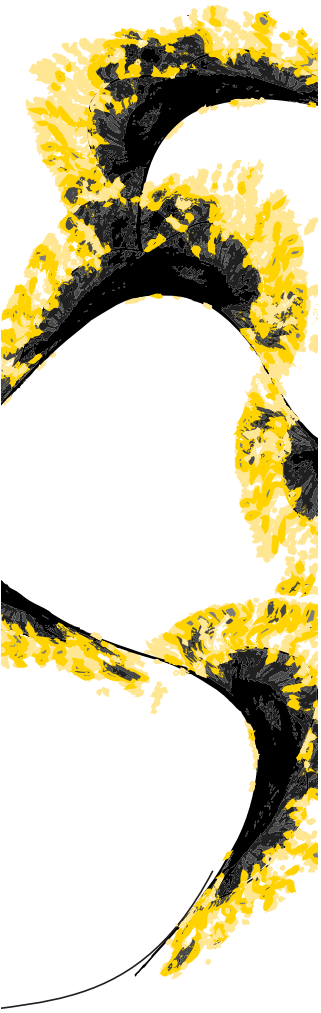

RAM ROBOTICS AND MECHATRONICS

REAL-TIME ROBOT SOFTWARE FRAMEWORK ON RASPBERRY PI USING XENOMAI AND ROS2

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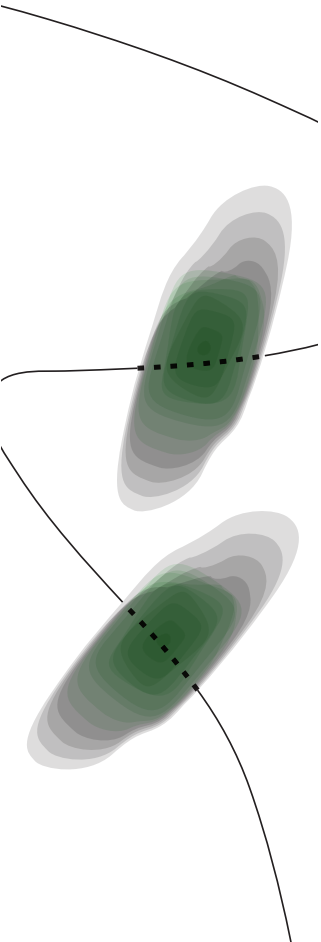

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Summary

This report introduces a real-time framework based on Xenomai to run 20-sim-generated models on a Raspberry Pi 4. The framework can interact with ROS2 to log the outgoing data and to instruct the framework with setpoints. The software and hardware choices are made based on a design space exploration and analysis of the various options that can fit the set requirements. The chosen software and hardware are the basis for the created framework.

This framework overcomes the problems that were found using the TERRA/LUNA framework that has been made at the University of Twente. The new framework consists of various classes, each producing an easy-to-use interface with the RT functionality of Xenomai. The framework consists of three main classes, which handle the thread, task, and communication. Functions that need to be executed inside a real-time task are created as a derived class, after which they are handed to the thread creator. Communication is done by using a Xenomai protocol that includes inter-process communication (IDDP) and inter-kernel communication (XDDP). The developed framework supports multiple Xenomai-scheduled tasks. ROS2 is integrated into the architecture giving the user a possibility to interact with a running RT task from a non-real-time interactive environment. Two ROS2 nodes are created that can handle incoming and outgoing data.

The viability of the framework is measured using multiple 20-sim-generated tasks implemented on the Raspberry Pi. Various tests are run to analyze the performance of the created framework, including core affinity and isolation, stress testing, and comparisons to actual 20-sim simulation data. The output of the framework is visually identical to the output of a 20-sim simulation. The jitter was measured using a Xenomai clock command due to the lack of performance of the secondary Raspberry Pi logic analyzer. The optimal performance of the framework is achieved in an isolated, non-shared setup, as predicted. When two 20-sim generated models containing a plant and controller of a two-degrees of freedom gimbal are used in the framework, the timing results show no deadline misses ($> 30\mu s$).

Test results indicate that the framework's performance meets the set requirements and can effectively provide the user with a stable RT framework that can be used in educational courses or research setups.

Subsequent steps are to integrate physical plant control using an external PWM generator that is communicated via SPI. Afterwards, the framework can be field-tested to see if all functionality is understandable and useable. This will probably result in small code adjustments and newly required functionality.

Contents

1 Introduction

1.1 Context

Robots are quickly becoming a natural occurrence in manufacturing workplaces. From 66 robots on every 10.000 employees in 2015, the distribution has risen to 74 for every 10.000 employees (International Federation of Robotics (IFR), 2019).

Robots are controlled repeatedly to ensure that their movement decisions are made with current knowledge of their surroundings and up-to-date input data. The sensors on the robot register the current state of the robot, which is used in a real-time controller. This controller computes the subsequent motor movement using the current motor position and its desired position. To ensure that all these steps are processed within a set period, real-time software is used to ensure that this requirement is met.

Robot Operating System (ROS) (Open Robotics, 2021) is often used as a sequence controller, laying out the connection between multiple parts of a robot. The sequence controller gives input data to the real-time controller to put the various parts of a robot in their desired position. Furthermore, ROS based programs are used to provide the user with a possibility to manually input data and for its connectivity using various communication protocols. ROS is a free and open-source framework. ROS is predominantly known for its modular communication and widely supported packages. The current iteration, ROS2, is a successor to the first ROS release. It is redesigned to improve internal communication and start to support embedded hardware. ROS2 also focuses on making the framework real-time friendly.

The Robotics and Mechatronics group (RaM) of the University of Twente uses ROS in research test setups and educational courses. As for the real-time controller, the university has developed the Twente Embedded Real-time Robot Application(TERRA) to design real-time systems for the same purposes. LUNA is a library that is used to formally describe the software architectures based on CSP (Communicating Sequential Processes). LUNA is introduced in the work of Bezemer et al. (2011). Subsequently, Hofstede (2020) and van der Werff (2016) worked on creating a bridge between LUNA and ROS to promote quick development and rapid prototyping.

The LUNA/TERRA framework, in conjunction with the ROS bridge, integrates the real-time planning and execution of LUNA and the structure and packages of ROS. However, due to the structuring of the framework, some principal features are impossible, such as multi-threading at the LUNA side. Moreover, TERRA/LUNA shields the real-time programming from the user, aiming to simplify the user experience. However, when using it for educational purposes, this is unwanted. Moreover, the interface of LUNA/TERRA is built to be convenient but becomes cluttered and difficult to use when creating larger projects.

Since ROS2 is still used within university courses and as base for research setups, a replacement for LUNA/TERRA must be found. The main issues herein lie that the replacement framework needs to be easy in use and its target device easy to obtain.

1.2 Goal

The aim of this thesis is to develop a framework that integrates real-time tasks and ROS2 to control physical robots. The functionality of these tasks is defined in code written by the user or by using code generation of a modelling tool. This framework can be used for easy deployment of tasks in a real-time environment and testing robot setups. The framework could be used within the University of Twente as an educational tool within the course *Real-Time Software Development* or when programming research setups.

Due to the restricted amount of time that can be spent on this thesis, the focus lies in creating the real-time environment within the selected hardware. IO interfacing and controlling a physical robot are out of scope of this thesis.

The framework must be able to run real-time threads which can communicate with each other. These threads are able to simulate plants and controllers or execute user-made functions. ROS2 provides inputs for these real-time threads and can also log the results. Therefore, a connection between the real-time environment of the thread and the non-real-time environment of ROS2 must be made.

The main goals of this thesis are formulated as follows:

- *Design space exploration to find the best hardware and software alternative for building the framework on top of.*
- *Creation of a framework to run tasks in real-time that can communicate to non-real-time ROS2 nodes.*
- *Testing and validating the created framework.*

1.3 Report structure

Chapter 2 focusses on the background of real-time, the Robot Operating System, and modelling tools. Chapter 3 applies this knowledge in deciding which software and hardware solutions are used best. Chapter 4 describes the framework and the design decisions. Subsequently, the method for testing the framework is described in Chapter 5. The results of these tests are shown and discussed in Chapter 6. Finally, the outcome of the thesis is concluded in Chapter 7 together with some recommendations.

2 Background

2.1 Introduction

This chapter introduces the necessary background information for understanding the following chapters of this thesis. It covers real-time as definition and when used in a system. Furthermore, ROS2 is covered, including its organization, communication, and functionality. Finally, modelling tools are treated shortly to provide context for later used generated code.

2.2 Basic concepts of real-time systems

The definition of real-time is given in many articles. The most general description from Kopetz (1997) is:

> *"A real-time computer system is a computer system where the correctness of the system behaviour depends not only on the logical results of the computations, but also on the physical time when these results are produced."*

However, this definition does not include deadlines or timing requirements. The definitions in Bruyninckx (2002) are more detailed and highlight the two most important aspects in real-time engineering:

> *"A real-time operating system is able to execute all of its tasks without violating specified timing constraints."*

This definition touches upon the set requirements for real-time tasks in the form of deadlines. However, this does not include the ability of the program to be predetermined. These *deterministic* processes are the backbone of any real-time system since their runtime can be calculated to a full extent. Another definition of real-time from Bruyninckx (2002) includes deterministic behaviour:

> *"Times at which tasks will execute can be predicted deterministically on the basis of knowledge about the system's hardware and software."*

The deterministic requirement is helpful when calculating if a program's longest execution time is sufficient such that it does not violate its timing constraints.

Concluding, a real-time task is a task that has to be finished before the deadline and can only do so consistently when the used software and hardware are able to perform the task in a deterministic environment. No undefined interruptions should happen within the task's execution window.

2.2.1 Periodic real-time tasks

A periodic real-time task is a repeated real-time task. It executes at regular intervals, called periods. A periodic real-time task has multiple properties which define its functionality (Buttazzo, 2011). These properties are:

- **Release time** (a_i) The time at which the process becomes available to execute.
- **Start time** (s_i) The time that the process starts to execute.
- **Finish time** (f_i) The time that the process is finished executing. ($f_{wc,i}$) represents the worst case finish time.
- **Period** (p) The time span that is available to execute the process.

- **Relative deadline** (d_i) The point in time, relative to the beginning of the execution, at which the process must be finished executing.
- **The worst-case execution time** ($WCET$) The maximum time that the process takes to execute completely.

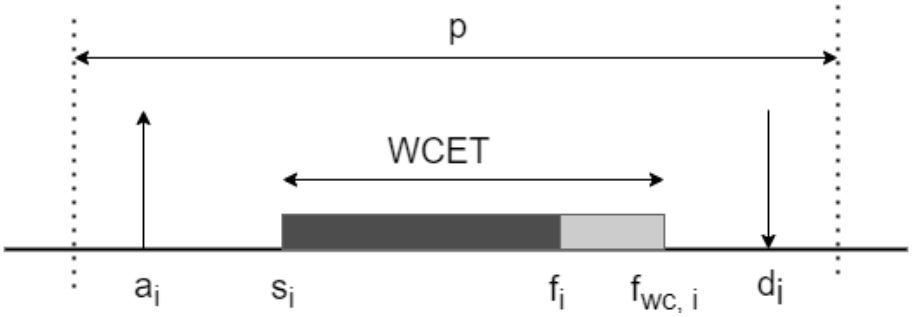


Figure 2.1: Periodic real-time task. Adapted from Buttazzo (2011)

Figure 2.1 visualizes a periodic real-time tasks with parameters. In real-time systems, the WCET must be less than the deadline minus the release time, such that the finish time can never be behind the deadline. The deadline of a process is not necessarily the end of the period. After meeting the deadline, the task awaits its next release time.

2.2.2 Classification of real-time tasks

There are three different classifications for real-time tasks. These all serve different situations in which real-time systems are necessary.

The result of a real-time task is of great importance when controlling robotics. When a task misses its deadline, the usefulness of this result changes. This usefulness or utility can be shown in a graph, which changes after a deadline miss. All different real-time classifications are listed below, shown with their appropriate utility function in Figure 2.2.

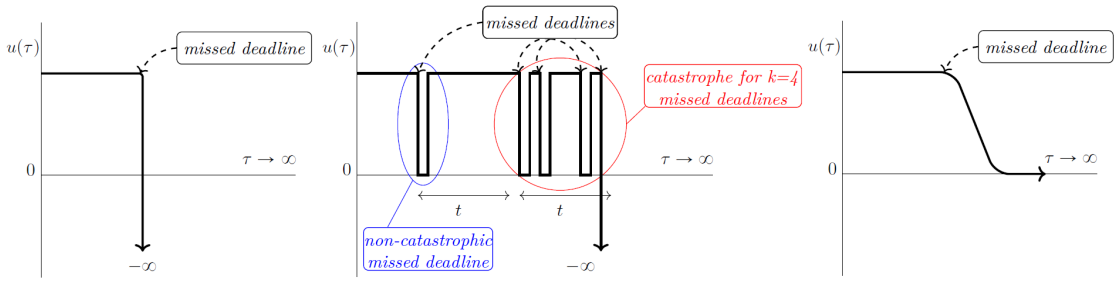


Figure 2.2: Utilities of the result of a real-time task. Image from Boode (2018).

1. **Hard real-time**
   Aviation computers, precise robotics, and power-plant applications all have in common that they must be controlled very precisely. If this is not achieved, the results are catastrophic. Applications such as these require the use of 'hard' real time. In the case of hard real-time, there is absolutely no flexibility. A missed deadline could cause a big disaster, which is why these systems are designed to be deterministic. Hard real-time task utility drops to minus infinity when a deadline is missed, shown in Figure 2.2a.

2. **Firm real-time**
   Systems where calculations are done in high frequency and are not a safety hazard often

allow a number of deadline misses. Multiple missed deadlines within a certain period of time could increase the likeliness of a critical failure. These tasks are considered firm real-time. Within a firm real-time system, a task may miss k deadlines within a period t before the utility drops to $-\infty$. The utility function of a firm real-time system is shown in Figure 2.2b.

3. **Soft real-time**
   Soft real-time is the most flexible system of all real-time systems, where the result of a missed deadline can still be used. Nevertheless, it can most often only be used up to a certain point in time. Soft real-time systems are most used in streaming services or internet services. The utility function of a soft real-time system is shown in Figure 2.2c.

2.2.3 Jitter

Jitter is the deviation from the true execution time of a task. When a task deviates excessively from its usual finish time, the deadline that is set could be missed.

In most real-time systems, there is some room for jitter. This room is present to catch unpredictable events, if they may happen. Jitter is an important characteristic of real-time computers since it defines how a system behaves when under load. The maximum measured jitter of a system can be used to check if that system is safe for its application.

Jitter is mainly caused by asynchronous events in the operating system. For example, an interrupt issued by the system could suspend a task and therefore delay it.

There are multiple sources of jitter. First of all, there is the distinction between deterministic and random jitter. Deterministic jitter is a bounded jitter, with the maximum and minimum extent are defined. Random jitter is not bounded and is Gaussian in nature (Bruyninckx, 2002).

