maiúsculas dobradas quando esgotadas as letras do alfabeto.

ANNEX A – DESCRIÇÃO 2

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