

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

## Abstract

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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could be adapted for legacy hardware in embedded systems, to enable the original and proven functionality of the outdated system, by providing an interface to control the legacy components.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 methods 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 the RP2A03 microprocessor, the microprocessor used in the Nintendo Entertainment System based on the MOS Technology 6502 architecture. 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 microprocessor, and measuring its performance in speed of execution as well as other key parameters.

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 modernizations, 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 into computer hardware 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] Details on experimental research is found under the section Experimental research.

## 1.6 Stakeholders

As previously mentioned, wrapping could provide an alternative for businesses to keep their legacy systems alive, meaning it could save a company a substantial economic and temporal investment. As such, our main stakeholders are businesses and corporations where the need to maintain old systems exists.

Another stakeholder, or rather a target audience, are electronic enthusiasts who design and create embedded systems of their own in hobby projects. Using ourselves as an example, the idea for this project sprung from our interest in constructing a music device that incorporated the Ricoh RP2A03 microprocessor, used in the Nintendo Entertainment System (more details on this in the Trackers and the Chiptunes scene section).

## 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 key parts of the 6502 instruction set, on a RP2A03 microprocessor. We chose to limit the instruction set by identifying groups of instructions that have similar characteristics, to ease implementation and testing, and to be able to better draw conclusions on the overall performance of the system. Performance evaluation has been limited to speed of execution across the implemented instruction set, as well as the overhead as measured in time between consecutive instructions. 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 not tested intended use case performance of the RP2A03, i.e. having it read program instructions from a regular ROM, and as such we were unable to make a tested comparison of execution speed.

## 1.8 Disposition

This report will firstly provide some background theory on legacy hardware and its use in a modern context, as well as an introduction to the hardware that has been used in this research. The research methodology used is presented in the following section together with other techniques and frameworks used to facilitate the research and development work. It is followed by a description of the project work, including the initial literature study and research phases, development phases and finally experiments and testing phases, followed by a section presenting the results from experiments. The last chapters will discuss the project work and the results from experiments, provide conclusions from the research work, and finally present ideas and thoughts about future work.

# 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 [13], 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

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.[14]

The 6502 microprocessor contains instruction families and addressing modes to control every part of the architecture. Other than instructions which target basic CPU functionality (such as controlling program counter, reading status register etc.), there are groups of instructions to perform operations with the accumulator and memory. Included in these groups are immediate, zero page and absolute addressing.

Immediate addressing utilizes a 2-byte instruction format, where the first byte is the opcode specifying the operation and the address mode. The second byte takes a constant, hexadecimal value known to the programmer. Immediate instructions are commonly used when comparing variables to known values, as it does not require the programmer to first store the value in memory and then load it upon comparison; they would only have to specify the immediate value in the source code. It requires a minimum execution time of 2 cycles (`OPCODE` + `VALUE`).

Another 2-byte instruction address mode is zero page addressing. Along with the opcode, it takes a second byte which contains the effective address in page zero of the memory. Effectively, this means that zero page instructions can be used for quick accesses to memory locations in the range of `0x0000-0x00FF`. Zero page instructions are often used when working with intermediate values in larger calculations, to shorten the total execution time.

Absolute addressing mode takes 3 bytes in its instruction format: `OPCODE` + `ADDRESS_LOW_BITS` + `ADDRESS_HIGH_BITS`. Since this gives the programmer access to the full 16-bit range of memory (`0x0000-0xFFFF`), it's considered the most normal addressing mode..

A full, detailed explanation of all of the available addressing modes can be found in the MC6500 Microcomputer Family Programming Manual.[15] This research will utilize the three aforementioned addressing modes of the 6502 microprocessor. See Delimitations for further details on the choice of instruction families.

## 2.4 Ricoh 2A03

The microprocessor that was used in the Nintendo Entertainment System was a Ricoh RP2A03 chip. 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. [14]

## 2.5 ATmega328P

The ATmega328P is an 8-bit, low-power CMOS microcontroller based on the AVR RISC architecture, with a throughput of up to 1 MIPS per MHz.[16] It is an easy-to-program, multi-purpose microcontroller that is included on the Arduino Uno and Nano microcontroller boards. It contains 32 KBytes ISP flash memory with true read-while-write operation, 1 KByte of EEPROM and 2 KByte of internal SRAM. It's 23 GPIO pins with programmable peripheral interfaces including SPI, I<sup>2</sup>C and USART makes it an excellent light-weight microcontroller for relatively small scale projects.

## 2.6 Related work

Since the topic of this research is to test the NESizer2 method as a way of implementing hardware wrapping, the NESizer2 project should be considered closely related to this project. [3] We have used and modified key parts of the communication protocol and expanded it to allow for general usage (i.e. enabled it to handle any instruction that targets the Accumulator, ALU or Memory, and that is within the Immediate, Zero Page and Absolute addressing modes), but other parts of the NESizer2 project may be of interest for enthusiasts and hobbyists that are interested in this kind of hardware wrapping.

During the literature study, we also encountered an article describing work on injecting instructions directly to the program memory of an older generation CPU. [17] Although our implementation does not inject instructions into a units program memory, the concept of injection is closely related. It is possible that the techniques described in that article could be used as an alternative method of hardware wrapping.

# 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 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

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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.

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*, which is a strategy where the researchers try to control all variables that can affect the outcome of an observation. By methodically manipulating 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 *per-instruction-overhead* and *completion time 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.[18] 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*. [18] 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.

## 3.2 Design and software development

This section provides a brief introduction to agile development and Scrum. These development frameworks were used during the project 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”[19], was made popular in the software development circuit by the Manifesto for Agile Software Development.[20] 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.[21]

### 3.2.2 Scrum

As previously mentioned, Scrum is one of many frameworks that implements the Manifesto for Agile Software Development. The creators Jeff Sutherland and Ken Schwaber define Scrum as the following [22, 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. 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 [22, 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.[23, 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 [22, 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[22, 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.[22, 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.[22, 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.[23, 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.

### 3.3 Evaluation criteria

In order to gain an idea of how well the NESizer2 functions as a method of hardware wrapping, and to have some additional guidance in identifying the relevant variables that needed to be tested in experiments, we established a few points that we wanted to test and evaluate;

**Performance in speed:** We need to know if the wrapping method was significantly slower than the component(s) being wrapped. Since the wrapping would allow the component to be used only at crucial times, and allow a larger portion of programs to be run on a more modern machine, we were mainly focusing on short and simple programs that would for instance utilize memory mapped functionality of the legacy hardware.

**Consistency in usage:** It is important that the method does not introduce any quirks that would have to be considered when implementing it as a wrapper. If certain programs or sequences of instructions behave differently when run via the wrapper compared to when run natively, the method would introduce too much friction to be viable as a wrapper. We decided to test this by grouping instructions by addressing mode into categories of instructions with similar properties, and to test groups of instructions both isolated and mixed together.

**Correctness:** Naturally, the wrapping method should not introduce or be responsible for any erroneous results during usage. We decided to use a digital logic analyzer in order to monitor the behavior of the system during the test programs.

**Bottlenecks and overhead:** For systems where timing is crucial, it is important to determine and understand any overhead or bottlenecks that come with the wrapper in order to determine its utility. Since the NESizer2 method was constructed to send one instruction at a time, we wanted to see how this affected a longer sequence of continuous instructions, and determine if there exists any significant delay between instructions.

## 4 Project Work and 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.

### 4.1 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 the 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. Figure 1 shows a simple illustration of the iterative process of the literature study.

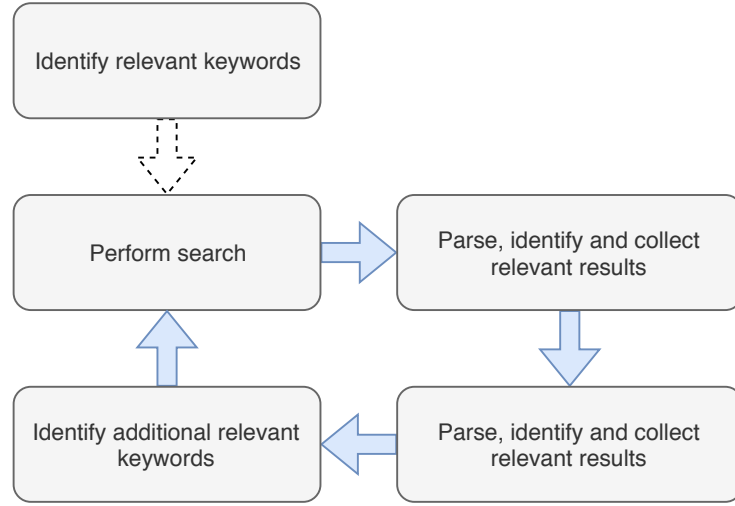


Figure 1: Illustrating the iterative process of the literature study.