Next to jitter causes, there are also distinct jitter variants (SiTime, 2021).

- **Period jitter** is defined as the deviation of the cycle time in comparison to the ideal period. This can be measured by measuring a large number of periods and comparing them to their ideal period.
- **Cycle-to-cycle jitter** is the inequality between the period of two adjacent cycles. This can be measured by measuring the period of two adjacent cycles and computing the difference.
- **Long-term jitter**, also called accumulated jitter, is the drift of the period time when measuring it over a long period of time. Measuring long-term jitter is done by measuring the start and finish of a 10.000 cycle period. Then it is compared to the ideal period of 10.000 cycles.

Within robotics the cycle-to-cycle jitter is the most commonly used type of jitter.

2.3 Real-time operating systems

Real-time systems are hard to manage, especially when there are multiple tasks that need to run simultaneously. Simple functionality can easily be designed on bare-metal (running a program directly on the chip, without an operating system), without additional tasks that can interrupt or preempt it. However, when multiple tasks are needed, scheduling is required. Scheduling is done by a kernel, which handles low-level tasks for the operating system (OS). The kernel schedules the different tasks that need to be run according to their set priority. A real-time operating system (RTOS) is an OS that is specialized in running one or multiple real-time tasks. These tasks have the requirement not to be interrupted at the wrong time. In addition, an RTOS has to handle real-time organizational items. The most important jobs of an RTOS are: (Buttazzo, 2011)

- Task management and scheduling
- Interrupt handling
- Inter-process communication and synchronization
- Memory management

A real-time operating system is no different from a general operating system. They focus on different key aspects of operating systems. Whereas a general OS has a higher throughput, a real-time operating system compromises that and focuses on better responsiveness. The most important part of an RTOS is to offer low response time and provide a deterministic latency.

2.3.1 RTOS architecture

Real-time kernels can be put into two categories. An RT kernel can be deployed as a standalone kernel, going by the name of a monolithic kernel. This kernel has all the OS services running on the same mode as the low-level processes. For instance, the scheduler and the interrupt handler. On the other hand, a micro-kernel separates these low-level tasks from the regular OS tasks. A monolithic kernel is easier to optimize since all the tasks are within one scheduler. A micro-kernel creates a distinction between an OS-task and an RT-task, which allows for better performance and determinism. Moreover, when an OS-Task blocks, the RT-tasks are not automatically blocked since they are not handled by the same scheduler. A schematic of these two layouts can be seen in Figure 2.3.

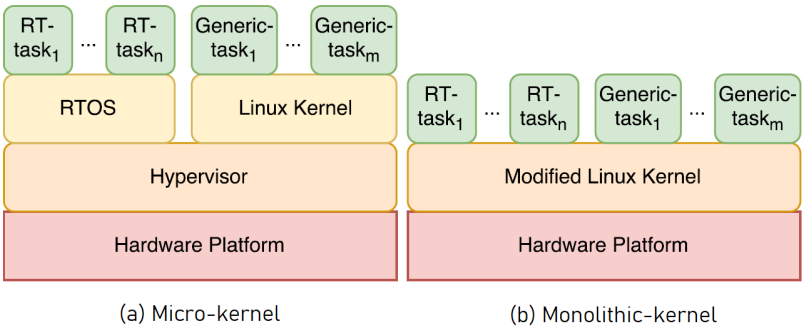


Figure 2.3: Different kernel architectures. (a) is a micro-kernel layout and (b) is a monolithic layout. Image from Johansson (2018).

When working with multiple kernels, various problems can arise. For instance, the resources that are available by the hardware must be shared when working with a micro-kernel layout. This is where a Hardware Abstraction Layer (HAL) comes into play. A HAL is a layer between the hardware and the kernels and can distribute hardware resources to both kernels (Huang and Wu, 2018). A typically used HAL for the Linux operating system is Adeos. Adeos is a resource virtualization layer that can be patched over Linux. Adeos got refactored into I-pipe, which is a pipeline that only contains the core functionality. This makes the patch easier to interpret and use (Gerum, 2005).

2.3.2 Linux and the PREEMPT_RT patch

Regular operating systems such as Linux cannot meet real-time requirements. The main cause herein lies in that high-priority tasks can still be interrupted by the OS. In 2005 the Linux foundation started researching a more deterministic kernel. In 2016 this work was continued in the *Real-time Linux collaborative project*, which worked on the implementation of a real-time patch for Linux. This patch is called PREEMPT_RT. With the PREEMPT_RT patch, the OS tasks become preemptable, which turns Linux into a real-time operating system (Reghenzani et al., 2019).

Linux with the PREEMPT_RT patch contains a monolithic kernel, just as the regular Linux operating system. This makes the implementation of real-time tasks similar to creating user-space tasks. Nevertheless, some scheduler and priority settings need to be made. PREEMPT_RT enables developers to reuse existing Linux libraries and tools. Despite that PREEMPT_RT was developed with hard real-time tasks in mind, it can only be considered 95% hard real-time (Reghenzani et al., 2019). This is due to the fact that it remains a monolithic kernel and has to run regular Linux tasks in the same scheduler as the real-time tasks. PREEMPT_RT can be considered a firm real-time operating system where deadline misses are allowed up to a probability of 5%.

2.3.3 Xenomai

Xenomai is a micro-kernel RTOS developed for Linux (Gerum, 2001). Recently, it also started supporting a single kernel approach, called the Mercury kernel. The main project, called the cobalt kernel, runs on top of the HAL I-Pipe. Xenomai runs, in cobalt-core setup, as a micro-kernel with a higher priority than Linux. Hence Xenomai can decide when Linux processes get to execute. This way, Xenomai can put priority on its tasks and therefore assure their in-time execution. Interrupts are first caught by I-Pipe. I-Pipe decides which interrupt goes where and distributes it correctly, again with Xenomai having a higher priority.

Xenomai reimplements numerous Linux functions, overwriting their original purpose with real-time behaviour. This overwriting of previous functions is called a *skin*. In this manner, Xenomai can be used with functions from the Posix definitions or other RTOS such as VxWorks and RTAI. Next to these, the native skin contains all real-time functionality in a proprietary instruction set (Kuppens, 2015). A schematic of Xenomai next to Linux is shown in Figure 2.4.

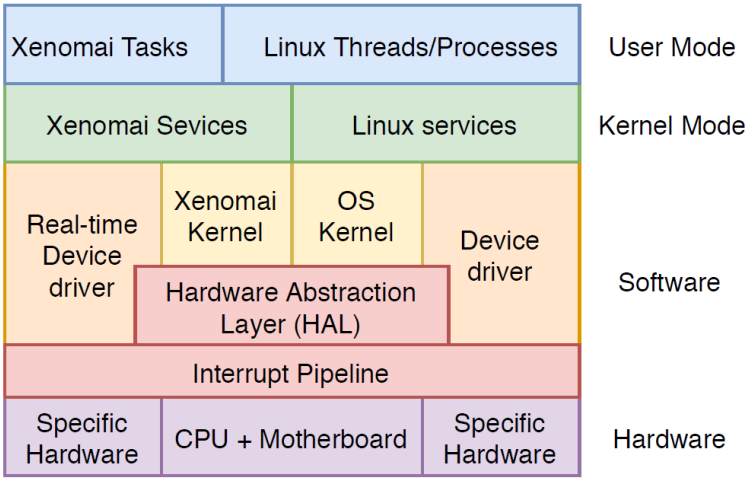


Figure 2.4: Architecture of the Xenomai cobalt kernel. Image from Johansson (2018).

As described above, the Xenomai kernel runs next to Linux. This way, Xenomai can decide when to schedule Linux. When a Xenomai real-time task wants to make a system call, a mode switch happens. This will put the Xenomai kernel out of control temporarily while the system call is being performed. System calls cause the program to be vulnerable to variation in execution, making them non-deterministic.

2.4 ROS2

The Robot Operating System (ROS) is a free and open-source software framework for developing robot applications. When using ROS, rapid application building can be expected without restrictions in complexity. One of the key strengths of ROS is the collaboration with other users. There are hundreds of software packages that are actively maintained. These can range from image recognition libraries to communication protocols. Hence, ROS has become one of the standards for research and development in the robotics field. The first iteration of ROS, ROS1, was developed with a single robot in mind. Consequently, the communication system in ROS1 was build with a single master node in mind. This was done since every node was on the same system. ROS2 addresses the shortcomings of ROS1 by developing it with a broader use case set in mind. ROS2 is being developed to maximize its flexibility and modularity.

2.4.1 Organization

As described above, one of the major shortcomings of ROS1 is that it uses one central node. ROS2 fixed this by applying the use of a Data Distribution Service (DDS). The DDS takes care of all the communication needs between processes. DDS uses a Real-Time Publish-Subscribe (RTPS) protocol. As described in Gutiérrez et al. (2018), this protocol is suitable for soft and possibly firm real-time messaging. This real-time behaviour is only present in one paid version of DDS, the ConnextDDS (rti, 2021). Since this is a paid version of DDS, the online community is smaller and most questions have to be asked via official help channels at the manufacturer. All ROS2 user-code and the DDS are separated by an API layer. This removes the need for code refactoring after an update to the DDS.

ROS2 encourages the user to separate all tasks into different services. These services can then be called via callbacks such as incoming messages or timers. The services are structured into *nodes*. ROS2 combines this with the above-mentioned publish-subscribe system. This enables all nodes to publish messages to *topics* to which other nodes can subscribe. The subscribed nodes will then receive the data that is published to said topic. An example of this described structure of topics and nodes can be seen in Figure 2.5.

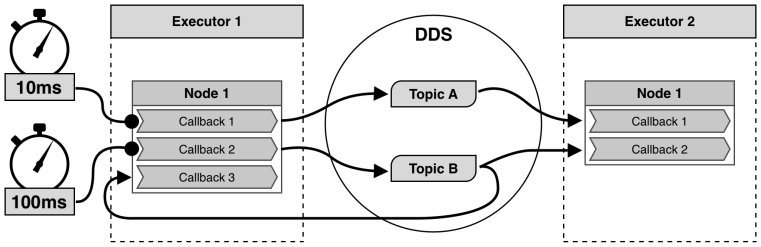


Figure 2.5: ROS publish-subscribe mechanism. Image from Randolph (2021).

Although ROS2 defines the structure of nodes and communication, it does not define how and when nodes react to messages and how many nodes are reacting. Moreover, it runs on top of Linux, which also adds additional jitter. All summed up makes ROS2 a potential candidate for real-time use in the future. At the moment it is less suitable since the performance is not sufficient.

2.5 Modelling software

Modelling software is used to build representative models for real-life plants and their appropriate controllers. Real-life behaviour can be modelled into modelling software using graphical objects or programming languages. There are many different modelling suites. Research within the University of Twente RaM group is mainly done using 20-sim, which is made by Controllab Products situated on the University campus (Controllab Products, 2021).

20-Sim excels at modelling and simulation in which users can create models graphically. With these models, one can simulate and analyze their behaviour and create control systems to control these or their accompanying real-life plant.

These models can be converted to code, enabling the user to use this code in their robot. Code generation is used in Chapter 4: Design and treated more specifically in Section 4.2.4.

3 Analysis

3.1 Introduction

The goal of this thesis is to create an easy-to-use framework that can be run on widely available hardware. The main functional requirements of this framework are that it must be able to run real-time tasks and integrate these with ROS2. Further requirements of the framework and its testing setup are described in this chapter. Because of a distinct separation in software and hardware requirements, the latter part of this chapter is divided into hardware and software.

The software part includes the options and choices that were made regarding operating system, communication protocol, and general integration. The hardware sections describe various hardware alternatives and their functionality. Furthermore, the system needs to be analyzed after construction, for which a test setup will be used. The test setup allows the framework to be tested if the requirements are met. The requirements to which the test setup must adhere are given in Section 3.2.2.

3.2 Requirements

3.2.1 Use cases

Education and research are the two use cases of the proposed framework. Educational use will be such that students can use real-time systems without having to write the complete task structure and communication structure. On the other hand, they should still be able to grasp it completely and must be able to take a look under the hood to see what is going on.

Regarding research, the framework must offer easy implementation since there is no learning aspect in this case. Rapid prototyping is in high demand in a research environment, mainly for creating research setups quickly. A framework that could easily execute and deploy a created model would be very useful.

3.2.2 Functional requirements

1. **Architectural requirements**

   (a) *The design **must** support firm real-time.*
   The main goal of the design is to implement a user-friendly way to combine real-time and non-real-time tasks. The system is used to control robots which, do not require an absolute 100% timing guarantee. Therefore, a reasonable requirement would be that the system must support firm real-time instead of hard real-time architecture. The maximum jitter should be no more than 3% of the set period. Moreover, the design may miss 0.01% of its deadlines.

   (b) *The design **must** be able to interface with ROS2.*
   ROS1 is an often-used tool within the RaM group. Since ROS2 is a successor to ROS1 and includes new functionality, this is a better alternative. ROS2 is becoming industry-standard, which makes it valuable knowledge for upcoming graduates.

   (c) *Externally generated controller code **must** be supported.*
   Pre-generated controller code must be supported to create a rapid-prototyping framework. Both 20-sim and Simulink are used within the university to create controllers using objects. The system must support 20-sim to enable rapid prototyping since 20-sim is the most used within the RaM group. Simulink, another frequently used modelling tool, could also be supported.

   (d) *The architecture **must** implement a multicore or multi-device layout.*
   An increasing amount of hardware contains a processor which consists of multiple

cores. Only using one is a waste of resources, which would be a shame in complex systems. To account for this change in hardware architecture and to sustain the need for large processing power, multi-core must be supported. Besides, the possibility to separate real-time and non-real-time tasks is useful.

(e) *The system **should** be able to support multiple real-time controller loops.*
Many modern controller setups include multiple running control loops. The architecture should try to support this by allowing multiple threads inside the real-time part. When the framework is not able to include this functionality, the possibility for extension must be available.

(f) *The system **should** implement an error handler and tracer.*
When working with multiple programs and priorities, it is beneficial to have a good error handler. An error handler improves the speed of bug fixing since the system can point towards code that has possible bugs. Without this, the user must guess in which part the bug is located, which would slow down debugging.

2. **Communication requirements**

(a) *The communication within the real-time part of the controller **must** be real-time capable.*
Because of the requirement that the system must support firm-real-time, the communication protocol must also support firm-real-time.

(b) *The communication between the non-real-time part and the real-time part of the design **must** not interrupt the real-time task.*
Since the system will support non-real-time task input, connecting communication must be established. This communication must be designed such that it does not interrupt the real-time task.

3. **Hardware requirements**

(a) *The hardware used by the system **must** be widely available.*
To ensure that research and educational staff can use the framework, the hardware on which it is built must be widely available. Furthermore, the hardware must be low in price since all students should be able to buy a device. Widely available hardware also ensures that there is a widespread online community for it.

(b) *The chosen hardware **must** support multi-core or multi-device.*
One of the main architecture requirements is that the framework must support multi-core. When choosing a hardware piece, this requirement should be taken into consideration. The chosen hardware can either be a multi-core device or multiple devices with one or more cores.

