

# Evaluation of the NESizer2 method as a means of wrapping embedded legacy systems

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## 1 Introduction

When integrating legacy information system components into a modern system, one of several usual approaches is to create an interface for the modern system to control or communicate with the legacy component. This approach is known as wrapping.[1], [2] Wrapping as a concept could be adapted for legacy hardware in embedded systems, to enable the original and proven functionality of the outdated system, by providing an interface to control the legacy components. There are few documented examples of migration of legacy systems that include the incorporation of the system including the hardware platform, and the few examples that exist are often designed with a specific functionality in mind. The NESizer2 project details a method wherein a modern microcontroller is used to wrap certain functionalities of the microprocessor used in a Nintendo Entertainment System, by dynamically injecting instructions to the microprocessor like an emulated ROM.[3] This thesis will evaluate how this method could be expanded upon to allow for a general use case of the legacy component, and to evaluate how well the method performs as a means of wrapping.

### 1.1 Background

Computer based information systems are an invaluable asset for modern enterprises and corporations. The use of information systems can range from data storage, analysis and organization, to communication systems such as mail servers. With continued updating and upgrading of these systems they become increasingly complex, and as technology evolves the existing technology of the systems are quickly rendered obsolete, and “eventually, the existing information systems become too fragile to modify and too important to discard” [4], and as such it can be considered a legacy system. [5] At this point the legacy systems must be modernized, or migrated into a more modern system to remain viable.

When incorporating legacy information systems into modern systems, there are usually three popular approaches: redevelopment, wrapping and migration [1, pp. 2–4]. While redeveloping an entire system is usually the best option in the long run, it is also the most expensive and risky. Therefore, migration is usually a more popular method, as it provides an interface to control the legacy components, while retaining its data and functionality. However, migrating systems to a modern platform can lead to unexpected behaviour, with a notable example being NASA’s Ariane 5 flight 501 [6], [7].

When redevelopment and migration is too risky or expensive, wrapping offers a cost-effective option with less risk. It surrounds existing data, systems and interfaces with new interfaces, giving the legacy components a “new and improved” look [1, p. 3], and lets organizations reuse trusted components in a new, more up-to-date manner. While these methodologies and frameworks usually focus on legacy software systems, they are very much applicable to hardware systems and components as well.

One way of wrapping a legacy hardware component is detailed in the hobby project NESizer2 by *Johan Fjeldtvedt*. [3] The project is a MIDI controlled synthesizer, using the original *Audio Processing Unit* (APU) found embedded in a RP2A03 microprocessor - the microprocessor used in the Nintendo Entertainment System. In his method he uses a modern microcontroller to handle the normal functionality of a MIDI-controller aswell as controlling the RP2A03 by dynamically injecting instructions into the microprocessor when the APU is needed.

## 1.2 Problem

To address the issues of unexpected behaviour in an otherwise proven, well functioning system, the solution could be to keep only the crucial legacy components including their hardware platforms, and provide an interface for a modern system to control them - creating a wrapper for both hardware and software. While there exists implementations of similar approaches, they are often designed with a specific functionality of the legacy component in mind, and as such does not provide a method of controlling the component for a general use case. This poses the question;

Could these specific implementations be generalized into methods of controlling a legacy component, without any specific use case in mind? If so, how well do they perform as a means of modernization?

To try and answer these questions, we will investigate the method used in the NESizer2 project, hereafter referred to as *The NESizer2 method*, to see if it can be expanded upon to be used as a *wrapper* for the RP2A03 microprocessor. The method is considered a wrapper if it can allow a general use case of the microcontroller - specifically if it can successfully utilize the entire instruction

set of the processor, thereby allowing any RP2A03 program to be run through the wrapper.

### **1.3 Purpose**

The purpose of this report is to investigate how the NESizer2 method performs as a means of modernization, by repurposing the method to handle the entire instruction set of the RP2A03/6502 microprocessor, and measuring its performance in speed of execution as well as investigating the complexity of implementing the method.

The purpose of the work is to provide some insight to how well a relatively simple method of wrapping an outdated microprocessor can be expanded upon to function as method of modernizing a legacy embedded system. Although our work is very basic and does not cover the entirety of how to wrap a whole legacy system, we hope our findings can be used as a future reference for others interested in modernizing embedded hardware.

### **1.4 Goal**

The goal with the work is to provide insight into how an existing method of controlling legacy hardware can be extended to allow for general usage, and to give a performance evaluation of the method. This can hopefully give an indication of their usefulness as a method of modernizing an information system that uses legacy components.