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 were *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.

## 4.2 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.

### 4.3 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

#### 4.3.1 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*. [24] 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.

#### 4.3.2 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. [25] 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. Figure 7 and 8 in Appendix A illustrates the misbehaving circuit and the corrected circuit, respectively.

### 4.3.3 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.

### 4.3.4 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.

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

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 and discussed in sections Results and [Conclusions & discussion].

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

## 4.4 Experiments phase

In order to measure time according to our criterias, we attempted to set up the SPI peripheral on the Atmega328P. Unfortunately, the programmer we used did not support two-way SPI communication, which forced us to further extend the implementation with a second microcontroller unit.

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

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, and further illustrated in figure 2:

1. Validate data output and record per-instruction-overhead 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

For step 1 we used a digital logic analyzer to measure the bit value on the output of the RP2A03, in order to ensure that an expected value was output. We also recorded the time and number of cycles between instruction for each instruction type at the same time.

For steps 2 through 5 we utilized the Arduino M0 Pro to act as a master controller unit, which we programmed to tell the Atmega328P to start executing programs on the RP2A03 on our command, and at the same time measure the time it took for the Atmega328P to execute. Three different test programs were written for each controller device (Arduino M0 Pro and Atmega328P), each following the same pattern:

The Arduino waits for the Atmega328P to signal that it has completed its setup routine. The Atmega328P then waits for a start signal from the Arduino, which is sent upon the press of a hardware button. When the button is pressed, the Arduino sends a *go* signal to the Atmega328P and starts a

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

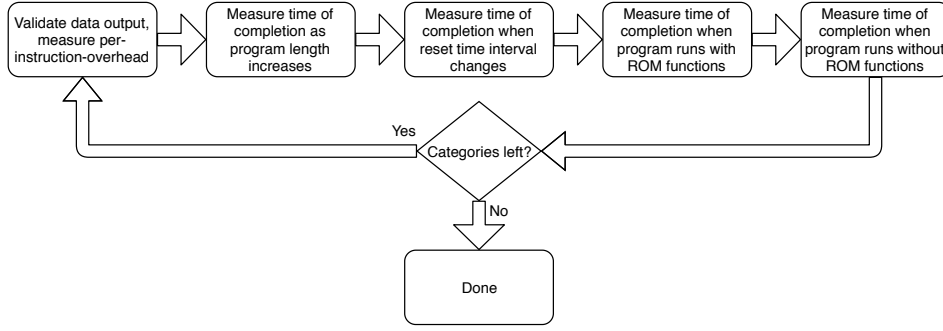


Figure 2: Block diagram illustrating the iterative testing process.

timer. It then waits for the Atmega328P to signal that it has finished its execution, where upon the Arduino will stop its timer and save the results. When the test program has finished, the Arduino outputs all the measured times.

## 5 Results

This chapter details the results of all tests that were performed on the system. The tests were performed as outlined in the subchapter Experiments phase, and the test results have been labeled

1. Data validation and per-instruction-overhead
2. Increasing number of instructions
3. Increasing frequency of resets
4. Using ROM-Emulation functions
5. Not using ROM-Emulation functions

, respectively.

Firstly, all tests are presented and compared across categories, followed by a comparison of tests for each separate category. The *Mixed* category was not applicable in test case 5, since the task of reading mixed instructions and placing them correctly in the data structures used for communication would effectively result in the exact steps taken by the ROM-emulation functions.

### 5.1 Comparison: Test cases

Test cases 1 through 5 are shown in figures 3, 4, 5 and 6 respectively. Categories are compared to each other in each figure where applicable. Table 3 details the number of cycles needed per instruction in each category, together with a comparison against the number of cycles needed in an unwrapped system. See Appendix B for tables of raw test result data.

Table 3: Performance measured in Cycles per Instruction

Category	Wrapped	Unwrapped	Difference
Immediate	8	2	400%
Zero Page	8	2	400%
Absolute	9	3	300%

As shown in figure 3, data could not be validated for categories *Zero Page* and *Absolute*, and subsequently not *Mixed*. The instructions sent from the master unit and the execution time on the slave unit behaves as expected, but the data output after execution is not correct. As shown in table 4, the LDA (0xA5) instruction loads the value 0x04 from Zero Page address 0x24, however trying to store the accumulator at another memory address strangely enough outputs 0x24 from the accumulator instead.

Table 4: Illustrating error in memory operations

Data bus	Comment
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	Zero Page STA instruction Opcode
0x06	Zero Page STA Operand, Zero Page Address 0x06
0x24	Value on accumulator to be written to memory (Expected 0x04)

When not performing memory operations, i.e. accumulator writes and ALU operations, all data was validated as expected, even when performing sequences of connected operations. Table 5 shows a short sequence of instructions storing a value in the accumulator and performing an *Exclusive OR* (EOR) operation on it.

Table 5: Illustrating a sequence of two accumulator operations

Data bus	Comment
0xA9	Immediate LDA instruction Opcode
0x01	Immediate LDA Operand, Immediate value 0x01
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x49	Immediate EOR instruction Opcode
0xFF	Immediate EOR Operand, Immediate value 0xFF
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	“Idle” Zero Page STA instruction
0x85	Zero Page STA instruction Opcode
0x85	Zero Page STA Operand, Zero Page Address 0x85
0xFE	Result of EOR in accumulator to be stored in memory

## 6 Discussion & conclusions

This chapter will present a summary of our thoughts on the project work and experiments. Firstly we present thoughts on our choice of methods, how effectively we perceived them to be in practice for this particular study, and thoughts on our choice of tools and technology, and the project work in general. Secondly we will discuss the experiments and measured results, and finally present selected conclusions.



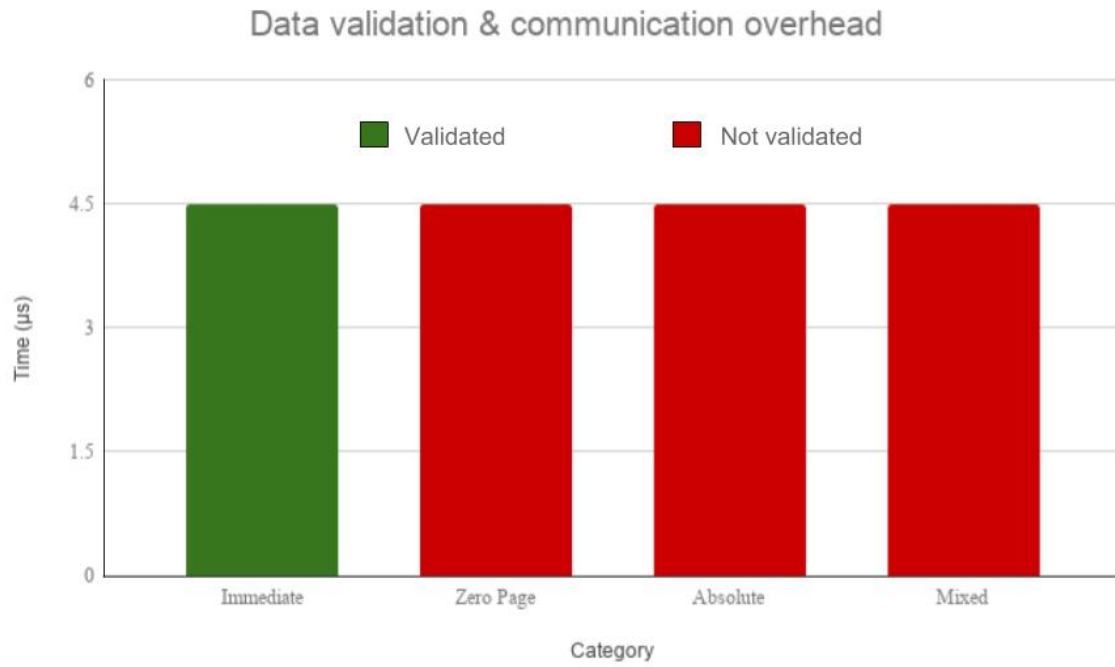


Figure 3: Validated and not validated instruction types, as well as their respective communication overhead.