(c) *The hardware **must** have sufficient I/O (inputs and outputs) to drive a robot controller.*
Because the framework is being developed to be used with robots, the hardware must also support this. This means that there must be sufficient I/O pins on the device. These outputs must also support SPI/I2C to communicate to a motor controller board or FPGA if needed.

4. **Test setup requirements**

(a) *The test setup **must** test the real-time capabilities.*
The real-time performance of the framework is set to be tested using a test setup. The test setup includes the hardware piece along with a logic analyzer and two real-time tasks running.

(b) *The test setup **should** be able to test multiple real-time loops.*
When the system can support multiple real-time loops, the test setup should also be able to test this.

3.2.3 Non-functional requirements

1. *The designed architecture **must** be able to run on open-source hardware or partly open-source hardware.*
When working with open-source hardware or partly open-source hardware, the online community is much bigger than with proprietary standards. Which, in its turn, could prove useful when bug fixing. Furthermore, the different onboard components are listed by the manufacturer, which makes finding compatibilities easier.

2. *All steps in the code generation or deployment **should** be accessible to users.*
The system should not shield its real-time code from the user for the sake of simplicity. Earlier done by TERRA/LUNA, which is not a good learning experience when used for learning real-time aspects.

3. *A comprehensive guide on how to run simple controllers and install the framework **must** be available*
For both the ROS2 implementation and the RTOS installation, there should be clear installation instructions. Next to these, example codes must be available to demonstrate the functionality of the framework.

3.3 Hardware

Hardware options are abundant, although many are unsuitable due to the set requirements.

The first thing to consider is the processor architecture since it has to be suitable for real-time tasks. Another thing is the different I/O connections that are present on the board, for the reason that it has to support motor controllers. The device must be multi-core. This can either be achieved by using two separate devices or a single device.

Considering that the useable software is highly dependent on the chosen hardware, preselecting hardware is the best option.

3.3.1 Selection criteria

The selection criteria are drawn up with the requirements in mind. Furthermore, the selection criteria are also given from within the University of Twente to be suitable for use within educational courses and research.

1. **Independency** describes the portability and independence of the device. When using a device that needs to be connected to multiple other devices, the independence is low. Low independence increases the complexity of a controller setup.
2. **Processing power** determines which programs can execute on the hardware. When considering multiple devices, the combined processing power is weighed.
3. **Input/output ports** need to support regular digital outputs. Some devices have specified ports for common hardware interfaces such as I2C, SPI, and UART.
4. **Supported protocols** are nice-to-have, not a priority. The common hardware interfaces are described in the previous criterion. The supported protocols refer to ethernet standards, USB ports, among others.
5. **Availability** makes sure that the device is obtainable.
6. **Ease of use** outlines the practicality of the hardware. Multiple pieces of hardware require intermediate communication, which increases its complexity. Additionally, programming multiple platforms can be cumbersome.

7. **Cost** is mainly a criterion from an educational viewpoint. Students should be able to afford the hardware. However, within research, the hardware should not consume the entire research budget either.

The weight factor of each selection criteria is dependant on its importance. The main requirement of the hardware is that it should be a suitable base for building a real-time framework. Therefore 'processing power', 'IO ports', and 'availability' are double as important as secondary selection criteria. The 'ease of use' criteria also has weight 2 since it describes the practicality of the selected hardware setup.

3.3.2 Alternatives

Raspberry Pi The Raspberry Pi (Raspberry Pi foundation, 2019) is one of the most used open-hardware devices, mainly because of its small form-factor, low price, and good performance. It is also widely available and has lots of support online. The current iteration, Raspberry Pi 4B, uses a Broadcom BCM2711 quad-core Cortex-A72 (ARM v8). This processor is running at 1.5GHz. The Raspberry Pi is mainly used with Linux and therefore supports most Debian packages and Linux-based RTOS. It also has a wide variety of in and output pins which make it great for robotics.

Arduino The Arduino (Arduino, 2010) is one of the most accessible devices when doing home projects. It can be easily programmed and is able to execute in hard real-time because of bare-metal programming. Because the Arduino contains an extensive I/O, it is able to communicate via the most general protocols such as SPI and I2C. This makes it suitable as a companion next to a more capable processor. A microcontroller in a two-board setup can be used to perform time-sensitive tasks. Although the Arduino is suitable for small real-time tasks, it lacks sufficient speed to perform extensive programs. The Arduino contains a low-frequency microcontroller (ATmega328P) which runs at 16MHz.

ESP32 The ESP32 (Espressif systems, 2016) is a microcontroller that is somewhat a successor to the Arduino. The most common form is a developer board with the ESP32 integrated, containing a crystal, GPIO, and flash memory. One of the main advantages of an ESP32 over an Arduino is its wireless connectivity. The ESP32 SoC includes Bluetooth Low Energy (BLE) and WiFi capabilities. Similar to the Arduino, this board also requires bare-metal programming. This makes this board suitable for real-time processes and excludes extensive and multiple tasks. The newer versions of the ESP32 also feature a multi-core microprocessor. The ESP32 contains an Xtensa dual-core (or single-core) 32-bit LX6 microprocessor, operating at 160 or 240 MHz.

RaMstiX The RaMstiX is a board developed by the RaM group at the University of Twente. It features an FPGA and an Overo Gumstix. The two are connected with a general-purpose memory controller (GPMC), which provides communication. The Gumstix contains an ARM® Cortex™-A8 processor and can be expanded by modules such as wireless communication or additional storage. The FPGA can be used to program time-sensitive tasks or to handle input/output.

Personal computer An alternative to all listed options is to use a Personal Computer(PC) to do all the tasks. Nevertheless, additional hardware would need to be purchased to enable input/output from the PC. Moreover, a seperate device is needed for real-time task execution.

3.3.3 Hardware conclusion

There are two main setup layouts: dual device and single device. Whether one or the other is better also depends on the devices used. The use-cases and requirements indicate that rapid-

prototyping is of great importance. A two-device setup requires an increased amount of code division, inter-device communication, and hardware equipment. Therefore a single device layout would be better suited.

The ESP32 and the Arduino contain too little processing power to run user tasks. As a consequence, they are only viable with a companion device.

The RaMstiX accommodates two devices on a single board. However, it requires requires communication between the FPGA and the Gumstix and VHDL Programming knowledge.

The weighted decision on each criterion for each of the options is shown in Table 3.1.

Table 3.1: Weighted decision table for hardware choices

	Weight	PC + arduino/ESP	Raspberry Pi	rPi + arduino	rPi + ESP32	Ramstix
Separability	**1**	- -	+	+	+	+
Processing power	**2**	+	+	+/-	+	+
Input/output ports	**2**	-	+	++	++	++
Supported protocols	**1**	+	++	++	++	+/-
Availability	**2**	++	+	+/-	+/-	+/-
Ease of use	**2**	+/-	+	-	-	-
Cost	**1**	+	+	+/-	+/-	-
Total:	**11**	2	**12**	5	7	4

The Raspberry Pi is a single-device setup. This layout fulfills the requirements since the Raspberry Pi is a multi-core device thus can run multiple tasks in parallel. The single-device setup enables quick debugging and straightforward communication.

3.4 Software

The single-device setup of the Raspberry Pi restricts the choice of the software. Small embedded real-time operating systems such as FreeRTOS (Real Time Engineers, 2003) or Zephyr (Linux Foundation, 2016) do not support the Raspberry Pi. The most used operating system on Raspberry Pi is Linux, which allows for any Linux-based RTOS.

3.4.1 Operating system

There are various options when choosing a valid RTOS for the Raspberry Pi. On one side, there is the possibility for upgrading the regular Linux release, and on the other side to use a specialized RTOS next to Linux.

Linux PREEMPT_RT As explained in Section 2.3.2, PREEMPT_RT is a patch to make regular Linux real-time capable. It has the advantage that regular Linux commands can be used to create real-time tasks. Next to that, Linux packages can still be used as they would be regularly.

On the downside, the performance of this real-time operating system is less than ideal. It substantially reduces the maximum latency in a timed loop. The maximum latency under stress can be reduced from 628μs to 149μs (Carvalho et al., 2019). Together with an average of 23μs and a standard deviation of 16μs, this is not suitable for firm or hard real-time systems.

Xenomai Xenomai, as Section 2.3.3 describes, is a specialized real-time OS. However, as it runs as a micro-kernel next to Linux, one can still use the native Linux packages. Moreover, Xenomai offers a Linux skin that overwrites Linux's Posix threads (Pthreads) with real-time implementation.

In Huang et al. (2015) the difference between Xenomai 2 & 3 and PREEMPT_RT was measured. In that study, PREEMPT_RT, Xenomai 3 and regular Linux are subjected to the same tests. The

PREEMPT_RT test results show a maximum jitter of 62μs while Xenomai had a maximum of 37μs in a CPU-stressed environment.

These results show that Xenomai is significantly better at ensuring timing. Due to these performance differences and identical programming interfaces, Xenomai is a better fit to be the backbone of the framework.

3.4.2 Communication

As Xenomai is the best option for the real-time operating system, the layout of the system is a micro-kernel. Thus, the Linux kernel will run next to Xenomai. Upwards from Xenomai 2.5.x, an RTIPC framework was merged into Xenomai. RTIPC stands for Real-Time Inter-Process Communication. This framework contains three communication protocols, described below. RTIPC is a meta-driver over which the three protocols are built. The goal of the RTIPC is to provide users with a socket-type interface running in Xenomai primary mode (Gerum, 2009).

Two of the three different communication protocols are designed to function within the primary mode of Xenomai. Therefore, they are used to communicate between multiple real-time tasks. These are BUFP and IDDP. The various communication protocol options are listed below.

- BUFP stands for Buffer Protocol, which starts a byte stream from one task to another. The BUFP protocol does not have a built-in message boundary system, which makes it a very simple protocol to use.
- IDDP is the more complex version of BUFP. It stands for Intra-Domain Datagram Protocol. It uses a socket interface on which datagrams can be sent. The functionality is nearly identical to the native socket implementation in the Linux Domain.
- XDDP is a cross-kernel protocol, which is used between the regular Linux user tasks and Xenomai real-time tasks. XDDP stands for Cross-Domain Datagram Protocol. It connects a Real-Time Driver Model (RTDM) to one of the /dev/rtp* pseudo-devices. The Linux side can also connect to this device, after which connection is established.

XDDP will be used for cross-kernel connection and IDDP for inter-kernel connection. BUFP is not suitable for creating larger scaled systems due to its simplicity. Therefore, IDDP is a better choice.

3.4.3 Integration

Multi-core operability is a major requirement for the framework. As described in Section 2.3.3, Linux Pthread commands can be used to start real-time processes. In a similar fashion, the affinity of the tasks can be set. The affinity determines which CPU core the task will run.

Additionally, integration with modelling software is a requirement. Section 2.5 mainly discusses 20-sim since it is the most used tool within the RaM group. The 20-sim code-generation tool can generate code in C or C++. C++ is a better choice for a framework since it is more suitable when programming object oriented. Xenomai also supports both languages and therefore C++ is the preferred choice.

ROS2 integration is discussed in Chapter 4. ROS2 can run packages as C++ and is able to integrate with Xenomai via the pseudo-devices that are created by the XDDP protocol.

3.5 Conclusion

Concluding, the Raspberry Pi is being used together with the latest compatible release of Xenomai as its real-time OS. Xenomai will run next to the latest compatible Linux release for

Raspberry Pi. Xenomai 3.1 is used next to Linux release 4.19.86. The full installation is listed in Appendix A.

Xenomai is chosen to be the RTOS due to its better performance and similar programming interface to Linux. The PREEMPT_RT patch also uses this interface, yet its real-time performance is not suitable.

An overview of the environment in which the framework is built is shown in Figure 3.1.

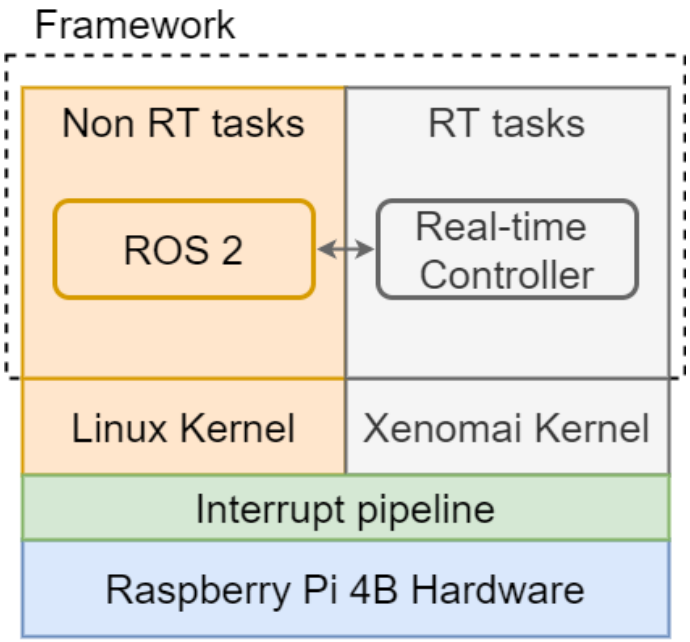


Figure 3.1: Hardware and software layout

4 Design

This chapter contains a description of all components in the framework. First, the design decisions are discussed, after which the implementation is highlighted together with an evaluation of the added components.

4.1 General design

The framework needs to be able to run multiple real-time tasks in parallel. Using dedicated cores to perform tasks increases the control over the task distribution in a machine.

Bruyninckx et al. (2019) discuss a pattern of the composition of (a)synchronous threads. This architecture is shown in Figure 4.1.

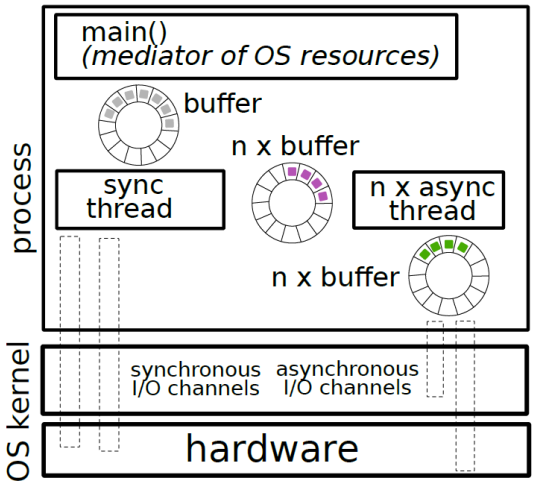


Figure 4.1: Multi-threading architecture as described in Bruyninckx et al. (2019)

It consists of at least three threads, all with varying capabilities. The architecture's main aim is to make sure that an important thread can run without being interrupted or blocked. The three different thread templates are listed below.

1. **The *Main* thread** This thread starts the other threads and manages its memory. When real-time threads would manage their own memory, it could cause latency or even failures. The thread affinity and priority are set from within the main thread. Also, I/O is assigned to these threads when necessary. Figure 4.1 shows a buffer between main and the synchronous thread; however, this is unlikely to be used since the main thread is used for initialization and not for data input.