#### **1.4.1 Social benefits, ethics and sustainability**

If it is possible to wrap entire embedded legacy systems with relatively easy means, it could provide an alternative for businesses that are dependent on legacy embedded components to upgrade their systems without having to invest in, what most likely would be, expensive migrations, and with minimized risk - as wrapping would keep the legacy components intact. We also hope that our work can contribute to other research that aims towards a more sustainable solution than discarding still functioning computer systems, which is becoming an increasing threat to our environment.[8]

We acknowledge that our research could contribute to the continued use of legacy hardware. While the process of discarding obsolete hardware etc. for new parts can have a negative impact on the environment, it is also important to note that upgrading hardware could prove to be a better solution, as much research and development is aimed towards lower power consumption and with a more up-to-date view on sustainable engineering.

## 1.5 Methodology

In order to expand our knowledge and theoretical background in the field of research and define the research objectives, literature studies were conducted on several occasions during the research. A literature study is the systematic and methodical analysis of literature for a scientific purpose [9].

A literature study was also conducted to decide on a suitable scientific method under which to conduct the research. The scientific method acts as a framework or guidance for the researcher to conduct their research in a well defined and systematic way, based on the works and experiences of researchers before them, and it is crucial to a research in order to ensure quality and correctness of gathered results and analysis.

We found that experimental research was most suited to the nature of our research. The experimental approach allows for observing how a system's behavior changes as one variable is manipulated while other variables are kept stable [10], and as such it is suitable for analyzing performance of a system [11].

## 1.6 Stakeholder

No stakeholder.

## 1.7 Delimitations

The scope of this report is limited to the design and performance analysis of the NESizer2 method when it has been expanded to handle the entire 6502 instruction set, on a RP2A03 microprocessor. Performance evaluation has been limited to speed of execution per cycle across different types of test programs, as well as the response time from when an instruction is issued until it is performed by the RP2A03. The details of the implementation and evaluation criteria can be found in subsequent sections.

For a better indication of how well the communication method studied in our research can be adopted for other microchips/hardware and for a better picture of the behaviour of these communication methods on other systems, it would have been beneficial to implement them for two or more devices with different architectures. We have compared the performance in execution time against a theoretical execution time of one instruction per second, however measuring the execution speed of the RP2A03 used "as intended" with a ROM could possibly have been more insightful.

## 1.8 Disposition

TODO

## 2 Background theory/Technical background

This chapter provides an introduction of what legacy hardware means, and also discusses how legacy hardware is used in modern systems and particularly how old hardware is still used to create and produce retro-sounding music. It also introduces a hobby project that sparked the idea for this research. The second part of this chapter discusses some earlier work related to the research problem, and work that was used as a basis for the communication methods designed for this research.

### 2.1 Legacy

Legacy is a term used in computing to mean “of, relating to, or being a previous or outdated computer system” [12]. This could, for example, be computer systems or components that might have had a widespread usage or been considered a standard in the past, but are no longer manufactured or maintained by the producer.

### 2.2 Trackers and the Chiptunes scene

In the mid 1980’s, a type of music sequencer commonly referred to as a “tracker” appeared on the personal computing markets. Today, a community colloquially named the “chiptune scene” consisting of musicians and retro enthusiasts fascinated with the characteristic sounds of the old video game consoles, create and perform their own music with these trackers. While many artists use software that can emulate the sounds of these machines on modern systems, it is often considered high status to create the music directly on the old hardware. An often recurring example representative of the scene is the tracker software LSDj [ref], written for the Nintendo Game Boy. Its portable nature makes it an ideal option for artists, being able to carry their “instrument” anywhere with ease.

We wanted to, as a hobby project, develop a prototype for a portable music tracker, similar to the Game Boy and LSDj, using the characteristic sound from the popular Nintendo Entertainment Systems (NES) processor Ricoh RP2A03. In our research, we realized that it would be beneficial if we could write the tracker software for a modern microcontroller that would in turn control the Ricoh chip as a slave unit. This would give us all the expansive capabilities of a modern microcontroller, while also providing us with the actual audio output of the NES.

We realized that our need to control the Ricoh chip in this fashion could also be applicable to other legacy systems that are in need of upgrades, and where emulation is not a viable option.