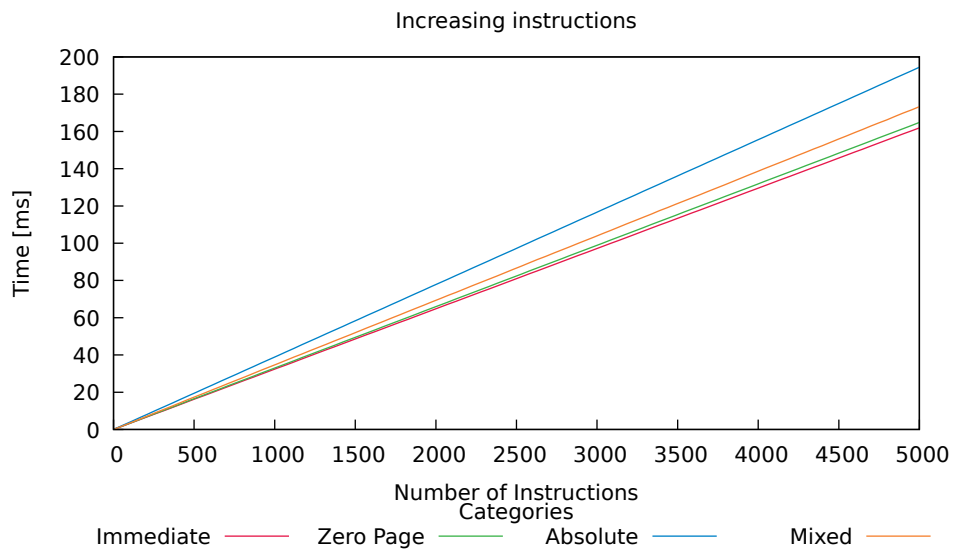


Figure 4: Execution time for each instruction type as a function of number of instructions.

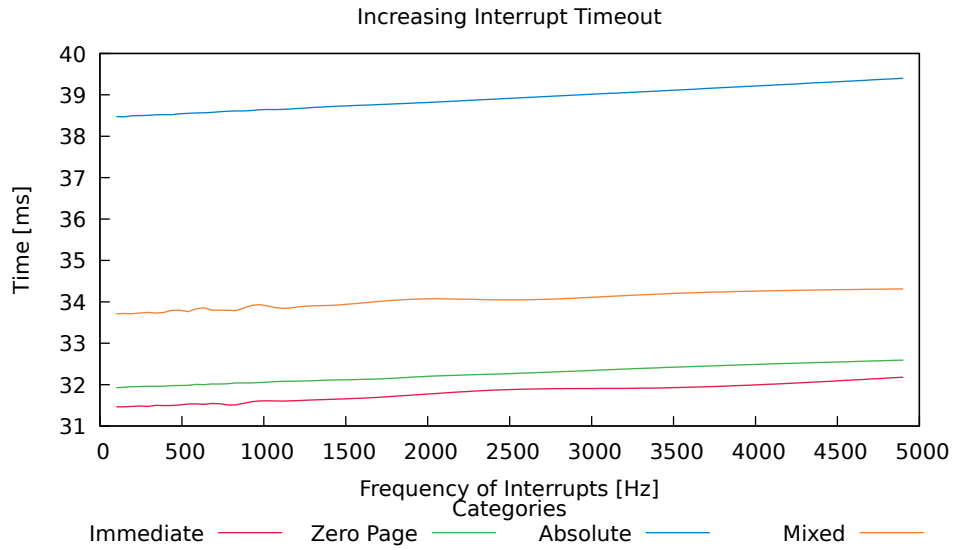


Figure 5: Execution time of 1000 instructions for each instruction type when increasing the frequency of interrupts.

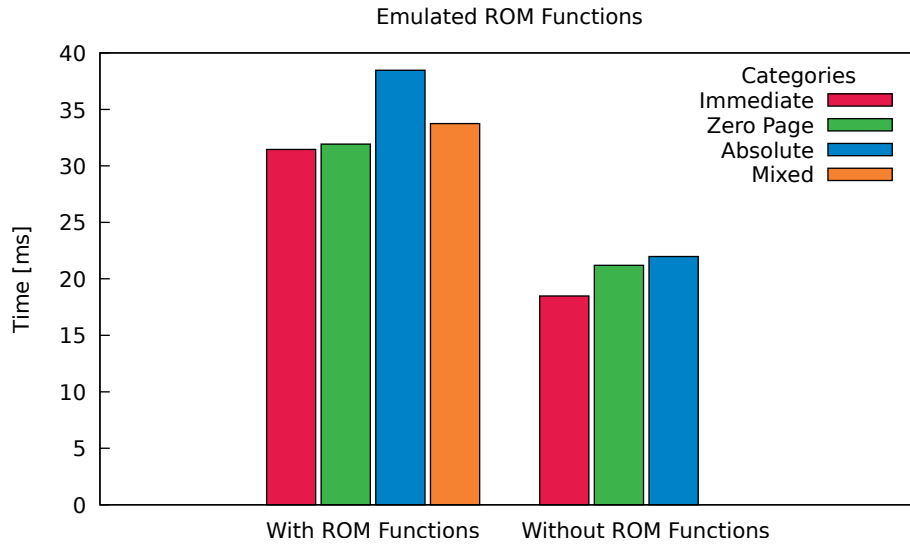


Figure 6: Comparison of each instruction types execution time of 1000 instructions with ROM functions, as well as without ROM functions.

## 6.1 Project work

### 6.1.1 Research Methodology

Since experimental research is based on identifying and testing the underlying variables that make up the entire system, much of the project was designed with these variables and how to structure experiments in mind. We found that experimental research was a good fit for this type of problem, however we believe that the process of identifying the variables requires a better theoretical understanding of the target system and the experimental approach than we had at the time of design and implementation. We would suggest a more thorough study of both experimental research philosophy and approach, as well as the system that should be analyzed, before designing an experimental research study of this kind.

When analyzing our results, we evaluated them against our evaluation criteria to draw conclusions. We feel that our conclusions are true, however in hindsight we realize that we should have applied a proven, more rigid framework or methodology in order to avoid potential bias.

### 6.1.2 Scrum in this project

We had initially planned to implement additional wrapping methods, in order to compare the performance between the different methods of wrapping, but due to technical issues and time limitation we were unable to implement them fully. However, this affected our choice of working method; we believed initially that *Scrum* could give us a good overview of the implementation work across the different wrapping methods, each with their own requirements and tasks. When we realized that it was no longer feasible to continue development of the additional wrapping methods, Scrum was not as effective anymore, since we started to focus more on either the same tasks or closely related tasks. This also meant since that we could continuously plan and discuss the iterative process, we no longer had much use for sprint and daily meetings. For projects of this limited scope, we believe that there may not be a need for more involved frameworks such as *Scrum*.

### 6.1.3 Arduino M0 Pro

As mentioned previously in the text, the idea for this project was sparked by a hobby project which was to implement a portable music tracker utilizing the NES processor Ricoh 2A03, together with a microcontroller. Initially, we set out to use an Arduino unit in this hobby project, but after experimenting with an Arduino M0 Pro we realized that, due to the lack of documentation and its limited flexibility, we'd much prefer a microcontroller with a more detailed documentation where we could, in a more familiar manner, create our own complementary library code and use a compiler of our choosing. We settled for the Atmega328P as the master controller in the circuit. The Arduino M0 Pro saw a comeback though, as it was used in the test phase of the project and proved to be quite useful for programming simple tasks, and its high clock frequency allowed us to produce more accurate measurements.

### 6.1.4 Atmega328P

The Atmega328P was useful in our project, as it is fairly easy to program (AVR architecture), and is very well documented. It is also the same processor that the NESizer2 method implements (with minor differences which do not affect the implementation), meaning that we only had to convert some of the source code, and that the assembly routines could be used as is. We felt that the choice was

appropriate for two reasons: (i) it made the software easier to implement, and (ii) we could stay closer to the source code that we wish to evaluate.