2. **The *synchronous* thread** This thread is running on its own core and handles the core activity of the application. This thread should never block because that might produce delays that are unwanted in real-time loops. The communication from this thread to hardware should only happen when the communication protocol is real-time capable.

3. **The *asynchronous* thread(s)** This thread or multiple threads are functioning as peripheral tasks for the synchronous thread. They can also provide the synchronous thread with data from non-real-time inputs. These threads can be blocked to handle blocking tasks such that the synchronous thread does not have to. There is a buffer between the

synchronous thread and its asynchronous threads such that the data can be read on a self-set time by the synchronous thread.

The asynchronous thread can be used to receive user input or to output logging data onto a non real-time communication protocol.

This system architecture gives a solid base structure for the further development of the framework.

The framework introduced in this thesis implements a variation on the architecture of Bruyninckx et al. (2019). It consists of a class structure that contains the various communication protocols and thread-creation code. Next to that, a wrapper class is used to encapsulate 20-sim code. ROS2 is linked to the framework using XDDP communication that crosses from non-real-time to real-time. The class system is set up such that it can be used with various purposes in mind and not solely for the deployment of a model + plant setup.

The 'main thread' from Bruyninckx architecture is implemented to create the various threads that need to be run together with the affinity and their priority. Moreover, the connection between the different threads is defined in the main code. In this manner, the exact amount of memory that is needed for the communication buffer is allocated before the thread is started. Controlling a physical plant is out of scope for this thesis. The design must nevertheless be made with this expansion in mind.

The asynchronous threads are not implemented at this moment but can be used later on to interact with blocking tasks or communication protocols such as UDP or ethernet.

The synchronous thread represents the main controller when working with a plant or some other form of real-time task. The requirements state that there must also be room for multiple controller tasks. Therefore it is necessary to extend Bruyninckx et al. (2019) architecture. Multiple synchronous threads can be created and placed on different cores. When working with multiple synchronous threads on one core, the priorities must be set with performance drops in mind. The highest-priority task must receive the highest scheduling priority. With a restriction that only one thread can receive the maximum priority.

A ROS2 node provides the conversion from real-time to non-real-time. This conversion is done by using two different node types. One provides reception of real-time data and publishes this to a topic. The second type of node receives data from a topic and sends that to the real-time task.

RTIPC is used between the different CPU cores and tasks. The cross-kernel RTIPC protocol implements a buffer that can be read from both real-time and non-real-time sides. An example of the complete framework architecture is shown in Figure 4.2.

The following sections go into more detail on the real-time design and the non-real-time design.

4.2 Real-time design

This section contains the explanation for the complete class structure created in this thesis. Moreover, it describes the steps to set up a communicating real-time task structure. Firstly, the complete structure and classes are described minimalistic to give the reader a birds-eye view. The subsequent subsections dive into the details of each part.

The main goal of this thesis is to run 20-sim generated tasks in a real-time environment and let them communicate with ROS2. 20-sim produces its own generated code in the form of a class structure. This class structure contains the necessary functions to execute the built model.

Figure 4.3 shows the complete class diagram, including a 20-sim and user-task implementation. The different classes are shortly discussed below.

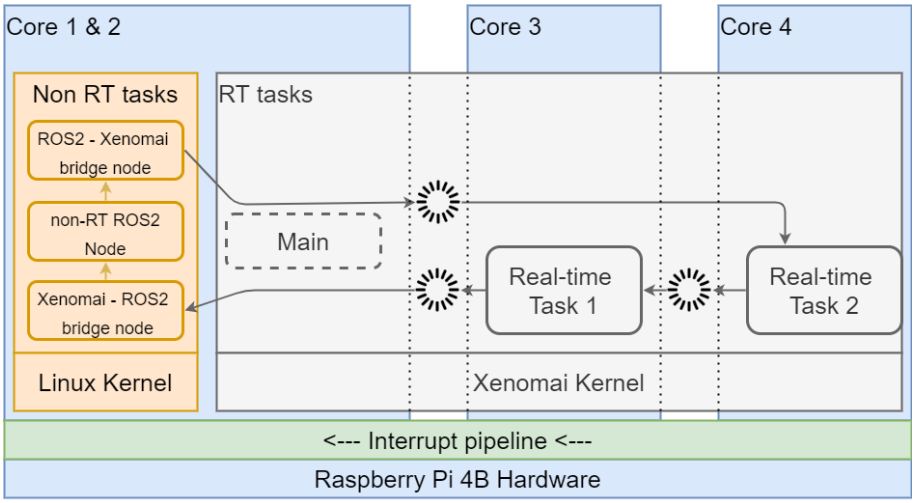


Figure 4.2: Example setup of the complete framework architecture.

- **`runnable`**
  `runnable` is the glue of the class structure. It is a class with merely pure virtual functions which have to be overwritten by derived classes. This function then provides an interface for `xenoThread` to execute and start a thread with.

- **`wrapper20`**
  This is one of the possible derived classes of `runnable` and the one most used in this thesis. It implements a 20-sim task in the interface form that is presented in `runnable`.

- **`xenoThread`**
  `xenoThread` can be used with any `runnable` derived class. Afterwards, `xenoThread` can initialize and start a real-time thread.

- **`frameworkComm`**
  The inter-task communication is handled by `frameworkComm`. This class is created and initialized previously to handing to a `runnable` derivate. This class is not mandatory to use since it is given as a private object to the derived class. `wrapper20` uses this communication class to communicate to other `wrapper20` based 20-sim classes. It is possible to use it in a user-made task; however, the implementation needs to be tailored for each individual task and needs to be written inside the user-made `runnable` derivative.

4.2.1 Framework setup

The task that needs to be executed in real-time needs to be shaped in the form of predetermined functions. These functions are all implemented in the virtual base class `runnable`.

All `runnable` functions are all declared as pure virtual, such that any class that inherits from `runnable` must overwrite these. The main strength of this solution comes from polymorphism. Polymorphism allows the use of the abstract base class as a public interface instead of the individual types. Subtype polymorphism has another key feature: the pointer to a derived class is type-compatible with a pointer to its base class.

Any `runnable` derived class can then be initialized as a pointer with the type of `runnable` itself. This allows easy use with the thread class `xenoThread`, explained in Section 4.2.2.

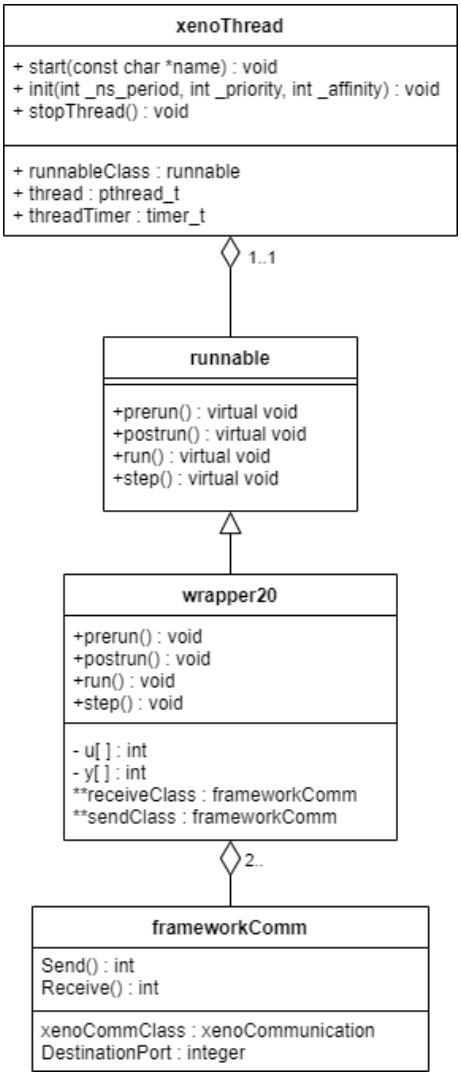


Figure 4.3: Complete simplified class diagram of the framework

Figure 4.4 contains two examples that can be derived from `runnable`. One is the `wrapper20` that is used for 20-sim classes and the other is `ownThread`, which can be used for own implementations. `wrapper20` is further explained in Section 4.2.4.

The main functions in `runnable` are:

- `prerun()` Initalizes all variables within the derived class and prepares for execution.
- `run()` Implementation for continuous execution of the derived class. Should include own timer implementation and `await()` statements. `xenoThread` does not call this function and its unused in the current framework setup; however, its included for completeness.
- `step()` Implementation for one-time execution of the derived class. When periodically calling this function, it operates similary to `run()`.
- `postrun()` Concludes the execution of the derived class. This function contains any finalizing computations that have to be done before class destruction. The class destructor is called with the virtual destructor of the `runnable`.

Section 4.2.4 describes the use of `wrapper20` which uses `u` and `y` as its task variables. For the example given in Figure 4.4, `ownThread` is also given these variables. The derived classes are

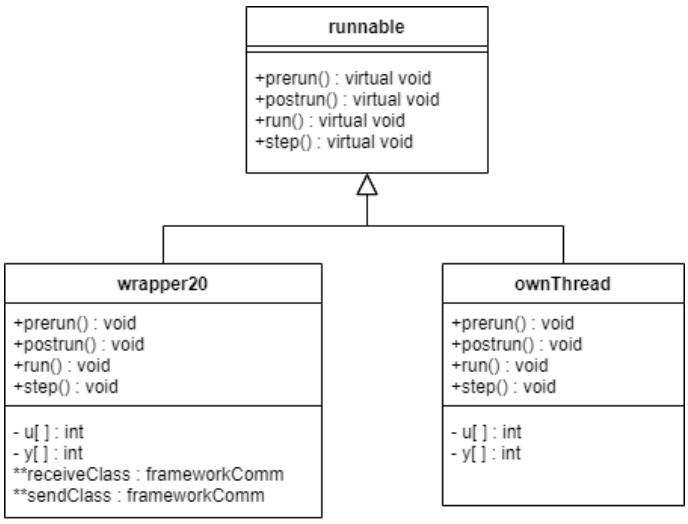


Figure 4.4: Example class diagram of `runnable`, reduced functionality described

free in their variable choice, since only the pure virtual functions of `runnable` are used in the `xenoThread` class. This class is described in the next subsection.

When creating a new task set to be given to `xenoThread`, its type must be `runnable`. This is done in the following way:
`runnable *controller_runnable = new ownThread(int a, int b);`
int a and b are random arguments for the sake of this example. When working with the 20-sim wrapper, the initialization is different from this example. Further details on this in Section 4.2.4.

4.2.2 Thread management

The framework's thread management part exists out of a class that creates the thread environment for a `runnable` derived task. The thread creation class is called `xenoThread`. The `runnable` is handed with the `xenoThread` constructor. `xenoThread` calls upon the virtually declared functions within `runnnable` and therefore can accept any `runnable` derived class. The class diagram of `xenoThread` and `runnable` is shown in Figure 4.5. This figure takes `wrapper20` as derived class.

After `runnable` is given with the constructor of `xenoThread`, the `xenoThread` can be initialized with three variables.

`xenoThread::init(int ns_period, int priority, int affinity)`

The `init` function accepts the period on which the task runs in nanoseconds, its priority within the Xenomai scheduler, and its CPU affinity. The listing below shows the three steps to start a thread using `plant_runnable` as `runnable` derived class.

```
xenoThread plantThread(plant_runnable);
plantThread.init(1000000, 80, 1);
plantThread.start("controller");
```

Listing 4.1: Initalization of `xenoThread`.

The thread is started using `xenoThread::start(std::string threadName)`

Timing is done from within `xenoThread`. The `xenoThread` class calls upon the `step()` function of the `runnable` after which the timer await is called. The affinity of the thread is set before the thread is started to prevent temporary running on incorrect cores and affinity switches while running time-sensitive code.

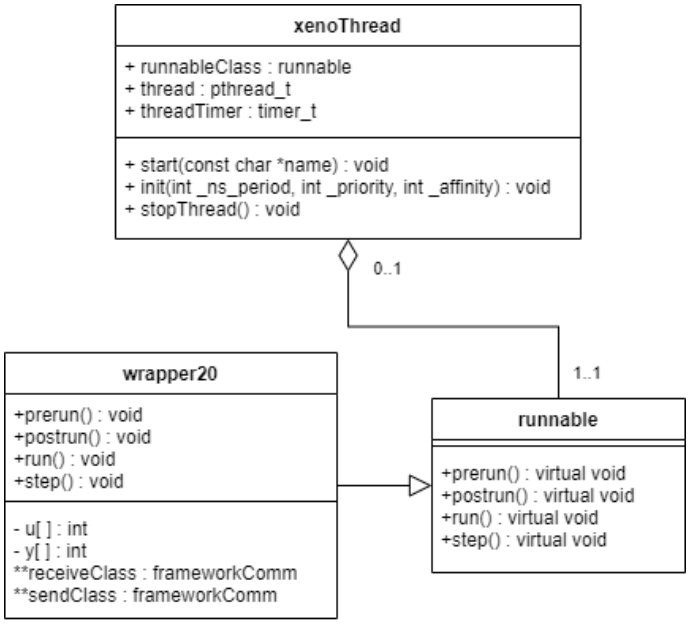


Figure 4.5: Class diagram of thread class architecture

4.2.3 Communication

This subsection is focussed on the functioning of communication within the `wrapper20` class. This class is described in more detail in Section 4.2.4. The functionality could be implemented similar to this in other task classes, such as `ownThread`.

When working with real-life plants, the control loop must work correctly from start to finish. Therefore, no mode-switches may happen after the threads have started executing. Because of this, initialization of the communication protocols is done before starting their respective threads. Another reason for communication initialization in 'main' is to simplify all task creation and put it in one visible code. This way, it is possible to create a ready-to-go code from within a 'main' code without changing real-time threads independently.

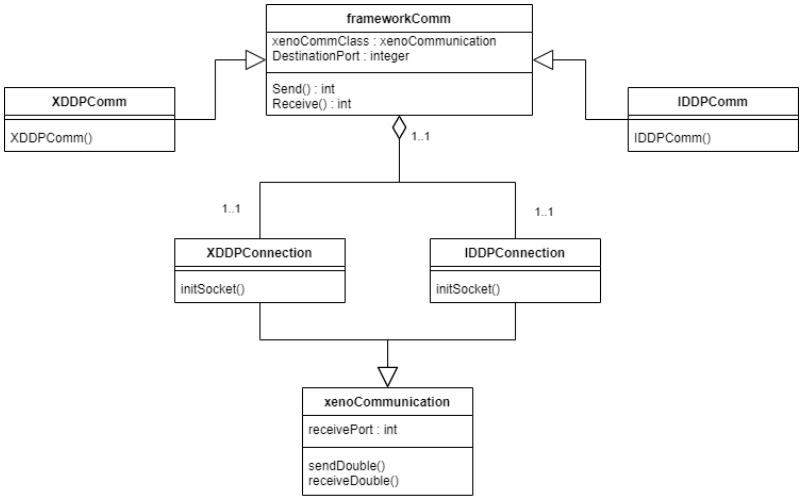


Figure 4.6: Class diagram of communication protocols

Figure 4.6 shows the class diagram of the framework's communication part. The IDDP and XDDP base communication is handled by their respective classes: `XDDPConnection` and `IDDPConnection`. These contain base functions such as `sendDouble()` to send doubles via an RTIPC protocol.