## 2.3 MOS Technology 6502 architecture and the Ricoh RP2A03

The MOS Technology 6502 microprocessor and architecture was introduced on the market in 1975. It gained almost instant popularity due to its competitive performance for a cheaper price than its competitors.[13]

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The microprocessor that was used in the Nintendo Entertainment System was a Ricoh RP2A03 chip. [får man reffa till Nintendos patent? isf reffa det här] The RP2A03 is a proprietary chip based on the MOS Technology 6502 microprocessor architecture, with the difference that it has an added Audio Processing Unit (APU), and it does not support *decimal mode*<sup>1</sup> that would normally be available on a 6502 architecture.[13]

## 2.4 Atmega328

## 2.5 Related work

- NESizer2
- Shared memory, injection-grejen
- Andra artiklar vi hittade tidigare

# 3 Development and methodology

This chapter gives an introduction to experimental research and how it can be used in system performance comparison and analysis, followed by a theoretical background to agile development.

## 3.1 Experimental research

During the research, a research method was applied to facilitate the process of analyzing and evaluating our implementation. A literature study was conducted in order to find an appropriate research method and strategy. The research methodology was chosen with the research question in mind; how to analyze and evaluate a system performance. The two main categories of research methodology are *quantitative* and *qualitative* research, which are separated by their founding philosophical assumptions. The qualitative research methodology assumes that observations, and importantly the conclusions drawn from them, are by their

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<sup>1</sup>Decimal mode allows the processor to compute memory addresses written in decimal values, whereas it otherwise would use hexadecimal. REVIEW THIS FOOTNOTE AND ADD REFERENCES.

nature connected and dependent on prior knowledge and skill of the researcher and that the same observations might lead to different conclusions depending on the researcher. Qualitative research is mainly inductive in its nature, and the researcher will use their observations to infer *possible* hypotheses based on observations. Quantitative research, on the other hand, stems from positivism; the philosophical stand point that all things are governed by principles or laws (e.g. natural) and as such it is possible for researchers to observe these laws to draw conclusions in their research.[10, p. 23] Contrary to qualitative research, a quantitative approach is generally deductive, and is often aimed to confirm or deny a hypotheses that has been stated beforehand.[10], [11]

One example of quantitative research is *experimental research*. Experimental research is a strategy where the researchers try to control all variables that can affect the outcome of an observation. By methodically manipulate the state of one variable at a time, while keeping other variables stable, it is possible to understand how different variables affect the phenomenon that is to be researched.[10, p. 26], [11] As its main method of data collection, experimental research relies on experiments that are performed in this fashion. The gathered data can then be analyzed and used as a basis for conclusion to confirm or deny the stated hypotheses. In computer systems this method can be used to isolate the behaviour of the system for a certain input or event, and can be a useful method to analyze system performance.[11]

We chose to work according to the experimental research strategy, seeing as it is a suitable approach to analyze computer systems. To analyze the performance of our implementation we have chosen to observe how *response time* and *time of completion of a program* varies with respect to different sets of instructions and the program length. Because of limitations in our implementation in its current state, further described in subsequent chapters, we hypothesize worse performance than if the chip could read instructions directly from a ROM, as intended. However, if the implementation is capable of executing the entire instruction set as expected, we believe that there are many areas of the implementation that can be optimized for better performance with relative ease.

### **3.1.1 Experimental techniques in computer system performance research**

The development of computer systems has long been an area heavily driven by the marketplace. In order to be competitive on the market, a computer system has to either provide the highest performance, or the most cost effective computing engines. This means that as developers of computer systems, we need to successfully “understand and then eliminate the system bottlenecks that prevent us from exploiting the available technologies”. To gain a good understanding of how modern computer systems behave, and to localize the source of bottlenecks in a precise manner, experimental techniques are required.[14] In our research we have chosen one of these techniques when designing experiments to gather data



and analyze the performance of our implementation - *hardware monitoring*. [14] The reason for choosing only one of these techniques is that the scope of interest for this research is mainly to see how well the embedded hardware functions as a means of wrapping older hardware, and to deduce this we can gain sufficient data by monitoring the timing of hardware signals. Techniques that could be used to further develop the systems are discussed in section Future work.

## 3.2 Design and software development

This section provides a brief introduction to agile development and Scrum. These development frameworks were used during the research work to facilitate the design and development process of the research.