### 6.1.5 Programming toolchain

During the research phase, we discovered that a popular compiler for AVR microcontrollers was AVRDUDE [26], a cross-platform programming software compatible with a wide range of programmers. It needs a compiled hex file, meaning a separate compiler is required. We used `avr-gcc` [27] for compiling our source code, and we used AVR Libc [28] which provides library functions for AVR microprocessors. As `avr-gcc` is a C compiler, a language both of us are comfortable with, and as all of the above mentioned tools are documented and widely used, we felt that this entire toolchain was the obvious choice.

We found, also during the research stage, that a popular programmer for AVR micro controllers was the USBasp [29], which we obtained and used for the project. One negative aspect of this was that there was no serial interface to use for debugging, something we did not notice until later in the project. Had we done more thorough research earlier in the project work, we could have found and used a different programmer that included this functionality so that we did not have to write Arduino programs for the testing phase, which could have saved us some time.

### 6.1.6 Oscilloscope, Digital logic analyzer

In attempts to verify that the RP2A03 would execute a basic program, we initially used an oscilloscope to monitor the R/W pin to see if it behaved according to the input instructions, which we were successful in doing. However we could not find any good way of validating our input and output data. After consulting with our supervisor, we were provided with a digital logic analyzer. This helped us immensely in moving forward with the project, as we could validate that our inputs produced expected outputs, and we would recommend any reproducing persons to use one as well.

## 6.2 Experiments & Results

### 6.2.1 Data validation & Memory operations

As shown in the Results section, a major part of the intended functionality did not produce correct results. Any program or sequence of instructions involving memory operations led to faulty data. Although we were unable to determine the cause of this error, we have established two possible explanations; (i) a bug in the software implementation of memory operations, or (ii) a defect memory unit of the RP2A03. Since this error did not occur for operations involving the ALU, accumulator or system level operations (i.e. disable interrupts etc.), and only for memory operations independent of instruction size, case (i) seems unlikely. We could also confirm that the data on the data bus, and the behavior of the R/W pin, was indicative of the correct instructions being sent at correct timing, which further makes (i) a less likely cause. However, since we did not have access to a replacement RP2A03 unit, or diagnostic tools to investigate the hardware of the unit we used, we were unable to rule out the RP2A03 as the cause either. Fortunately, as this error only affected the actual stored and loaded data and not the machines behavior in terms of cycles per instruction etc., we could still use memory operations in our test programs in order to measure timing.

### 6.2.2 Minimum communication overhead

We could see a minimum communication overhead, measured as the time between each consecutive instruction in a program, of  $4.5 \mu s$ . This time was independent of instruction type and size, and seems to affect each instruction equally. We found that this minimum communication overhead (or possibly main bottleneck of the communication method) was made up of two sets of the idle instruction, running over a total of six RP2A03 CPU cycles. An example of this can be seen in the Results section, in Table 5. Since each instruction sending starts with a synchronization step and ends by placing the idle instruction on the data bus before returning to the calling function, the lowest theoretical overhead is one full idle instruction. The resulting performance hit can be seen in table 3 which shows as much as 400% difference at least.

However, upon returning to the main program, the master unit will have to load a new instruction and turn off all interrupts before initiating communication again, and we believe that the time it takes for the master unit to perform these steps causes it to initiate communications somewhere during the second idle instruction. Between instructions, the master unit also has to handle timer interrupts and perform periodic resets of the RP2A03 program counter. This will cause longer times between instructions at periodic intervals. We decided not to include this in our results since it occurs relatively infrequently, and is highly dependent on the settings for the timer interrupts.

If it is possible to increase the frequency gap between the master and slave unit, it may be possible to further decrease the minimum communication overhead. This could perhaps be done by using a master unit that runs on a higher frequency in combination with a greater clock divider. Since our implementation requires six whole cycles between each contiguous instruction, it is clearly not suited for systems where timing is critical as of its current state. It is possible that this can be remedied by modifying the communication protocol; given a reset of the slave unit, the system should theoretically be able to continuously send instructions by simply fetching and putting one byte at a time on the data bus, as long as the sequence of instruction fits within a full period without the need for a reset. We can however not confirm this hypothesis, and it is possible that the communication protocol can only guarantee synchronization for shorter bursts of data.

### 6.2.3 Running times of test programs

The behavior of the system when increasing the program length was as expected, and we could observe a linear increase with increasing the number of instructions. The Absolute and Mixed category had a longer execution time than the other categories which is to be expected, considering that absolute addressing mode instructions require 4 Bytes. Interestingly, we can observe a difference between Zero Page and Immediate categories, even though the instructions are of the same length. It would have been beneficial to compare against a regular ROM to see if this is normal behavior or not.

As for increasing the frequency of the timer interrupts, that are needed to reset the program counter of the slave unit, it produced hardly any noticeable difference. This means that the settings for the timer could be set to trigger more often, in order to further ensure a safety margin of not accidentally interpreting internal memory data as instruction data, without a significant performance hit.

## 7 Future work

First and foremost, we acknowledge that the proposed method of hardware wrapping presented in this work shows inconclusive results. In order to tell whether this method is at all viable, it is required to (i) investigate whether the “broken” memory operations encountered during the tests was caused by a faulty RP2A03 unit, or if it was because of an error in the proposed implementation, and (ii) compare

it against other methods of hardware wrapping on roughly equal level of complexity in implementation. As for case (ii), we had originally intended to compare this implementation against a different method of wrapping, which used a *shared memory* to communicate between the master and slave unit, however we were unable to complete it because of the aforementioned problematic memory operations. The schematics for the shared memory approach can be found in Appendix A.

A natural step from our work would be to expand the functionality further by allowing for a complete instruction set. As discussed in section Sprint 5, Entire instruction set, there is no need for branching or jumping instructions, but there are still a large number of instructions left that was outside the scope of our study. When all relevant parts of the instruction set has been implemented, the final step(s) would be to test a real application of the method, and test how well this method works in practice.

## 8 References

- [1] J. Bisbal, D. Lawless, B. Wu, and J. Grimson, “Legacy information systems: Issues and directions,” *IEEE Software*, vol. 16, no. 5, pp. 103–111, 1999.
- [2] H. M. Sneed, *Annals of Software Engineering*, vol. 9, no. 1/4, pp. 293–313, 2000.
- [3] “Jaffe-/nesizer2.” <https://github.com/Jaffe-/NESizer2>; GitHub.
- [4] K. Wallnau, R. C. Seacord, and S. C. Dorda, “A survey of black-box modernization approaches for information systems,” in *Proceedings international conference on software maintenance ICSM-94*, 2000.
- [5] R. C. Seacord, D. Plakosh, and G. A. Lewis, *Modernizing legacy systems: Software technologies, engineering process and business practices*. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 2003.
- [6] M. Downson, “The ariane 5 software failure,” *SIGSOFT Softw. Eng. Notes*, vol. 22, no. 2, pp. 84, Mar. 1997.
- [7] “N° 33–1996: Ariane 501 - presentation of inquiry board report.” [https://www.esa.int/For\\_Media/Press\\_Releases/Ariane\\_501\\_-\\_Presentation\\_of\\_Inquiry\\_Board\\_report](https://www.esa.int/For_Media/Press_Releases/Ariane_501_-_Presentation_of_Inquiry_Board_report).
- [8] “Poison pcs and toxic tvs, californias biggest environmental crisis that you’ve never heard of.” <http://svtc.org/wp-content/uploads/ppc-ttv1.pdf>.
- [9] “Examensarbete t5 läkarprogrammet: Göra litteraturstudie.” <http://libguides.lub.lu.se/c.php?g=297461&p=4112444>.
- [10] D. Ary, L. C. Jacobs, A. Razavieh, and C. K. Sorensen, *Introduction to research in education*. Wadsworth Publishing, 2009.
- [11] A. Håkansson, “Portal of research methods and methodologies for research projects and degree projects,” in *Proceedings of the international conference on frontiers in education : Computer science and computer engineering fecs’13*, 2013, pp. 67–73.
- [12] “Legacy.” <https://www.merriam-webster.com/dictionary/legacy>; Merriam Webster.
- [13] “Little sound dj.” <https://www.littlesounddj.com/>.
- [14] “IEEE chip hall of fame: MOS technology 6502 microprocessor.” <https://spectrum.ieee.org/tech-history/silicon-revolution/chip-hall-of-fame-mos-technology-6502-microprocessor>.
- [15] “MOS mcs6500 microcomputer family programming manual.” MOS Technology, Inc., 1976.
- [16] “Atmega328/p.” <http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-42735-8-bit-AVR->

Microcontroller-ATmega328-328P\_Datasheet.pdf; Microchip, 2016.