Each `frameworkComm` creates its own RTIPC connection. Figure 4.7 shows that `frameworkComm` has a uni-directional association with `XDDPConnection` or `IDDPConnection`. This type of association should be interpreted as a "has a" relationship, meaning that every `frameworkComm` has a `(XDDP/IDDP)Connection`.

`frameworkComm` provides both IDDP and XDDP with base function declarations, such that they can be used within `runnable` derived tasks.

Communication between tasks is initialized via the following steps:

1. **Task variables**
   `wrapper20` uses an input array (`u[]`) and an output array (`y[]`). The task uses the elements from `u[]` as input for computations and stores the results in `y[]`. Elements from these arrays are called the task variables.
   There are also n communication channels in a task.
   Data is received and put in elements of `u[]` and sent from elements of `y[]`.
   To explain the communication process in more detail, an example with two tasks is used. It contains two real-time tasks: a controller and a plant. They communicate mutually and also log their data to a non-real-time task. The controller receives setpoints from a non-real-time task and processes them. Moreover, it receives current plant information. Figure 4.7 and Figure 4.8 visualize this example.

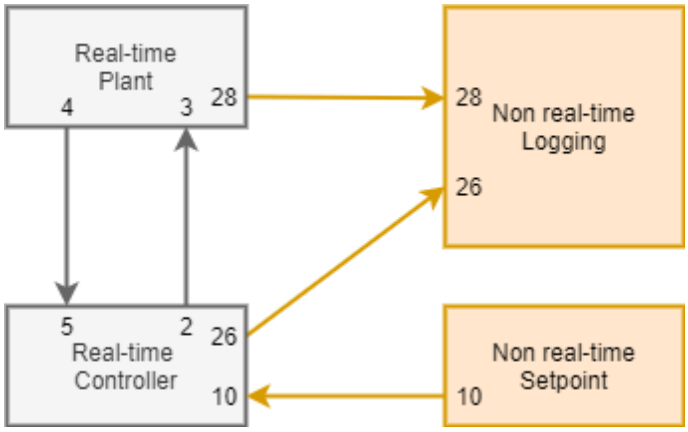


Figure 4.7: Block diagram of communication example with communication ports

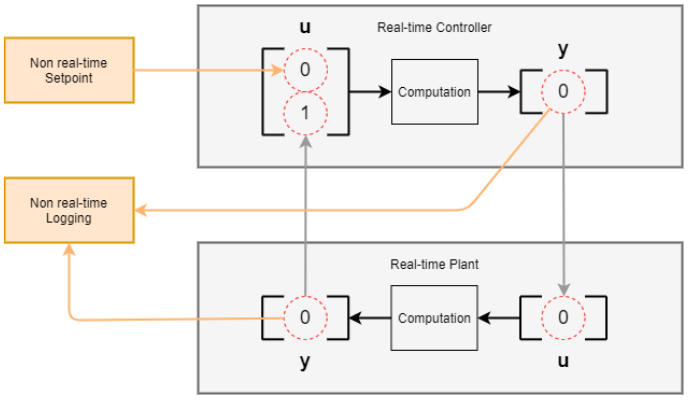


Figure 4.8: Block diagram of communication example with task variable indexes

Figure 4.7 shows a layout with two real-time tasks and two non-real-time tasks. The real-time tasks are communicating with each other via IDDP (grey). Both real-time tasks also log their output to a Logging thread in non-real-time via XDDP (orange). Next to this, the

Controller thread receives setpoint data from a setpoint thread. The numbers next to the communication arrays represent the input and output ports.

2. **Element parameters**
   Every timestep, the task receives and sends data from the the task variables. Which index the data is put on to or taken from is described in input/output parameters. This data can be put into `frameworkComm`'s child classes when creating them.
   An `(IDDP/XDDP)Comm` class takes an array of element parameters, an input and an output port, and the number of element parameters. The element parameters define on which index of the task variable array the incoming/outgoing data is set or taken from.
   When looking at the example in Figure 4.8, the real-time controller has two inputs and one output. The one output is being sent to two different addresses.
   Resulting, the Controller task needs four `frameworkComm` Connections. All connections are singular, meaning that only one variable is received and put on one index. This results in four parameter-arrays with only one variable in each.
   The input from the Setpoint thread is set to go on index 1 of the task variables array. The input from the plant is set to index 0. There is only one output; however, it needs to be sent to both the plant and the logging thread. The indexes of `u[]` and `y[]` are also shown in Figure 4.8.
   This results in the following parameter arrays:

```
int iddp_uParam_PlantData[] = {0};
int xddp_uParam_Setpoint[] = {1};
int iddp_yParam_ControlOutput[] = {0};
int xddp_yParam_Logging[] = {0};
```

Listing 4.2: Creation of communication parameters

3. **`frameworkComm` creation**
   The next step involves the assignment of port numbers and the parameter size. To use this communication class structure, the task receives one or multiple arrays of `frameworkComm` derived pointers. These all indicate one connection either going in or out of the task.
   When this communication protocol is used, an array or multiple arrays of `frameworkComm` pointers is given to the derivate class of `wrapper20`. These `frameworkComm` classes are initalalized with the following arguments:
   `(IDDP/XDDP)Comm(int ownPort, int destPort, int size, int parameters[]);`
   An XDDP connection sends to its own address, whereas IDDP connection needs to send to a different address. The addresses are identical to the example in Figure 4.7. The `frameworkComm` arrays are initalized as shown below:

```
frameworkComm *controller_uPorts[] = {
        new IDDPComm(5, -1, 1, iddp_uParam_PlantData),
        new XDDPComm(10, -1, 1, xddp_uParam_Setpoint)};
frameworkComm *controller_yPorts[] = {
        new IDDPComm(2, 3, 1, iddp_yParam_ControlOutput),
        new XDDPComm(26, 26, 1, xddp_yParam_Logging)};
```

Listing 4.3: Creation of `frameworkComm` derived pointers

It is also possible for a task to instantly send multiple values to another task. This is done by declaring multiple arguments and setting the right size when initalizing the `frameworkComm` pointer.
The size of the `u` and `y` parameters is predetermined by the model that is used, passed on with the creation of `runnable`. In this case, `u[]` has length 2 and `y[]` length 1.

4. **Use with threads**
   After the threads are created, the `uPorts` and `yPorts` are handed to the `runnable` constructor.
   Furthermore, the size of the arrays is given to the thread, since C++ arrays are not self-conscious about their length. `std::vector` is not used since they are not real-time friendly because of their variable length and exceptions that they can rise. the uPort and yPort arrays are given to the `wrapper20` in Section 4.2.4, specifically in Listing 4.4.

4.2.4 Model management

20-Sim is used as modelling language, and supports c++ code generation from its model software. This C++ code contains a class structure with all the common capabilities and a top class with the main task functions. The main functions are `Initalize()`, `Calculate()`, and `Terminate()`.

As described in Section 4.2.1, `runnable` is a base class which executes various tasks. To execute 20-sim C++ code, `wrapper20` is used. This is a class which is derived from `runnable` used to run 20-sim generated classes. In the following sections a typical 20-sim class is called `Controller`.

To ensure that `wrapper20` functions with all different 20-sim classes, `wrapper20` is declared with a C++ `template`. The template is filled during compilation and therefore the `wrapper20` class does not have to be declared with one 20-sim C++ class. `wrapper20` is initialized as follows, in the case that the user wants to use the 20-sim class '`Controller`'.

```
Controller *controller_class = new Controller;
runnable *controller_runnable = new wrapper20<Controller>(
      controller_class, controller_uPorts,
      controller_yPorts, uPorts_length, yPorts_length
);
```

Listing 4.4: Creation of of `wrapper20` class.

First of all, a pointer to a `Controller` is created. This pointer is then given with the initialization of `wrapper20` with as type `runnable`. The template of `wrapper20` is specified with the type of `controller_runnable`. This `wrapper20` can then be used when creating `xenoThread`, as in Listing 4.1

Listing 4.4 shows that `controller_uPorts` and `controller_yPorts` from Listing 4.3 are given to the constructor of `wrapper20`. The uPorts are put onto `receiveArray` and the yPorts onto `sendArray`.

After the `xenoThread` is initialized and started (Listing 4.1), the following operations are executed.

1. Receive data with the `receiveArray` that was passed to the `runnable`.

   ```
   for (int i = 0; i < receiveArraySize; i++)
         {
               receiveClass[i]->receive(u);
         }
   ```

   Listing 4.5: Receiving data via the receiveArray, initalized in Listing 4.4

   In Listing 4.5, all elements of the `receiveArray` are called to perform function `receive`. Since the `frameworkComm` already knows how much information it is going to receive, the complete task variable array `u` is given as variable to the `receive` func-

tion. The parameters given with the `frameworkComm` constructor are used to identify on which index of `u` the received data must be written.
2. Calculate the tasks response with the newly received data. This is done by calling the `calculate()` function within the 20-sim generated class.
3. Send the results from the calculated data. This is similar to Listing 4.5, only with `sendClass` and using `send()`.
4. Await timer to start over. This functionality is implemented in the loop function of `xenoThread`.

The reason for this order is the performance difference. When working with real-time models and plants, reaction time is very important. A period-old value from a sensor could already be worthless if the output of the controller changed during that period. Therefore the input values are read before execution.

Operation 1-3 happen in the `step()` function of `wrapper20` and operation 4 happens within `xenoThread`. This particular division is made to ensure that all thread related operations are performed within the `xenoThread` class and all model/task related operations within a `runnable` derived class.

4.3 Non-real-time design

ROS2 functions as the connection point from real-time to non-real-time. A ROS2 package is built to connect to the pseudo-device created by the XDDP connection from the real-time task. There are two different ROS2 nodes:

- **Receiving node**
  The receiving node connects to the XDDP port and receives all data that is sent from the real-time side. This information is type converted and published on a supplied topic.
- **Sending node**
  The sending node receives data on a topic after which sends it to a supplied XDDP port.

When controlling an actual robotic setup, a sequence controller sets the setpoint for motor movement. Most likely, there will be external inputs into the sequence control, such as user inputs or automated image recognition loops. ROS2 provides an excellent base to create this sequence control loop. A connecting node is built to ensure a complete connection from real-time to non-real-time. This connecting node receives data from the receiving node and process this. This information is then combined with data from other ROS2 nodes that provide general setpoints or other input data.

A complete example is shown in Figure 4.9.

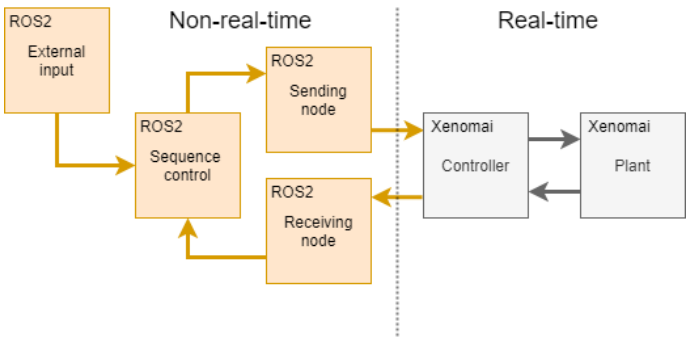


Figure 4.9: Example of plant-controller setup with ROS2 integration

The receiving node requires a sending topic and a port to listen to, while the sending node needs a topic to listen to and a port to send information via XDDP. These parameters are

handed with ROS2 command line parameters. These allow a user to start a node with their parameters. A listening node can be set up as such:

```
ros2 run ros2-xenomai listener --ros-args -p "topicName:=receivedData"
-p "xddpPort:=26"
```

and a sending node:

```
ros2 run ros2-xenomai talker --ros-args -p "topicName:=sendData"
-p "xddpPort:=10"
```

5 Testing method

5.1 Introduction

In the final part of this thesis, the framework is subjected to performance analysis. These are performed to determine if the requirements are fulfilled and if the main goals of this thesis are achieved. Latency tests are done to access the real-time performance of the framework.

5.2 Test setup

To access the performance of the framework, a setup with two real-time tasks is used. One simulates a real-life robot used by the University of Twente for educational purposes, called 'plant' from now on. This robot, called JIWY, consists of two motors that each control the gimbal that gives the webcam 2 degrees of freedom. The JIWY robot is shown in Figure 5.1.

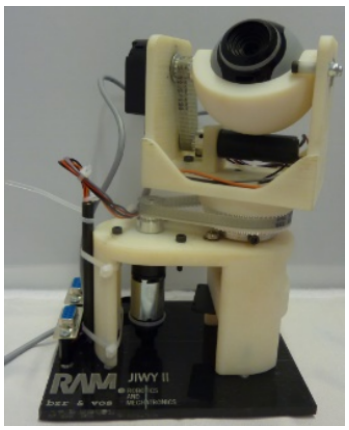


Figure 5.1: JIWY robot setup at the University of Twente

Controlling the real-life robot is out of scope for this thesis; however, as mentioned, a simulated model is available. A controller is designed to control the JIWY robot. Both are made in the 20-sim modelling software.

Both the controller and the plant run at 1000Hz as specified in the requirements. This corresponds to the refresh rate when controlling a physical JIWY robot.

A period is measured by toggling a GPIO pin or a timing signal after the computations are done. The change on the GPIO pin or timing signal can be registered by a logic analyzer. The difference between the previous measurement and the most recent is the length of the period.

`xenoThread` possesses a specific function for jitter measurement via General Purpose In Out (GPIO). `enableGPIOTiming()` enables a GPIO toggle every time a period is completed. This makes this GPIO pin suitable to be read with a logic analyzer to determine jitter.

A separate Raspberry Pi is used to function as the logic analyzer with the software from PiGPIO (PiGPIO, 2021). Due to corona restrictions, the laboratory at the university was unavailable during the time span of this thesis. Although the Raspberry Pi is functional as a logic analyzer, its accuracy is questionable.

Another manner in gathering timing information is to let the thread retrieve the system clock. This clock is the most accurate clock on the Raspberry Pi; however, the native system-call to retrieve the necessary information is not. Luckily, Xenomai implemented a real-time-friendly call to receive the time with `clock_gettime()`. Next to this, Xenomai 3.x.x also implements a real-time-friendly version of `printf()`, included in its Posix skin.

`rt_printf()` works using a circular buffer, which overwrites itself when there are too many items in the buffer. This command is usually used with printing status information and other logging statements; however, it is not meant for printing multiple lines every 0.001s. Therefore it is better to use communication to send them to the non-real-time environment. Afterwards, these retrieved items can be put in a Comma Separated Value file (CSV).