### 3.2.1 Agile development

The term agile, meaning “to have a quick resourceful and adaptable character” [15], was made popular in the software development circuit by the Manifesto for Agile Software Development [16]. The manifesto describes a model that, in contrast to traditional models for software development, embraces the fact that product description and requirements will most likely change during a development process, and adapts accordingly. It encourages building projects around motivated individuals, and promotes self-organization, continuous team meetings to reflect on the work that has been done, and regularly delivering work-in-process products to the product owner.

The agile software development model has spawned a number of frameworks to uphold the manifesto, including Extreme Programming (XP) and Scrum. These frameworks have helped set the standard of agile development, and has as such gained an immense foothold in the software development field. More recently, many universities are offering courses in the agile software development model, with research continuously being done on how to effectively do so [17].

### 3.2.2 Scrum

As previously mentioned, Scrum is one of many frameworks that applies/upholds/maintains(?) the Manifesto for Agile Software Development. The creators Jeff Sutherland and Ken Schwaber define Scrum as the following [18, p. 3]:

“Scrum (n): A framework within which people can address complex adaptive problems, while productively and creatively delivering products of the highest possible value.”

Scrum utilizes an iterative, incremental approach to manage risks, and to dynamically develop a solution to a problem (osäker på denna). The project

is broken down into a set of time boxes known as “Sprints”. The creators of Scrum recommend a sprint length of no longer than a month [18, p. 8], however the author of the popular Scrum introduction book “Scrum and XP from the Trenches” Henrik Kniberg recommends new Scrum teams to experiment with sprint lengths until they find a time frame that the team feels comfortable with [19, p. 22].

Each member of the Scrum team is assigned a role. These roles include product owner, developers and Scrum master. Each role have a specific set of tasks to fulfill.

- Scrum Master
  - Responsible for ensuring that Scrum is understood and enacted [18, p. 6] by making sure that the each member of the team follows the Scrum theory, practice, and rules.
- Product Owner
  - Responsible for maximizing the value of the product and the work of the development team [18, p. 5], and of managing the so called “Product Backlog”, which contains items/tasks/requirements(?) that are to be completed in order for the product to meet the definition of done.
- Developer
  - Professionals who do the development work by delivering potentially releasable software at the end of each sprint [18, p. 6].

The framework employs four formal events that help make sure that the team can deliver at the end of each sprint. These events are known as Sprint Planning, Daily Scrum, Sprint Review and Sprint Retrospective [18, p. 7].

- Sprint Planning
  - The Scrum team collaboratively decides on what can be delivered at the end of the sprint by moving tasks from the Product Backlog to a Sprint [19, p. 24]. A Sprint Goal is then created, which is a goal set by the team that can be reached by implementing the items in the Sprint backlog.
- Daily Scrum
  - A short meeting, usually around 15 minutes, where the team discusses the work that they will do on that day. This is done in order to synchronize team members, improve communication and improve the teams knowledge.
- Sprint Review
  - Held at the end of each sprint, where the Scrum team and possible stakeholders collaborate and discuss what was done in the sprint. The attendees inspect the Product Backlog and any changes that was made, decide on what could be done in the next sprint in order to optimize value. The meeting is held with the intention of generating feedback.
- Sprint Retrospective

- Held after the Sprint Review and before the next Sprint Planning meeting. It is held in order to inspect how the last Sprint went with regards to the team members, their relationships, the process and tools. The team tries to identify what went well, and what can be improved, with the aim to create a plan that improves performance in the next sprint.

## 4 Evaluation criteria

- Performance in speed
  - How fast is the wrapper method compared to non-wrapped?
  - Measure time of completion of programs categorized in types of operations
- Functionality as a wrapper method
  - Same behaviour as non-wrapped?
  - Response time

## 5 Project work/Development

This section details the project work, including literature studies and the hardware and software implementation/design process as governed by the Scrum framework, and the design and implementation of experiments according to the experimental research approach. It has been structured to closely follow the steps of the project work in chronological order.

### 5.1 Literature study

The project work started with a literature study, to gain knowledge on related work and theoretical background knowledge in the field of modernizing legacy hardware and legacy hardware used in modern applications. The search was performed using mainly the following databases of scientific publications: (i) IEEE Xplore, (ii) ACM Digital Library and (iii) Google Scholar. Additional searching tools used was simple internet searching tools such as *Google*, which could often provide ideas for additional keywords used when further searching in the databases. The results from this literature study was searched for using keywords: modernization/modernizing, legacy, hardware, microprocessor, computer. Based on the results of this search we further defined our keywords to target specific methods that seemed relevant, in order to find references on related previous work. The keywords used in this search was: legacy, microcontroller, microprocessor, master, slave, injection, wrapping, shared memory. The results from both searches was selected with title, abstract and publication year taken into consideration. Most of the related work was found to be older than 10

years, but considering that the articles mentioned methods of controlling legacy hardware, and that the problem of upgrading/modernizing hardware is generally a problem for machines older than 10-20 years, we found them relevant to the research.