[17] J. L. Alberi, “A method of interprocessor communication for a multiprocessor environment,” *Nuclear Science, IEEE Transactions on*, vol. 29, pp. 84–86, Mar. 1982.

[18] Y. N. Patt, “Methodologies for experimental research in computer architecture and performance measurement,” in *Twenty-third annual hawaii international conference on system sciences*, 1990, vol. 1, pp. 2–5 vol.1.

[19] “Agile.” <https://www.merriam-webster.com/dictionary/agile>; Merriam Webster.

[20] K. S. et al, “Manifesto for agile software development.” <http://agilemanifesto.org/>, 2001.

[21] M. Kropp and A. Meier, “Teaching agile software development at university level: Values, management, and craftsmanship,” in *2013 26th international conference on software engineering education and training (csee t)*, 2013, pp. 179–188.

[22] K. Schwaber and J. Sutherland, <http://https://www.scrumguides.org/>, 2016.

[23] H. Kniberg, 2nd ed. C4Media, InfoQ.com, 2015.

[24] “Nesdev wiki.” [http://wiki.nesdev.com/w/index.php/Nesdev\\_Wiki](http://wiki.nesdev.com/w/index.php/Nesdev_Wiki).

[25] “How to quickly get a 6502 cpu running.” <http://lateblt.tripod.com/bit63.txt>.

[26] “AVRDUDE.” <https://savannah.nongnu.org/projects/avrdude>.

[27] “Avr-gcc.” <https://gcc.gnu.org/wiki/avr-gcc>.

[28] “AVR libc.” <https://www.nongnu.org/avr-libc/user-manual/index.html>.

[29] “USBasp.” <https://www.fischl.de/usbasp/>.

## 9 Appendix

This section contains material that may be of use to the reader. Appendix A presents circuit diagrams and flowchart figures. Appendix B presents the produced data in a raw form, compiled into tables.

### 9.1 Appendix A

In this section, the flowcharts and circuit diagrams that were created during the research design and design phase are compiled, as well as revised versions from later in the project work.

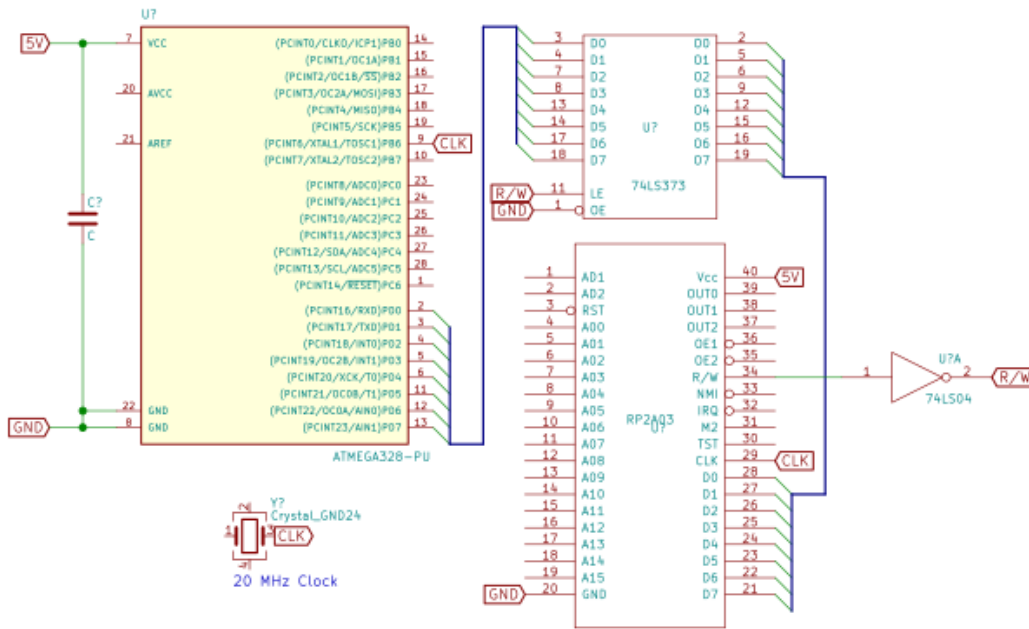


Figure 7: The first iteration of the circuit, with the misplaced LE pin on the 74LS373 latch .



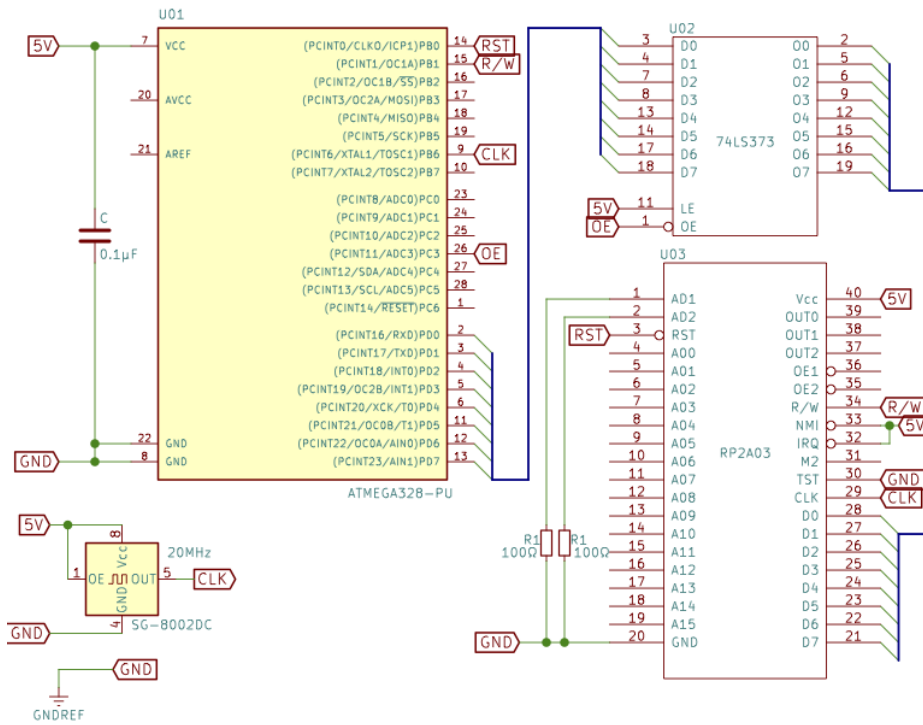


Figure 8: The second iteration of the circuit, with the corrected LE pin on the 74LS373 latch.

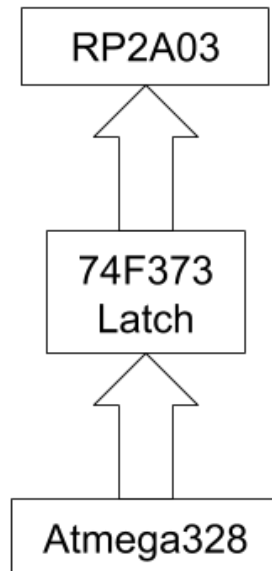


Figure 9: Block diagram of the hardware components and the communication channels of the analyzed implementation.



## 9.2 Appendix B

This section contains the raw data collected during the experiment phase, each presented in a table.