An external non-real-time thread provides setpoint info to the controller. A similar thread is used to receive timing information and save that for analysis. Both these threads are standard linux threads and connect to the XDDP pseudo-device. The block diagram of the setup is shown in Figure 5.2. The core affinity is not shown in this figure since it is adjusted in the different tests.

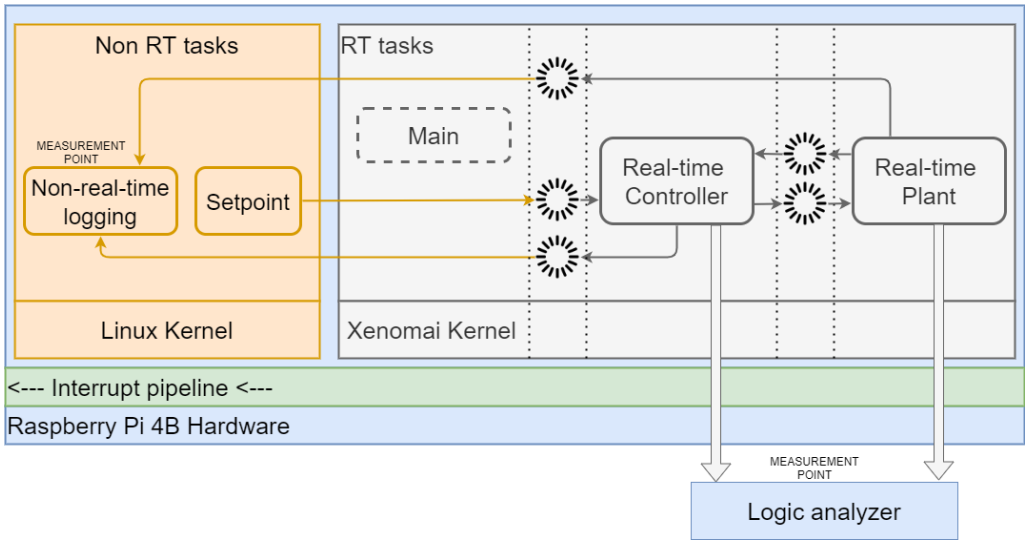


Figure 5.2: Test setup block diagram

5.3 Test method

Section 2.2.3 describes different manners for testing the jitter of a system. Since update rate is most important when controlling robotic systems, long period jitter is of lesser importance. When the clock drifts ever so slightly, the performance of the controller does not suffer. However, when jitter appears as significant cycle-to-cycle jitter, the performance of the robot will be affected.

5.3.1 Measurement accuracy

Before testing, the accuracy of the measurement tools needs to be validated. The `gettime()` statement is used to measure the complete jitter spread and is afterwards checked by overlaying it with the Raspberry Pi logic analyzer results. If these seem identical, one can assume that `gettime()` is accurate enough.

5.3.2 Functionality

Once the accuracy is validated, the functionality of the framework can be tested. To check if the framework can produce the same results as the modelling tool that created the code, the results of the modelling tool simulation and the results produced by the framework can be compared. This will show if the framework can replicate simulated results.

To determine the performance of the framework, the optimal performance mode needs to be found. This is done by using tests that change the core isolation and affinity of the real-time threads.

5.3.3 Performance

Core isolation Core isolation is set in the boot instructions of the Linux OS. These instructions determine which cores the Linux kernel cannot run. The 'xenomai supported cpus' instruction determines which cores the Xenomai kernel will run. Therefore to have an equal spread over the cores, we need to isolate two cores and allocate them to Xenomai.

`isolcpus=0,1 xenomai.supported_cpus=0x3` is added to `cmdline.txt` to enable core isolation. These steps are also included in Appendix A. This shields Linux from cores 0 and 1 and will put Xenomai on these. The 0x03 represent the binary number '0011', which indicates the first two cores.

Core isolation testing will research the difference in performance due to the task's core. This is tested with and without core isolation.

The core isolation tests are described below:

- A Xenomai thread is run on a core which is isolated from the Linux kernel.
- A Xenomai real-time thread is run on a core which is not isolated but shared with the Linux kernel.

Core affinity The affinity of the task can be set from within `xenoThread`. This enables the user to put specific tasks on specific CPU cores. When a user sets the affinity of a real-time task to a core that is not specified for Xenomai, the scheduler will correct this and place the task on any of the defined cores.

From pre-running the framework, it is clear that the main thread is visible and running in both the Xenomai and the Linux domain. The full test can be seen in Appendix C.

- Both real-time tasks are run on the same core. This core is also used by the main thread.
- Both real-time tasks run on the same core; however, this core is not the same as the Xenomai main thread.
- The real-time tasks are separated on different cores, One on the core with the Xenomai main thread and one on a separate core.
- The real-time tasks are separated. Both task run on different cores, the Xenomai main thread runs on a separate core.

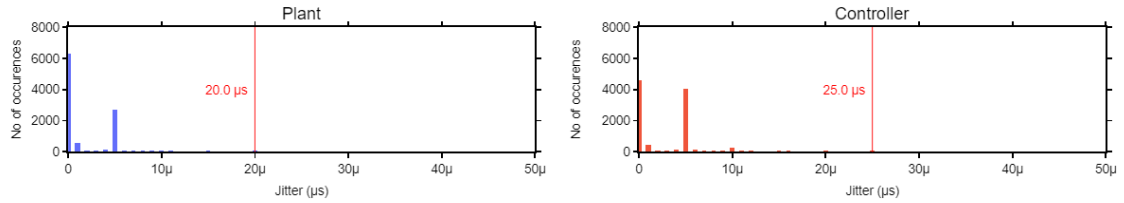
Stress All previous tasks are performed within Xenomai's kernel. Stress is added to the Linux kernel to check the performance of the Xenomai tasks when Linux is stress tested. The performance of the controller and plant could be a hint towards its performance when running ROS2 simultaneously. Stress is added using the stress-NG library made for Linux. Within this stress-tool, the `taskset` property is used to pinpoint stress tests to certain cpu's. The scheduling option `sched` is set to 'other' to prevent interruption with the Xenomai scheduler.

6 Results

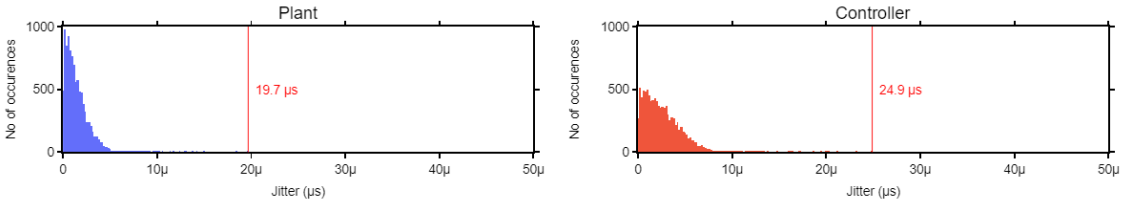
This chapter shows the results of testing the framework. The tests are described in Chapter 5. Furthermore, some basic functioning of the framework is shown in Section 6.2. This includes the basic controller-plant layout and some ROS2 functionality. The results are shown, explained, and discussed in the same chapter to make the information more compact. The complete code is shown and explained in Appendix C. This chapter includes snippets from this 'main' code, simplified to make presenting them more concise.

6.1 Measurement accuracy

To determine if the testing setup is sufficiently accurate to measure the timing of the framework's real-time threads, an accuracy test is performed. A controller-plant setup is run with the framework while both the Raspberry Pi-powered logic analyzer and the `clock_gettime()` command log the timing information of a thread. The results of these measurements can be seen in Figure 6.1. The configuration of the setup does not matter in this instance.



(a) Output from the Raspberry Pi logic analyzer



(b) Output obtained using the `clock_gettime()` command.

Figure 6.1: Jitter performance of the controller and plant from both internal clock measurement (a) and logic analyzer (b).

As seen in Figure 6.1 the resolution of the logic analyzer is approximately 1μs. The logic analyzer seems to round to 5μs. Compared to `gettime()` this is a significantly lower accuracy. In Figure 6.1b the visible accuracy is limited by the size of the histogram bins.

The maximum jitter is shown with a vertical red line when this is within the range of the graph. When it is outside of the range, the arrow and subscript indicate the maximum jitter.

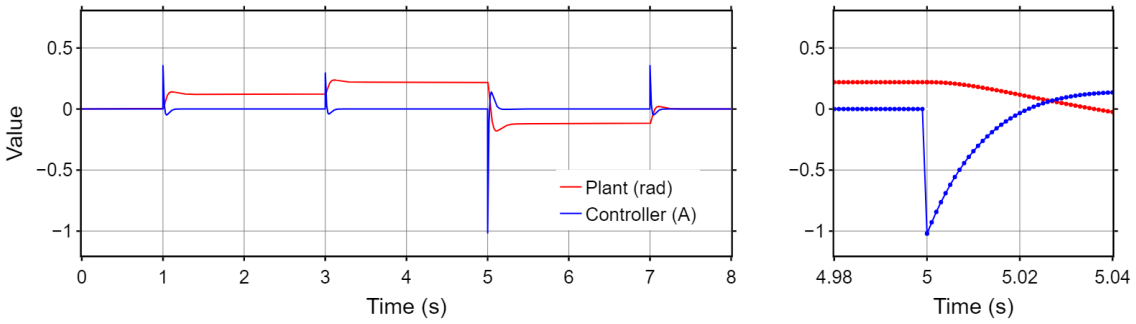
The histogram bin size is chosen such that the comparison between the logic analyzer and the internal clock is adequately visible. The difference between Figure 6.1a and Figure 6.1b is mainly in resolution. The results are approximately the same which is visible in a similar maximum jitter.

The following tests in this chapter will be shown using internal clock measurements. The results are still double-checked with the logic analyzer. This double-check is done to make sure that the maximum jitter measured by the internal clock is not significantly above or below the logic analyzer.

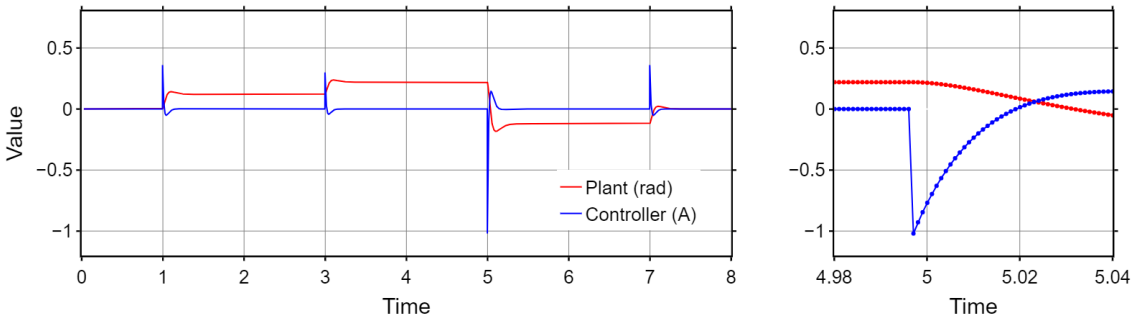
When measuring jitter the first and last few samples can be the cause of a high maximum jitter since the code has to start up and finish up in those periods of time. This is also measured when using both the `clock_gettime()` statement or the internal clock measurement. Therefore, the first 20 samples and the last 20 samples of each measurement are removed to prevent unrealistic maximum jitter.

6.2 Functionality

First of all, the framework must be able to execute a 20sim task. This is done by using `wrapper20` as described in Chapter 5. For the controller-plant test, only one of the two inputs is used. The JIWY has two motors that correspond to the pan and tilt of the webcam. During the performance tests, only the pan input is used. An example output of the JIWY plant and the controller as simulated in 20-sim can be seen in Figure 6.2a.



(a) Output of JIWY simulation in 20-sim



(b) Output of JIWY simulation with framework generated threads

Figure 6.2: JIWY-setup simulated outputs both from 20-sim simulation (a) and the framework's output (b) with identical setpoint data.

The framework is set up as described in Section 4.2.3 and specifically Figure 4.7. The Real-time controller and plant are the 20-sim generated code combined with the `wrapper20`. The results of the controller and plant are sent to a non-real-time task that receives and logs them. The output of this setup is shown in Figure 6.2b. Figure 6.2 a and b are nearly identical, except for the framework's output which is slightly ahead of the 20-sim simulated output in Figure 6.2b. This is due to the fact that the setpoint thread is activated at the moment that the XDDP-port opens and not at the moment that the thread is started.

6.3 Performance

To check what influence core affinity has on performance, various tests as described in Chapter 5 are executed.

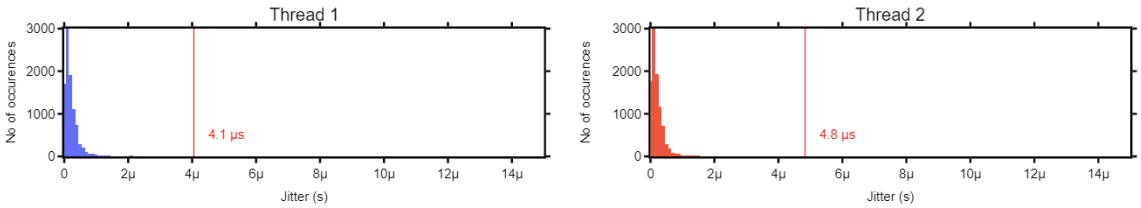
6.3.1 Core affinity

Figure 6.1 shows the results of a jiwy simulation when running the controller on core 0 together with the main thread and the plant on its individual core 1. The difference is clearly visible between the shared core and the individual core. The controller is placed on the shared core with the main, which results in more jitter from 5μs to 10μs.

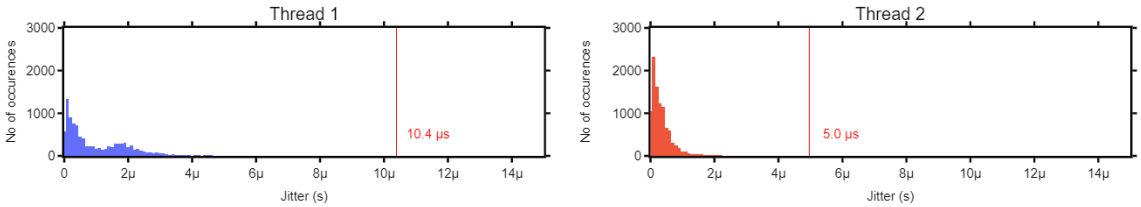
Subsequent tests are performed with the controller on the individual core and the plant on the shared core; however, the maximum jitter stayed similar to the results in Figure 6.1. This proves that the controller/plant setup is not suitable to measure core affinity performances since their individual task performance is different.

The logical step is to instruct the framework to start two similar threads. This way, the two can be compared more fairly. This is done by using a prime number calculator. A small piece of code is put into two threads that calculate all the prime numbers up to a certain point. To implement this, `runnable` is used to create a new class, called `ownThread`.

Two threads with prime calculations up to 700 are run simultaneously. More calculations per period are not feasible on the Raspberry Pi, since the processor is not able to process both at the same time. Prime calculations up to 700 give the task room to calculate these primes, send XDDP timing information, and toggle GPIO pins. The result for two different core layouts with two threads running on 1kHz is shown in Figure 6.3.