Another literature study was conducted in order to gain further knowledge on experimental research, how it is used in performance comparison and evaluation, and general information on scientific methodology and how it is used in research. The keywords used in this search was: experimental, research, methodology, computer, system, performance. The search was conducted over the same databases mentioned above, and evaluated and selected using the same process. Anne Håkansson's article *Portal of Research Methods and Methodologies for Research Projects and Degree Projects*[11] mentions the book *Introduction to Research in Education*[10] as a source, and it has proved to be of great help when trying to understand what experimental research means, and how it can be used as a research strategy/methodology.

## 5.2 Designing experiments

The experiments had to be designed not only to reflect our evaluation criteria, but in accordance with the experimental research approach they had to be designed around understanding how *the single independent variable* and *the single significant variable* affect the system performance.

When designing the experiments to evaluate performance in time, we used the categories of programs discussed in section Evaluation criteria and identified a set of all controllable variables that could have a significant impact on the results from each category. The variable chosen were:

- i. Length of program, as measured in number of instructions
- ii. Selection of timing for reset function
- iii. Using emulated ROM functions or “pure” assembly

For each category we then designed an experiment that would test the performance when changing each of these variables while keeping the others stable.

To address the evaluation criteria *behaviour*, we included a data validation test to each experiment. The data validation is simply to verify that all test programs produced the expected output at each RP2A03 write cycle.

The outline of the experiments are further detailed in section Experiments phase.

## 5.3 Hardware and Software implementation process

When planning the project work we decided to use agile development and the framework *Scrum* to govern the design and implementation process. We chose divide design and implementation work into categories *hardware* and *software*,

with one person responsible for each category. Before our first sprint we set up milestones and goals, and created a backlog of stories, or tasks, that would work towards reaching set goals. This backlog is what we used to define tasks to include in each sprints.

The sprint goals were then set to reflect stages of iteratively increasing implemented functionality in the method, and stories and tasks for that specific sprint were then chosen to reflect the sprint goal. For each sprint we also defined a set of one or more deliverables that should represent the result of that sprint. A detailed description of the work concluded in each sprint during the implementation process will be given below, and a summary of the sprint goals and deliverables can be seen in Table 1.

Table 1: Overview of sprints and deliverables

Sprint #	Goal	Deliverables
1	Research and Design phase done	Research and design documents for hardware and software
2-3	Basic communication working	Components, circuitry, and basic software needed for communication
4	Sending instructions	Hardware for debugging, Software for sending instructions
5	Entire instruction set working	Software supporting entire instruction set

### 5.3.1 Sprint 1, Research and design phase

The research and design phase included research the NESizer2 software and hardware implementation. This research was made in order to pinpoint the parts from NESizer2 that we would need, and what modifications had to be done to it. We found that we could use the assembly routines (which was at the heart of the communication with the RP2A03) together with a simple 8-bit databus through an 8-bit latch to control flow of instructions, as a foundation for our implementation. This is detailed in the circuit diagram found in Appendix A.

We also made research on the RP2A03 microprocessor, but since the RP2A03 is a proprietary chip, owned by Nintendo, there was not much official information available. However, a community of NES enthusiasts has, through reverse engineering, gathered much information on the processor on their forums and wiki-site *Nesdev Wiki*[20]. Through these channels we were able to learn that the chip differs little from the MOS Technology 6502 architecture, and as such we could learn much about the chip through official 6502 hardware and software development guides.

Hardware design work then included research and decision of what hardware components were needed for our implementation, and finally to create a circuit

diagram that we could use when building. Software design work resulted in a program flowchart and diagram of software components.

### 5.3.2 Sprint 2 & 3, Basic communication

The first part of the sprint was aimed at basic testing of components. Testing the RP2A03 was hard without any specialized tools, but we found a online document detailing a simple method of testing (i) power on and (ii) data bus of 6502.[21] The method mentions how to test this by using an array of LEDs on the address pins, but we decided to expand the test to observe the chip with an oscilloscope; we monitored the Read/Write and Clock output pin of the chip to confirm that different inputs produced expected sequence of RW signals. This gave us the confidence that the data bus and instruction parsing functioned, at least on some level.