Table 6: Time to execute 1000 instructions on default settings with ROM functions, measured in ms

No. of instructions	Absolute	Immediate	Zero Page	Mixed
1000	38.47	31.45	31.93	33.74

Table 7: Time to execute 1000 instructions on default settings without ROM functions, measured in ms

No. of instructions	Absolute	Immediate	Zero Page
1000	21.98	18.48	21.20

Table 8: Time to execute programs of varying instruction size, ranging from 10 to 5000, measured in ms

No. of instructions	Absolute	Immediate	Zero Page	Mixed
10	0.396	0.337	0.333	0.363
20	0.784	0.656	0.667	0.712
30	1.173	0.980	0.996	1.030
40	1.563	1.297	1.326	1.352
50	1.952	1.627	1.653	1.791
60	2.336	1.948	1.983	2.032
70	2.724	2.276	2.316	2.484
80	3.116	2.594	2.643	2.732
90	3.506	2.921	2.976	3.149
100	3.892	3.240	3.306	3.508
110	4.286	3.568	3.641	3.803
120	4.679	3.889	3.958	4.161
130	5.067	4.215	4.293	4.518
140	5.454	4.544	4.618	4.870
150	5.837	4.865	4.959	5.214
160	6.228	5.182	5.282	5.489
170	6.620	5.517	5.603	5.922
180	7.020	5.836	5.939	6.290
190	7.405	6.158	6.272	6.532
200	7.788	6.483	6.599	6.983
210	8.180	6.807	6.933	7.265
220	8.560	7.127	7.261	7.595
230	8.953	7.462	7.583	7.991
240	9.348	7.773	7.924	8.359
250	9.737	8.112	8.241	8.680
260	10.124	8.424	8.575	9.012
270	10.511	8.749	8.908	9.330
280	10.910	9.075	9.236	9.677

No. of instructions	Absolute	Immediate	Zero Page	Mixed
290	11.293	9.396	9.569	10.092
300	11.678	9.720	9.894	10.437
310	12.075	10.041	10.227	10.687
320	12.464	10.364	10.552	11.157
330	12.845	10.698	10.880	11.393
340	13.239	11.020	11.212	11.820
350	13.624	11.340	11.545	12.157
360	14.017	11.664	11.875	12.467
370	14.397	11.984	12.203	12.810
380	14.797	12.302	12.530	13.175
390	15.181	12.642	12.861	13.527
400	15.572	12.957	13.193	13.886
410	15.961	13.281	13.521	14.233
420	16.355	13.608	13.850	14.519
430	16.733	13.937	14.183	14.902
440	17.122	14.250	14.509	15.303
450	17.518	14.573	14.840	15.548
460	17.903	14.892	15.168	15.981
470	18.296	15.228	15.503	16.295
480	18.683	15.551	15.830	16.605
490	19.075	15.878	16.166	16.961
500	19.460	16.198	16.492	17.363
510	19.842	16.519	16.817	17.677
520	20.238	16.855	17.145	18.013
530	20.622	17.174	17.479	18.380
540	21.016	17.495	17.813	18.751
550	21.411	17.824	18.141	19.087
560	21.792	18.142	18.462	19.331
570	22.189	18.464	18.803	19.819
580	22.568	18.791	19.132	20.051
590	22.965	19.118	19.451	20.531
600	23.352	19.435	19.782	20.766
610	23.740	19.768	20.111	21.122
620	24.127	20.076	20.446	21.507
630	24.518	20.412	20.773	21.853
640	24.903	20.732	21.107	22.190
650	25.294	21.056	21.432	22.516
660	25.689	21.382	21.768	22.870
670	26.072	21.709	22.093	23.249
680	26.455	22.030	22.422	23.607
690	26.857	22.355	22.753	23.843
700	27.242	22.679	23.088	24.323
710	27.629	22.991	23.415	24.542
720	28.017	23.324	23.740	25.037
730	28.405	23.650	24.073	25.281
740	28.795	23.963	24.398	25.622
750	29.182	24.290	24.726	25.989
760	29.572	24.624	25.059	26.363
770	29.963	24.937	25.385	26.693
780	30.343	25.266	25.725	27.021

No. of instructions	Absolute	Immediate	Zero Page	Mixed
790	30.743	25.602	26.044	27.415
800	31.128	25.910	26.379	27.767
810	31.520	26.234	26.705	28.074
820	31.904	26.568	27.034	28.388
830	32.296	26.888	27.371	28.823
840	32.675	27.214	27.696	29.069
850	33.075	27.532	28.024	29.465
860	33.459	27.859	28.355	29.855
870	33.853	28.179	28.684	30.136
880	34.237	28.503	29.016	30.483
890	34.632	28.829	29.350	30.848
900	35.017	29.146	29.671	31.201
910	35.408	29.483	30.002	31.560
920	35.792	29.798	30.334	31.913
930	36.179	30.119	30.661	32.219
940	36.579	30.452	30.993	32.555
950	36.953	30.773	31.320	32.979
960	37.347	31.098	31.664	33.213
970	37.737	31.417	31.979	33.688
980	38.130	31.736	32.313	33.932
990	38.516	32.062	32.641	34.283
1000	38.910	32.384	32.975	34.698
1010	39.297	32.706	33.301	35.029
1020	39.681	33.037	33.629	35.363
1030	40.074	33.362	33.957	35.693
1040	40.459	33.691	34.288	36.018
1050	40.851	34.010	34.615	36.376
1060	41.243	34.339	34.955	36.784
1070	41.627	34.655	35.279	37.102
1080	42.017	34.978	35.603	37.387
1090	42.400	35.302	35.938	37.836
1100	42.793	35.625	36.266	38.085
1110	43.178	35.960	36.598	38.454
1120	43.577	36.277	36.924	38.882
1130	43.959	36.597	37.258	39.149
1140	44.354	36.925	37.586	39.505
1150	44.741	37.263	37.911	39.862
1160	45.130	37.568	38.247	40.217
1170	45.518	37.892	38.571	40.564
1180	45.910	38.223	38.907	40.869
1190	46.294	38.541	39.233	41.227
1200	46.686	38.859	39.559	41.642
1210	47.069	39.179	39.889	41.881
1220	47.465	39.507	40.221	42.346
1230	47.850	39.827	40.548	42.582
1240	48.236	40.154	40.877	43.014
1250	48.626	40.480	41.205	43.340
1260	49.017	40.812	41.538	43.659
1270	49.410	41.138	41.871	44.012
1280	49.798	41.449	42.196	44.362

No. of instructions	Absolute	Immediate	Zero Page	Mixed
1290	50.182	41.782	42.528	44.723
1300	50.571	42.110	42.864	45.070
1310	50.965	42.435	43.189	45.389
1320	51.346	42.755	43.516	45.713
1330	51.741	43.087	43.846	46.152
1340	52.127	43.408	44.179	46.386
1350	52.517	43.728	44.508	46.850
1360	52.909	44.058	44.839	47.094
1370	53.296	44.366	45.165	47.509
1380	53.685	44.691	45.502	47.860
1390	54.076	45.024	45.826	48.168
1400	54.459	45.345	46.156	48.518
1410	54.849	45.668	46.478	48.872
1420	55.236	45.987	46.815	49.229
1430	55.625	46.314	47.143	49.574
1440	56.027	46.646	47.474	49.847
1450	56.405	46.965	47.803	50.283
1460	56.799	47.299	48.133	50.641
1470	57.180	47.615	48.463	50.890
1480	57.574	47.930	48.796	51.341
1490	57.962	48.256	49.125	51.627
1500	58.357	48.583	49.452	51.939
1510	58.735	48.892	49.779	52.349
1520	59.131	49.229	50.115	52.706
1530	59.512	49.551	50.434	53.030
1540	59.904	49.886	50.764	53.372
1550	60.304	50.206	51.092	53.695
1560	60.680	50.529	51.431	54.034
1570	61.070	50.859	51.761	54.449
1580	61.462	51.177	52.083	54.797
1590	61.845	51.500	52.414	55.046
1600	62.239	51.812	52.748	55.517
1610	62.626	52.140	53.073	55.752
1620	63.014	52.458	53.405	56.173
1630	63.403	52.787	53.741	56.515
1640	63.798	53.113	54.073	56.826
1650	64.182	53.442	54.407	57.163
1660	64.572	53.770	54.719	57.535
1670	64.960	54.088	55.058	57.894
1680	65.353	54.410	55.392	58.246
1690	65.737	54.731	55.718	58.591
1700	66.132	55.070	56.041	58.881
1710	66.519	55.379	56.382	59.268
1720	66.913	55.715	56.708	59.664
1730	67.294	56.035	57.031	59.906
1740	67.683	56.347	57.360	60.341
1750	68.078	56.674	57.695	60.658
1760	68.464	56.999	58.020	60.970
1770	68.851	57.328	58.345	61.321
1780	69.244	57.655	58.685	61.710