(a) Thread 1 and thread 2 on the same core, not shared by main



(b) Thread 1 on a shared core with main and thread 2 on an individual core.

Figure 6.3: Timing results when running two threads that are calculating prime numbers up to 700 every 0.001 seconds.

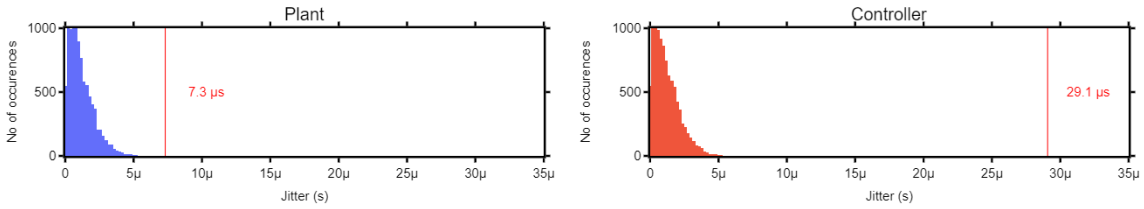
Figure 6.3a shows two threads running on identical cores. This is an isolated core on which nothing is set to run, not even the main thread. Therefore the performance of threads 1 and 2 is similar.

The results in Figure 6.3b show the jitter results from running on two different cores. Thread 1 is running on core 0 together with the main thread and thread 2 is on core 1. The main thread is also using processing power on core 0, which is visible in the spread in jitter of thread 1.

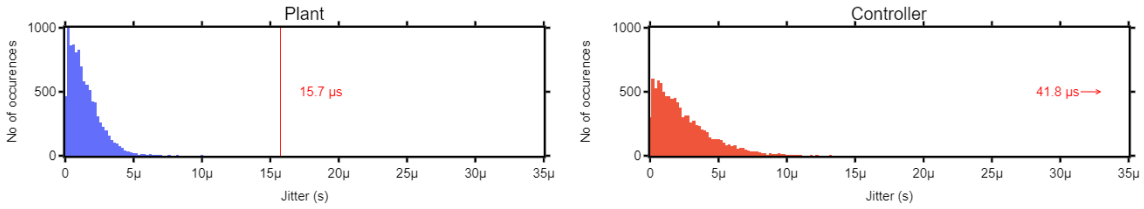
6.3.2 Core isolation and stress

Core isolation can be measured using the controller/plant layout when a base for measurement is set from the beginning. To prevent the main thread from influencing the test results, it is set to run on a separate isolated core.

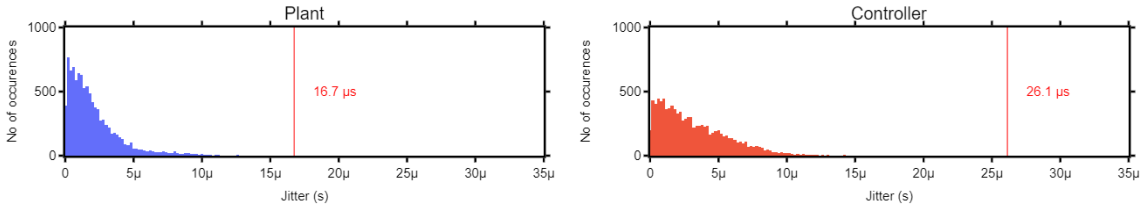
Therefore, three cores are used for Xenomai in the first test, running either main, controller, or plant. This result is shown in Figure 6.4a. The second test changes the Xenomai usage from 3 to 2 cores. The results can be seen in Figure 6.4b. To check whether Linux influences the performance of tasks running on the same core, the third test includes stressing the second core. The final test is shown in Figure 6.4c.



(a) Plant on core 1, Controller on core 2, main on 0. Core 0, 1, and 2 are Linux isolated.



(b) Plant on core 1, Controller on core 2, main on 0. Core 0 and 1 are Linux isolated. Core 2 is shared with Linux.



(c) Plant on core 1, Controller on core 2, main on 0. Core 0 and 1 are Linux isolated. Core 2 is shared with Linux. Stress is applied to Linux.

Figure 6.4

The controller in Figure 6.4c shows a similar result to the plant in Figure 6.1. Both are on an isolated core with approximately similar performance. The plant results in Figure 6.4 are all on an individual core which is visible with almost identical results.

The difference can be seen when looking at the controller. The isolation influences the performance of the task significantly, as seen in the difference between (a), (b), and (c) in Figure 6.4.

6.4 Discussion

As discussed in Appendix C, first pointed to in Chapter 4, the main thread is not only present on the Linux kernel. The main thread also runs on the Xenomai side, which shows when running another thread on the same core as the main thread. The main thread was expected to only run in the Linux domain; however, when calling Xenomai threads from code, it will show up in the Xenomai scheduler and therefore is able to run on Linux isolated cores.

The Raspberry Pi logic analyzer underperformed since it is almost only useable for determining the maximum delay and examining if the internal clock results match that of the logic analyzer.

Figure 6.4 shows the result of changing the isolation of cores of the controller task. The plant in Figure 6.4b and Figure 6.4c have slightly higher jitter, which is probably caused by the delayed messaging from the controller thread. The results of the controller task are expected since the cores are shared in Figure 6.4 b and c. Therefore, when a real-time task is on a shared Linux-

Xenomai core, the task is sometimes interrupted by Linux interrupts. This can cause higher jitter values.

The quantitative requirements that were set describe that the maximum jitter may not be above 3% of the period. Moreover, the number of deadline misses should not be above 0.01% of the number of periods. The performed tests were all analyzed on a sample of 10.000 periods, resulting in a total number of allowed deadline misses of 1. The maximum jitter that would not cause a deadline miss is in this instance: $0.001s \cdot 0.03\% = 30\mu s$.

When looking at Figure 6.4b the maximum jitter crosses the threshold, which results in a deadline miss. This effect can not be seen in Figure 6.4c, which could prove that the deadline miss in Figure 6.4b is a one-time event. In all three measurements in Figure 6.4, the plant thread does not have any jitter higher than $30\mu s$.

7 Conclusion

7.1 Conlusion

The goal of this thesis is to create a framework that integrates real-time task functionality and ROS2. Modelling software integration is also a requirement to enable the framework to run premade controllers and plants. The framework has been built with these goals in mind. Hardware and software options have been analyzed and selected to focus on availability and ease of use. In the end, the Raspberry Pi together with the Xenomai real-time kernel is used. The class system, in combination with the ROS2 package, creates an accessible entry point for real-time programming. To test if the framework suffices the requirements, period jitter has been measured. The results show a sufficient real-time performance with jitter being below the set 3%. Error handling is implemented in the form of adequate print statements, which translate the state of the threads. These results prove that the framework is suitable to be adapted for real-life robotic systems and is suitable to perform hardware simulations of robotic hardware.

7.2 Future work

The framework functions on a base level; however, to provide wide useability for various platforms, the framework requires future work. Small programming work is needed inside the framework to fit it to the need of the course 'Real-time software development'. Items such as error handling and logging functions need to be updated to be ready for larger systems. On a similar note, there are some redundant classes that can be merged together. These small issues are mostly present inside the communication classes. The `XDDPComm` and `IDDPComm` could be refactored in the `XDDPConnection` or `IDDPConnection` to simplify the class structure.

Physical plant integration is one of the first things to tackle after these small changes. The ability to control physical plants using real-time threads that are started by the framework is the main goal of the framework. The communication framework allows for the extension with the addition of a new `frameworkComm` derived class. This way, the send and receive code inside `runnable` loop through the `frameworkComm` arrays and also send some of the data to an external device. This external device tackles the conversion of data to a motor suitable PWM signal. One possibility for an external device is an FPGA (Field Programmable Gate Array). The Raspberry Pi is capable to communicate with the FPGA using the SPI protocol. Xenomai 3 claims to have implemented a real-time-friendly driver for SPI, which can be used to send data to the FPGA.

A test that was not executed to check the performance of the framework was measuring the delay of the RTIPC protocol. When this is measured, it could be helpful in fully understanding latency inside the framework. The latencies in ROS2 are already mapped by Maruyama et al. (2016). When working with a remote topic monitor, these delays increase significantly. To gauge if the framework is actually useful and easy to use, field testing should be performed. The best way to implement this is to let students test the framework. Afterwards, their requested changes can be put into the framework to increase its usefulness. This approach also reduces possible bugs that are present in the framework.

The real-time capabilities of ROS2 need to be further explored. This could prove useful when implementing a sequence controller inside a ROS2 node. Moreover, for educational purposes, the difference between a non-real-time execution of the framework and the original performance could be insightful.

A Xenomai installation

The repository can be found on:
https://git.ram.eemcs.utwente.nl/meijera/xenomai-ros2-20sim-pipeline/-/tree/master/.

A.1 Xenomai installation

These steps will help you through the installation of xenomai on the raspberry pi 4. The kernel that is used is the 4.19.86 linux kernel. Patches from Tantham-h are used to help the installation and make the USB work through the PCIE-bus that is added in the Raspberry pi 4.

Requirements:

- Raspberry pi 4
- 16gb Micro-SD card + reader
- Computer with Ubuntu
- Wifi/LAN connection

A.2 Directory initialization

1. We start by pulling the linux repository and the patches on the host computer.
   ```
   host@ubuntu:~$ git clone git://github.com/raspberrypi/linux.git
   linux-rpi-4.19.86-xeno3
   ```

(if git is not installed, install it by using `sudo apt-get updates` and then `sudo apt-get install git`)

1. Then we enter the directory and reset the git repository to
   ```
   host@ubuntu:~$ cd linux-rpi-4.19.86-xeno3
   host@ubuntu:~/linux-rpi-4.19.86-xeno3$ git reset -
   -hard c078c64fecb325ee86da705b91ed286c90aae3f6
   host@ubuntu:~/linux-rpi-4.19.86-xeno3$ cd ..
   ```

2. Then we create a linked folder for easy access.
   ```
   host@ubuntu:~$ ln -s linux-rpi-4.19.86-xeno3 linux
   ```

3. Download the xenomai tar.bz2 and extract it. Also create a linked folder for the xenomai installation.
   ```
   host@ubuntu:~$ wget https://xenomai.org/downloads/xenomai/stable/xenomai-
   3.1.tar.bz2
   host@ubuntu:~$ tar - xjvf xenomai-3.1.tar.bz2
   host@ubuntu:~$ ln -s xenomai-3.1 xenomai
   ```

4. Download the patches into xeno3-patches
   ```
   host@ubuntu:~$ mkdir xeno3-patches && cd xeno3-patches
   host@ubuntu:~/xeno3-patches$ wget https://github.com/thanhtam-h/
   rpi4-xeno3/blob/master/scripts/ipipe-core-4.19.82-arm-6-mod-4.
   49.86.patch
   host@ubuntu:~/xeno3-patches$ wget https://github.com/thanhtam-h/
   rpi4-xeno3/blob/master/scripts/pre-rpi4-4.19.86-xenomai3-simplerobot.
   ```

```
patch
host@ubuntu:~/xeno3-patches$ cd ..
```

A.3 Patching linux with xenomai

1. Patch linux with the pre-patch from Tantham-h
   ```
   host@ubuntu:~$ cd linux
   host@ubuntu:~/linux$ patch -p1 <../xeno3-patches/pre-rpi4-
   4.19.86-xenomai3-simplerobot.patch
   ```
   (If the patch returns with error, just ignore)

2. Patch linux with xenomai
   ```
   host@ubuntu:~/linux$ ../xenomai/scripts/prepare-kernel.sh -
   -linux=./ --arch=arm --ipipe=../xeno3-patches/ipipe-core-
   4.19.82-arm-6-mod-4.49.86.patch
   ```

A.4 Building linux

1. Get the default config of the BCM2711 into the linux directory
   ```
   host@ubuntu:~/linux$ make -j8 O=build ARCH=arm CROSS_COMPILE=arm-
   linux-gnueabihf- bcm2711_defconfig
   ```

2. Set the menuconfig to the right settings
   ```
   host@ubuntu:~/linux$ make -j8 O=build ARCH=arm CROSS_COMPILE=arm-
   linux-gnueabihf- menuconfig
   ```
   Edit the following variables:

   Kernel features —>

   ```
   Timer frequency 1000Hz
   ```

   General setup —>

   ```
   (-v72-xeno3) Local version - append to kernel release
   ```

   CPU power management –> CPU Frequency scaling –>

   ```
   [] CPU Frequency scaling
   ```

   Memory Managament options —>

   ```
   [] Allow for memory compaction
   ```

   Kernel hacking —>

   ```
   [] KDGB: kernel debugger
   ```

   Xenomai/cobalt —> Drivers —> Real-time GPIO drivers —>

   ```
   [*] GPIO controller
   ```

   Xenomai/cobalt —> Drivers —> Real-time IPC drivers –>

```
[*] RTIPC protocol familty
```

3. Build the linux kernel, edit the -jX variable so that 'X' is: (your number of CPU's - 1).
   `host@ubuntu:~/linux$ make -jX O=build ARCH=arm CROSS_COMPILE=arm-linux-gn`
   `bzImage modules dtbs`
   (This can take some time, so get coffee or tea...)

A.5 Installing the linux kernel on the Micro-SD card

1. Create a new raspbian image on the micro-SD card with the Pi imager. Choose the "Raspberry PI OS 32-Bit lite" version.

   Also create a shortcut to the identifier for the PI4 ARM version of the kernel:

   ```
   host@ubuntu:~/Linux$ KERNEL=kernel7l
   ```

2. In terminal, locate the fresh installed SD card and see which mounts points are created:\
   `host@ubuntu:~/Linux$ lsblk sdb sdb1 sdb2`
   with sdb1 being the FAT (boot) partition, and sdb2 being the ext4 filesystem (root) partition.