After component testing was concluded, the next step was building a simple circuit of components that, together with basic software and a simple test program, could confirm that basic communication between the microcontroller and RP2A03 was working as intended. The results were inconsistent and erroneous, and the build had to be debugged, which resulted in the sprint “overflowing” to the next sprint.

We finally realized that the problem was due to a misunderstanding in how the latch was used in NESizer2, and a simple edit to the circuitry resulted in consistent expected results. This confirmed that communication between the chips worked at a basic level.

### 5.3.3 Sprint 4, Sending instructions

Hardware work included implementing simple debugging and diagnostics that could be used to determine if something was not working as intended in a quick manner, and proved to be very helpful during the sprint. After concluding the hardware work of the sprint, the software work was distributed to both parties and implemented together.

The NESizer2 uses high(er) level functions for instructing the RP2A03 to play a note, or to modify the sound, etc., with the help of hardcoded assembly instructions that performed set memory operations. We wanted to extend these assembly routines to allow for any instruction to be sent, and to build our own higher level C functions that could be used in a C program for the microcontroller used in the implementation. This was achieved by categorizing the 6502 instruction set (which is the instruction set used by the RP2A03) into instruction families that use the same number of operands. At this stage we chose to focus on three main families; (i) Immediate operations, (ii) Absolute addressing memory operations, and (iii) Zero Page addressing memory operations. A summary of the characteristics of these families can be found in Table 2.

Table 2: Instruction families and their characteristics

Instruction family	Size of instruction [B]	# Cycles / instruction	R/W Cycle sequence
Immediate	2	2	R, R
Absolute	3	4	R, R, R, R/W
Zero page	2	3	R, R, R/W

These characteristics was then used to redesign the assembly routines and to build the functions mentioned above. When implemented it was possible to send any opcode<sup>2</sup> together with any operand, handled properly by the assembly routines.

### 5.3.4 Sprint 5, Entire instruction set

The first part of this sprint focused on further extending the functionality of the previously written instruction handling, allowing a 6502 program to be stored and parsed as an array of byte instructions, functioning as a simple emulated ROM. This simplified the setup routine that had to be performed on boot of the RP2A03, as it could simply be written into the ROM, followed by the rest of the RP2A03 instructions we wanted to run.

When analyzing the 6502 instruction set further, we concluded that we were not interested in implementing support for branching instructions that conditionally jumps the program counter. This is because the RP2A03 reads instructions directly from the microcontroller, and as such branching has no real effect.

The second part of the sprint was aimed at thoroughly testing the entire instruction set, making sure that all instructions produced expected results. While all operations that used the accumulator register (immediate loads, ALU<sup>3</sup> operations, etc.) worked consistently and as expected, we noticed that seemingly *none of the memory operations worked*. This is further detailed in section Results.

The sprint, and some continuous work during the experiments phase, was concluded without managing to resolve this issue.

## 5.4 Experiments phase

The implementation was extended in hardware and software to include simple communication with an Arduino M0 board, which was used to measure time. The choice of the Arduino M0 as a hardware timer was the increased resolution

<sup>2</sup>Operation Code, the portion of a machine code instruction that specifies what operation to perform.

<sup>3</sup>Arithmetic and Logic Unit. In a CPU it is the component responsible for arithmetic and logic operations.

of time, and the fact that it ran on a clock with more than double the frequency of the wrapper system, further increasing accuracy of the measurements.

To measure communication timing and cycles between instructions, we used a digital logic analyzer to monitor digital output. The data from the analyzer could then be collected both numerically (in the form of CSV) and as diagrams. On the RP2A03 we chose to monitor all bits of the data bus, as well as the R/W and output clock pins, and on the microcontroller we monitored a signal pin to measure response time.

The experiments phase was conducted according to design, with the exception that any test cases involving memory operations could not be confirmed to produce expected results. The experiments were performed according to the following steps:

1. Validate data output and record response time when all variables are at default values
2. Measure time of completion as program increases in length
3. Measure time of completion as time interval of reset increases
4. Measure time of completion when program is called with emulated ROM functions
5. Measure time of completion when program is called without emulated ROM functions
6. Switch to next category and repeat process until all categories have been tested

## 6 Results

## 7 Conclusions & discussion

## 8 Future work

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