No. of instructions	Absolute	Immediate	Zero Page	Mixed
1790	69.629	57.967	59.008	62.034
1800	70.024	58.289	59.349	62.370
1810	70.407	58.617	59.675	62.743
1820	70.796	58.934	60.001	63.116
1830	71.187	59.257	60.334	63.449
1840	71.572	59.593	60.664	63.692
1850	71.960	59.909	60.990	64.185
1860	72.352	60.239	61.324	64.409
1870	72.740	60.556	61.650	64.889
1880	73.130	60.888	61.976	65.115
1890	73.520	61.201	62.311	65.482
1900	73.907	61.537	62.641	65.861
1910	74.303	61.854	62.968	66.221
1920	74.683	62.188	63.298	66.548
1930	75.070	62.507	63.629	66.867
1940	75.460	62.842	63.951	67.228
1950	75.844	63.151	64.281	67.602
1960	76.238	63.468	64.609	67.969
1970	76.628	63.802	64.942	68.202
1980	77.018	64.117	65.274	68.684
1990	77.405	64.448	65.600	68.913
2000	77.797	64.772	65.928	69.399
2010	78.184	65.090	66.272	69.643
2020	78.572	65.414	66.596	69.976
2030	78.966	65.744	66.924	70.339
2040	79.356	66.084	67.253	70.721
2050	79.741	66.400	67.581	71.044
2060	80.131	66.717	67.913	71.377
2070	80.520	67.045	68.237	71.766
2080	80.908	67.376	68.572	72.125
2090	81.287	67.691	68.901	72.430
2100	81.684	68.006	69.228	72.744
2110	82.071	68.328	69.561	73.183
2120	82.460	68.652	69.891	73.422
2130	82.855	68.974	70.218	73.827
2140	83.239	69.315	70.556	74.202
2150	83.633	69.628	70.884	74.500
2160	84.020	69.952	71.212	74.843
2170	84.408	70.294	71.545	75.208
2180	84.799	70.590	71.875	75.560
2190	85.183	70.935	72.198	75.922
2200	85.573	71.249	72.531	76.259
2210	85.965	71.571	72.853	76.583
2220	86.348	71.900	73.187	76.909
2230	86.745	72.228	73.513	77.344
2240	87.130	72.548	73.842	77.578
2250	87.522	72.858	74.169	78.051
2260	87.904	73.183	74.503	78.290
2270	88.299	73.507	74.836	78.634
2280	88.689	73.831	75.166	79.053

No. of instructions	Absolute	Immediate	Zero Page	Mixed
2290	89.072	74.162	75.493	79.393
2300	89.466	74.487	75.826	79.727
2310	89.844	74.812	76.157	80.045
2330	90.628	75.451	76.810	80.742
2320	90.244	75.157	76.484	80.375
2340	91.017	75.784	77.149	81.143
2350	91.408	76.104	77.473	81.459
2360	91.791	76.425	77.800	81.747
2370	92.191	76.754	78.128	82.199
2380	92.568	77.077	78.468	82.441
2390	92.966	77.407	78.789	82.803
2400	93.359	77.732	79.119	83.238
2410	93.739	78.056	79.444	83.517
2420	94.125	78.386	79.778	83.864
2430	94.525	78.708	80.119	84.218
2440	94.907	79.028	80.440	84.573
2450	95.299	79.350	80.764	84.923
2460	95.687	79.665	81.099	85.234
2470	96.081	80.000	81.430	85.576
2480	96.464	80.322	81.752	85.990
2490	96.857	80.655	82.087	86.238
2500	97.238	80.962	82.416	86.702
2510	97.627	81.288	82.751	86.938
2520	98.024	81.615	83.074	87.375
2530	98.407	81.932	83.403	87.708
2540	98.797	82.259	83.727	88.011
2550	99.184	82.591	84.071	88.365
2560	99.576	82.911	84.390	88.719
2570	99.961	83.238	84.724	89.079
2580	100.356	83.570	85.062	89.434
2590	100.751	83.894	85.380	89.741
2600	101.131	84.214	85.720	90.073
2610	101.517	84.531	86.047	90.509
2620	101.904	84.854	86.369	90.751
2630	102.294	85.181	86.704	91.217
2640	102.690	85.479	87.034	91.447
2650	103.076	85.825	87.356	91.870
2660	103.466	86.144	87.689	92.220
2670	103.852	86.463	88.022	92.522
2680	104.238	86.793	88.348	92.879
2690	104.621	87.116	88.682	93.228
2700	105.024	87.432	89.018	93.581
2710	105.405	87.764	89.343	93.927
2720	105.795	88.101	89.668	94.210
2730	106.192	88.408	89.993	94.641
2740	106.571	88.749	90.334	95.011
2750	106.963	89.071	90.656	95.252
2760	107.353	89.384	90.987	95.699
2770	107.741	89.717	91.317	95.989
2780	108.133	90.055	91.638	96.307



No. of instructions	Absolute	Immediate	Zero Page	Mixed
2790	108.515	90.350	91.973	96.713
2800	108.914	90.672	92.314	97.073
2810	109.292	91.008	92.631	97.399
2820	109.686	91.325	92.963	97.728
2830	110.078	91.652	93.297	98.063
2840	110.462	91.971	93.627	98.399
2850	110.855	92.284	93.956	98.815
2860	111.245	92.625	94.287	99.158
2870	111.629	92.947	94.607	99.400
2880	112.022	93.276	94.941	99.875
2890	112.411	93.615	95.271	100.112
2900	112.793	93.916	95.600	100.532
2910	113.189	94.257	95.935	100.871
2920	113.573	94.555	96.266	101.187
2930	113.962	94.906	96.596	101.533
2940	114.357	95.201	96.918	101.891
2950	114.744	95.542	97.244	102.235
2960	115.133	95.863	97.571	102.603
2970	115.515	96.189	97.912	102.946
2980	115.905	96.509	98.235	103.238
2990	116.294	96.827	98.565	103.627
3000	116.690	97.146	98.903	104.015
3010	117.070	97.477	99.226	104.268
3020	117.460	97.814	99.558	104.701
3030	117.859	98.117	99.893	105.018
3040	118.246	98.449	100.222	105.330
3050	118.625	98.772	100.553	105.680
3060	119.023	99.099	100.874	106.072
3070	119.407	99.427	101.205	106.400
3080	119.797	99.749	101.532	106.726
3090	120.185	100.077	101.863	107.096
3100	120.573	100.394	102.193	107.471
3110	120.970	100.724	102.518	107.813
3120	121.347	101.043	102.850	108.049
3130	121.746	101.364	103.186	108.545
3140	122.128	101.700	103.513	108.772
3150	122.516	102.022	103.853	109.242
3160	122.909	102.330	104.175	109.480
3170	123.300	102.656	104.500	109.841
3180	123.688	102.993	104.834	110.220
3190	124.073	103.314	105.157	110.576
3200	124.471	103.639	105.488	110.905
3210	124.850	103.951	105.814	111.229
3220	125.235	104.296	106.145	111.586
3230	125.630	104.614	106.477	111.967
3240	126.017	104.940	106.810	112.328
3250	126.409	105.269	107.140	112.560
3260	126.798	105.560	107.479	113.047
3270	127.187	105.898	107.801	113.258
3280	127.578	106.223	108.131	113.751

No. of instructions	Absolute	Immediate	Zero Page	Mixed
3290	127.974	106.553	108.459	113.998
3300	128.356	106.870	108.787	114.331
3310	128.746	107.194	109.117	114.701
3320	129.130	107.504	109.449	115.082
3330	129.521	107.842	109.778	115.408
3340	129.912	108.171	110.117	115.735
3350	130.296	108.486	110.430	116.132
3360	130.688	108.814	110.770	116.476
3370	131.077	109.145	111.092	116.790
3380	131.472	109.466	111.419	117.100
3390	131.850	109.794	111.758	117.549
3400	132.245	110.088	112.075	117.792
3410	132.630	110.443	112.408	118.179
3420	133.018	110.753	112.743	118.567
3430	133.406	111.081	113.084	118.849
3440	133.802	111.400	113.403	119.200
3450	134.187	111.726	113.743	119.565
3460	134.572	112.055	114.065	119.917
3470	134.969	112.387	114.398	120.286
3480	135.354	112.675	114.725	120.621
3490	135.741	113.027	115.049	120.938
3500	136.138	113.350	115.381	121.275
3510	136.517	113.680	115.709	121.701
3520	136.905	113.988	116.041	121.925
3530	137.294	114.312	116.368	122.411
3540	137.684	114.646	116.707	122.647
3550	138.075	114.963	117.033	122.990
3560	138.464	115.291	117.358	123.403
3570	138.865	115.608	117.686	123.756
3580	139.241	115.947	118.018	124.075
3590	139.638	116.262	118.346	124.408
3600	140.016	116.576	118.683	124.740
3610	140.412	116.908	119.006	125.104
3620	140.795	117.231	119.346	125.492
3630	141.183	117.565	119.665	125.816
3640	141.580	117.872	119.992	126.103
3650	141.968	118.203	120.322	126.560
3660	142.356	118.530	120.657	126.803
3670	142.737	118.850	120.980	127.174
3680	143.130	119.174	121.308	127.600
3690	143.521	119.499	121.647	127.878
3700	143.911	119.827	121.975	128.221
3710	144.297	120.154	122.303	128.568
3720	144.687	120.467	122.633	128.928
3730	145.080	120.791	122.970	129.282
3740	145.464	121.125	123.289	129.584
3750	145.858	121.449	123.620	129.927
3760	146.242	121.757	123.948	130.353
3770	146.632	122.087	124.278	130.608
3780	147.020	122.431	124.612	131.059