3. Create mount points for both these partitions and mount the sd card to them.
   ```
   host@ubuntu:~/Linux$ mkdir mnt
   host@ubuntu:~/Linux$ mkdir mnt/fat32
   host@ubuntu:~/Linux$ mkdir mnt/ext4
   host@ubuntu:~/Linux$ sudo mount /dev/sdb1 mnt/fat32
   host@ubuntu:~/Linux$ sudo mount /dev/sdb2 mnt/ext4
   ```

4. Install the modules of the build linux system and install them on the root partition.
   ```
   host@ubuntu:~/Linux$ sudo env PATH=$PATH make O=build ARCH=arm
   CROSS_COMPILE=arm-linux-gnueabihf- INSTALL_MOD_PATH=mnt/ext4
   modules_install
   ```

5. Install the kernel image, bts packets and the overlays into the boot partition.
   Also the original kernel image is saved, in the case that the kernel does not boot.
   ```
   host@ubuntu:~/Linux$ sudo cp mnt/fat32/$KERNEL.img
   mnt/fat32/$KERNEL-backup.img
   host@ubuntu:~/Linux$sudo cp arch/arm/boot/zImage mnt/fat32/$KERNEL.img
   host@ubuntu:~/Linux$sudo cp arch/arm/boot/dts/*.dtb mnt/fat32/
   host@ubuntu:~/Linux$sudo cp arch/arm/boot/dts/overlays/*.dtb*
   mnt/fat32/overlays/
   ```

6. Edit the neccessary boot configs and cmdline such that the pi can boot, also add the ssh access file.
   ```
   host@ubuntu:~/Linux$ touch mnt/fat32/ssh
   host@ubuntu:~/Linux$ sudo nano mnt/fat32/cmdline.txt
   ```
   Add:
   `dwc_otg.fiq_enable=0 dwc_otg.fiq_fsm_enable=0 dwc_otg.nak_holdoff=0`
   `isolcpus=0,1 xenomai.supported_cpus=0x3` at the end of the FIRST line.
   ```
   host@ubuntu:~/Linux$ sudo nano mnt/fat32/config.txt
   ```
   Add somewhere in the beginning:

```
total_mem=3072
```

7. Unmount the SD card and insert it into the Raspberry pi and power it up with the ethernet cable attached to the host computer.
   ```
   host@ubuntu:~/Linux$sudo umount mnt/fat32
   host@ubuntu:~/Linux$sudo umount mnt/ext4
   ```
8. Boot the raspberry pi and ssh into it, check the linux kernel with `uname -r`

A.6 Installing the xenomai libraries on the Raspberry pi

1. Also on the host PC, build the xenomai libraries.
   ```
   host@ubuntu:~$ cd xenomai
   host@ubuntu:~/xenomai$ ./scripts/bootstrap
   host@ubuntu:~/xenomai$ ./configure --host=arm-linux-gnueabihf
   --enable-smp --with-core=cobalt
   host@ubuntu:~/xenomai$ make
   host@ubuntu:~/xenomai$ sudo make install
   host@ubuntu:~/xenomai$ tar -cjvf rpi4-xeno3-deploy.tar.bz2
   /usr/xenomai
   ```
2. Copy the constructed tar.bz2 file to your raspberry pi.

   ```
   host@ubuntu:~/xenomai$ scp rpi4-xeno3-deploy.tar.bz2 pi@<raspberry pi IP add
   ```

   (if you do not know the pi IP address check it using an ipscanner)

3. Switch to the raspberry pi (SSH into the raspberry pi)
   ```
   host@ubuntu:~/xenomai$ ssh pi@<raspberry pi IP address>
   ```
4. Inside the raspberry pi, unpack the tar.bz2 and copy it to /usr
   pi@raspberrypi:~$ cd /usr
   pi@raspberrypi:~$ sudo tar -xjvf rpi4-xeno3-deploy.tar.bz2 -C /
5. Create a config file and add the xenomai libraries to it.
   ```
   pi@raspberrypi:~$ sudo nano /etc/ld.so.conf.d/xenomai.conf
   ```
   And add:
   ```
   /usr/local/lib /usr/xenomai/lib
   ```
6. Load the config and reboot, then run some tests and you are done!
   ```
   pi@raspberrypi:~$ sudo ldconfig
   pi@raspberrypi:~$ sudo reboot

   pi@raspberrypi:~$ sudo /usr/xenomai/bin/xeno-test
   pi@raspberrypi:~$ sudo /usr/xenomai/bin/latency
   ```

B ROS2 installation

Installation of ROS2 Eloquent

Installation is from ROS2 on RPI4 and ROS2 eloquent building.

1. Add the appropriate locales to the RPI4.

```
pi@raspberrypi:~ $ sudo nano /etc/locale.gen
```

and uncomment the line: `en_US.UTF-8` after that run:

```
pi@raspberrypi:~ $ sudo apt update && sudo apt install locales
pi@raspberrypi:~ $ sudo locale-gen en_US en_US.UTF-8
pi@raspberrypi:~ $ sudo update-locale LC_ALL=en_US.UTF-8 LANG=en_US.UTF-8
pi@raspberrypi:~ $ export LANG=en_US.UTF-8
```

and

```
pi@raspberrypi:~ $ sudo locale-gen en_US.UTF-8
pi@raspberrypi:~ $ sudo update-locale en_US.UTF-8
```

and check if all the locales are set to en_US.UTF-8 with:

```
pi@raspberrypi:~ $ locale
LANG=en_US.UTF-8
LANGUAGE=en_US.UTF-8
LC_CTYPE="en_US.UTF-8"
LC_NUMERIC="en_US.UTF-8"
LC_TIME="en_US.UTF-8"
LC_COLLATE="en_US.UTF-8"
LC_MONETARY="en_US.UTF-8"
LC_MESSAGES="en_US.UTF-8"
LC_PAPER="en_US.UTF-8"
LC_NAME="en_US.UTF-8"
LC_ADDRESS="en_US.UTF-8"
LC_TELEPHONE="en_US.UTF-8"
LC_MEASUREMENT="en_US.UTF-8"
LC_IDENTIFICATION="en_US.UTF-8"
LC_ALL=en_US.UTF-8
```

2. Add the repositories to your RPI4

complete the steps on Add the ROS-2 repo. until you are at the Build the code in the workspace.

3. let Cmake ignore some packages to save time and errors

```
pi@raspberrypi:~ $ cd ros2_eloquent
pi@raspberrypi:~/ros2_eloquent $ touch src/ros2/rviz/AMENT_IGNORE
pi@raspberrypi:~/ros2_eloquent $ touch src/ros-visualization/AMENT_IGNORE
pi@raspberrypi:~/ros2_eloquent $ touch src/ros2/system_tests/AMENT_IGNORE
```

4. Add some colcon build instructions to .colcon

```
pi@raspberrypi:~ $ mkdir .colcon
pi@raspberrypi:~ $ sudo nano .colcon/defaults.yaml
```

and add:

```
build:
  cmake-args:
--DCMAKE_SHARED_LINKER_FLAGS='-latomic -lpython3.7m'
--DCMAKE_EXE_LINKER_FLAGS='-latomic -lpython3.7m'
--DCMAKE_BUILD_TYPE=RelWithDebInfo
```

repeat the steps above within the directory `ros2_eloquent`.

5. Building ROS2

Continue with the steps on Building ROS-2

C xenoThread class

This appendix describes a more in-depth example using the different classes created in this thesis. The complete main code is shown in Listing C.1.

```
1
2  bool exitbool = true;
3
4  void my_handler(int s)
5  {
6          printf("Caught␣signal␣%d\n", s);
7          exitbool = false;
8      }
9
10 int main()
11 {
12 //CREATE CNTRL-C HANDLER
13 signal(SIGINT, my_handler);
14
15 //CREATE PARAM AND WRAPPER FOR CONTROLLER
16 int iddpcontroller_uParam[] = {0, 1};
17 int xddptiltcontroller_uParam[] = {2};
18 int xddppancontroller_uParam[] = {3};
19
20 frameworkComm *controller_uPorts[] = {
21 new IDDPComm(5, -1, 2, iddpcontroller_uParam),
22 new XDDPComm(10, -1, 1, xddptiltcontroller_uParam),
23 new XDDPComm(11, -1, 1, xddppancontroller_uParam)};
24 int controller_yParam[] = {0, 1};
25 int controller_yParam_logging[] = {0};
26 frameworkComm *controller_yPorts[] = {
27 new IDDPComm(2, 3, 2, controller_yParam)
28 };
29 Controller *controller_class = new Controller;
30 runnable *controller_runnable = new wrapper<Controller>(
31     controller_class, controller_uPorts, controller_yPorts, 3, 1);
32 controller_runnable->setSize(4, 2);
33
34
35 //CREATE PARAM AND WRAPPER FOR PLANT
36 int plant_uParam[] = {0, 1};
37 frameworkComm *plant_uPorts[] = {
38 new IDDPComm(3, -1, 2, plant_uParam)};
39 int plant_yParam[] = {0, 1};
40 int plant_yParam_logging[] = {0};
41 frameworkComm *plant_yPorts[] = {
42 new IDDPComm(4, 5, 2, plant_yParam)
43 };
44 Plant *plant_class = new Plant;
45 runnable *plant_runnable = new wrapper<Plant>(
```

```
46      plant_class, plant_uPorts, plant_yPorts, 1, 1);
47  plant_runnable->setSize(2, 2);
48
49
50  //INIT XENOTRHEAD FOR CONTROLLER + PLANT
51  xenoThread plantClass(plant_runnable);
52  xenoThread controllerClass(controller_runnable);
53  plantClass.init(1000000, 99, 1);
54  controllerClass.init(1000000, 98, 0);
55
56  plantClass.enableLogging(true, 25);
57  controllerClass.enableLogging(true, 26);
58
59  //START THREADS
60  controllerClass.start("controller");
61  plantClass.start("plant");
62
63  // WAIT FOR CNTRL-C
64  while (exitbool)
65  ;
66  printf("STOP_RUNNNING...\n");
67
68  //CLEANUP
69  controllerClass.stopThread();
70  plantClass.stopThread();
71  controller_runnable->~xenoThread();
72  plant_runnable->~xenoThread();
73  controller_runnable->~runnable();
74  plant_runnable->~runnable();
75  return 1;
76  }
```

Listing C.1: Example of xenoThread code with controller and plant, simulating pan and tilt of the JIWY robot.

The example is essentially an increased complicated version of the example used in Section 4.2.3. It does not only include one channel from the Controller but two variables over the same channel. This is due to the fact that the JIWY robot has two degrees of freedom and has two motors that need to be controlled.

A signal handler is used to make the program exit whenever the user requests this. Line 2-9 include the handler which makes the `exitbool = true;`.

This is then used in the infinite while loop running on lines 66-68. When cntrl-c is pressed, the `exitbool` is put to true and the loop is finished. Afterward, the complete code is cleaned up. Line 13 starts a signal monitor with as interrupt handler the function `my_handler`.

Afterward, the different parameters and `frameworkComm` arrays are created in lines 16-50. These lines also include the creation of the `wrapper20` classes. The created arrays are passed when creating these and afterward their `u` and `y` sizes are set.

The size of the controller is twice as big since there needs to be information from the plant and from the setpoint thread for both tilt and pan.

Next in line is the initialization of the thread classes. This is done on lines 53-56 and the timing logs are enabled on 58-59. The plant thread is initialized with priority 99 on core 1. The controller receives a lower priority and is put on core 0. When these are created and initialized, the threads can be started with their name as an argument. This results in the following print statements in the Raspberry Pi terminal, shown in Figure C.1.

```
pi@raspberrypi:~/xenomai-ros2-20sim-pipeline/build $ sudo ./main
Done setting up the IDDP for port:5 - return: 0
Done setting up the XDDP for port:10 - return: 0
Done setting up the XDDP for port:11 - return: 0
Done setting up the IDDP for port:2 - return: 0
Done setting up the IDDP for port:3 - return: 0
Done setting up the IDDP for port:4 - return: 0
Done setting up the XDDP for port:25 - return: 0
Done setting up the XDDP for port:26 - return: 0
```

Figure C.1: Print statements when starting the main c++ program.

Figure C.1 shows the different ports being initialized correctly. First, are the communication ports described until line 50 and then the two logging ports on lines 58-59.

Afterward, the program begins to spin periodically on the set period of 1000000ns. When the program is set to verbose, the terminal will print every step with all the received and sent data. This can be used for debugging. Figure C.2 shows the output when running the program from Listing C.1 with only the tilt receiving external inputs.

```
 --- 1s 6071999ns ---
XDDP - sent 8 bytes, "1.006072" to port: 25
IDDP - received: 0.0095830.000000 on port 5
u[0] = 0.009583  ---  u[1] = 0.000000  ---  u[2] = 0.120000  ---  u[3] = 0.000000  ---
y[0] = 0.142400  ---  y[1] = 0.000000  ---
IDDP - sent 16 bytes:  0.1258140.000000  to port: 3 from port 2 - return: 16
 --- 1s 8097536ns ---
XDDP - sent 8 bytes, "1.008098" to port: 26
IDDP - received: 0.1258140.000000 on port 3
u[0] = 0.125814  ---  u[1] = 0.000000  ---
y[0] = 0.009583  ---  y[1] = 0.000000  ---
IDDP - sent 16 bytes:  0.0116300.000000  to port: 5 from port 4 - return: 16
```

Figure C.2: Print statements while running the main c++ program.

`sudo cat /proc/xenomai/sched/stat` can be called to check the scheduler statistics on all running Xenomai programs. The output of this command while running the main code is shown in Figure C.3

```
pi@raspberrypi:~/xenomai-ros2-20sim-pipeline/build $ sudo cat /proc/xenomai/sched/stat
CPU  PID    MSW        CSW        XSC        PF    STAT       %CPU  NAME
  0  0      0          27276      0          0     00018000   99.9  [ROOT/0]
  1  0      0          26933      0          0     00018008   99.9  [ROOT/1]
  2  0      0          0          0          0     00018000  100.0  [ROOT/2]
  3  0      0          0          0          0     00018000  100.0  [ROOT/3]
  0  1650   17         17         31         0     000600c0    0.0  main
  0  1652   2          10690      96184      0     00048042    0.0  controller
  1  1653   2          10689      74805      0     00048040    9.7  plant
  0  0      0          70925      0          0     00000000    0.0  [IRQ18: [timer]]
  1  0      0          27596      0          0     00000000    0.0  [IRQ18: [timer]]
```

Figure C.3: Print statement when calling the scheduler statistics function of Xenomai while running the main c++ program.

The main thread is visible next to the controller and the plant. `MSW` represents the number of mode switches made by Xenomai. This only changes when firing up the program, not while running. This proves that the programs keep running in real-time for their complete duration. Also visible is the CPU core in the left column and the name assigned on lines 60-61 in the right column.

When cntrl-c is pressed, the cleanup starts and all the threads are stopped and destroyed. All the runnables are destructed too, which automatically closes the ports of the communications that were given to the runnables. The output of this can be seen in Figure C.4

```
Caught signal 2
IDDP - received: 0.0000010.000000 on port 3
u[0] = 0.000001  ---  u[1] = 0.000000  ---
y[0] = 0.120002  ---  y[1] = 0.000000  ---
IDDP - sent 16 bytes:  0.1200020.000000  to port: 5 from port 4 - return: 16
 --- 1s 655078387ns
XDDP - sent 8 bytes, "1.655078" to port: 25
STOP RUNNNING...
u[0] = 0.000001  ---  u[1] = 0.000000  ---
y[0] = 0.120002  ---  y[1] = 0.000000  ---
close wrapper and free memory...
Close IDDP connection and close port: 5
Close XDDP connection and close port: 10
Close XDDP connection and close port: 11
Close IDDP connection and close port: 2
close Runnable
close wrapper and free memory...
Close IDDP connection and close port: 3
Close IDDP connection and close port: 4
close Runnable
close XenoThread
close XenoThread
pi@raspberrypi:~/xenomai-ros2-20sim-pipeline/build $
```

Figure C.4: Print statements when cleaning up the main c++ program.

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