No. of instructions	Absolute	Immediate	Zero Page	Mixed
3790	147.413	122.732	124.944	131.298
3800	147.795	123.054	125.272	131.746
3810	148.190	123.388	125.599	132.059
3820	148.577	123.721	125.921	132.374
3830	148.971	124.027	126.250	132.734
3840	149.348	124.357	126.583	133.077
3850	149.745	124.689	126.919	133.432
3860	150.130	125.007	127.240	133.788
3870	150.525	125.343	127.578	134.109
3880	150.914	125.661	127.906	134.434
3890	151.299	125.989	128.243	134.862
3900	151.687	126.319	128.565	135.107
3910	152.079	126.623	128.905	135.561
3920	152.463	126.945	129.220	135.805
3930	152.856	127.266	129.553	136.226
3940	153.240	127.617	129.877	136.577
3950	153.635	127.939	130.220	136.881
3960	154.019	128.251	130.545	137.235
3970	154.420	128.571	130.875	137.588
3980	154.805	128.896	131.204	137.942
3990	155.183	129.224	131.539	138.292
4000	155.572	129.531	131.856	138.570
4010	155.967	129.850	132.188	138.994
4020	156.360	130.194	132.516	139.369
4030	156.746	130.506	132.852	139.601
4040	157.130	130.830	133.181	140.062
4050	157.525	131.164	133.517	140.344
4060	157.909	131.480	133.830	140.672
4070	158.300	131.795	134.171	141.079
4080	158.689	132.138	134.505	141.441
4090	159.074	132.459	134.822	141.759
4100	159.464	132.769	135.154	142.085
4110	159.848	133.100	135.488	142.413
4120	160.240	133.438	135.818	142.754
4130	160.634	133.750	136.151	143.165
4140	161.027	134.095	136.490	143.522
4150	161.413	134.414	136.805	143.760
4160	161.802	134.729	137.134	144.226
4170	162.189	135.045	137.461	144.469
4180	162.580	135.372	137.798	144.900
4190	162.964	135.693	138.128	145.229
4200	163.357	136.012	138.460	145.546
4210	163.746	136.338	138.783	145.886
4220	164.129	136.683	139.112	146.248
4230	164.518	136.977	139.438	146.610
4240	164.912	137.302	139.764	146.968
4250	165.295	137.635	140.097	147.308
4260	165.686	137.959	140.434	147.599
4270	166.070	138.281	140.767	147.988
4280	166.471	138.609	141.095	148.385

No. of instructions	Absolute	Immediate	Zero Page	Mixed
4290	166.864	138.928	141.418	148.621
4300	167.248	139.255	141.755	149.059
4310	167.632	139.584	142.079	149.366
4320	168.018	139.899	142.395	149.683
4330	168.413	140.226	142.741	150.038
4340	168.804	140.572	143.070	150.434
4350	169.187	140.873	143.404	150.755
4360	169.581	141.211	143.726	151.093
4370	169.964	141.529	144.064	151.466
4380	170.356	141.835	144.387	151.831
4390	170.741	142.175	144.718	152.176
4400	171.131	142.487	145.052	152.416
4410	171.519	142.816	145.376	152.904
4420	171.912	143.155	145.713	153.119
4430	172.301	143.475	146.037	153.599
4440	172.693	143.807	146.368	153.842
4450	173.077	144.110	146.697	154.200
4460	173.468	144.434	147.022	154.592
4470	173.854	144.770	147.355	154.938
4480	174.239	145.076	147.683	155.259
4490	174.633	145.405	148.018	155.596
4500	175.024	145.734	148.342	155.949
4510	175.410	146.051	148.676	156.313
4520	175.804	146.373	149.006	156.678
4530	176.194	146.707	149.328	156.919
4540	176.578	147.026	149.660	157.398
4550	176.967	147.349	149.983	157.628
4560	177.352	147.688	150.323	158.113
4570	177.739	148.010	150.653	158.359
4580	178.133	148.313	150.984	158.698
4590	178.520	148.657	151.305	159.065
4600	178.905	148.970	151.642	159.434
4610	179.302	149.301	151.970	159.767
4620	179.692	149.604	152.299	160.092
4630	180.074	149.954	152.627	160.497
4640	180.466	150.234	152.963	160.838
4650	180.853	150.578	153.291	161.159
4660	181.248	150.915	153.619	161.467
4670	181.630	151.241	153.946	161.897
4680	182.018	151.559	154.274	162.152
4690	182.418	151.898	154.614	162.539
4700	182.800	152.194	154.942	162.934
4710	183.191	152.531	155.267	163.218
4720	183.580	152.867	155.596	163.555
4730	183.963	153.176	155.926	163.916
4740	184.356	153.504	156.259	164.281
4750	184.742	153.825	156.587	164.639
4760	185.134	154.156	156.921	164.975
4770	185.522	154.477	157.246	165.293
4780	185.911	154.804	157.574	165.628

No. of instructions	Absolute	Immediate	Zero Page	Mixed
4790	186.300	155.120	157.907	166.054
4800	186.691	155.444	158.230	166.293
4810	187.078	155.775	158.563	166.771
4820	187.464	156.100	158.895	167.010
4830	187.857	156.425	159.224	167.353
4840	188.249	156.745	159.559	167.773
4850	188.632	157.062	159.878	168.114
4860	189.029	157.389	160.205	168.443
4870	189.413	157.718	160.544	168.765
4880	189.798	158.032	160.868	169.095
4890	190.190	158.357	161.209	169.453
4900	190.580	158.688	161.534	169.863
4910	190.976	159.007	161.862	170.174
4920	191.357	159.337	162.182	170.469
4930	191.740	159.660	162.506	170.919
4940	192.138	159.985	162.848	171.158
4950	192.526	160.299	163.180	171.528
4960	192.915	160.636	163.507	171.957
4970	193.298	160.975	163.833	172.223
4980	193.695	161.283	164.170	172.575
4990	194.080	161.611	164.495	172.932
5000	194.465	161.926	164.828	173.285

No. of instructions	Absolute	Immediate	Zero Page	Mixed
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Table 9: Measured time to run 1000 instructions with increasing frequency of the interrupt service routine (ISR) to run, measured in ms

No. of timeouts per second	Absolute	Immediate	Zero Page	Mixed
100.04	38.475	31.463	31.924	33.713
101.07	38.465	31.451	31.932	33.728
102.12	38.469	31.449	31.944	33.795
103.20	38.468	31.468	31.937	33.770
104.30	38.471	31.434	31.926	33.707
105.42	38.465	31.452	31.942	33.720
106.56	38.465	31.458	31.937	33.724
107.74	38.472	31.447	31.934	33.783
108.93	38.469	31.453	31.929	33.796
110.16	38.468	31.460	31.934	33.715
111.41	38.473	31.462	31.941	33.735
112.69	38.478	31.470	31.928	33.717
114.00	38.463	31.464	31.925	33.764
115.34	38.464	31.455	31.929	33.802
116.71	38.469	31.450	31.936	33.714
118.12	38.467	31.447	31.936	33.720
119.56	38.476	31.441	31.932	33.732
121.04	38.480	31.457	31.941	33.709
122.55	38.478	31.443	31.943	33.830
124.10	38.479	31.467	31.933	33.754
125.69	38.475	31.455	31.935	33.703
127.32	38.471	31.463	31.938	33.737
129.00	38.475	31.462	31.945	33.747
130.72	38.479	31.456	31.933	33.805
132.49	38.473	31.469	31.934	33.768
134.30	38.478	31.455	31.939	33.730
136.17	38.477	31.457	31.935	33.729
138.08	38.485	31.459	31.934	33.735
140.06	38.475	31.450	31.931	33.792
142.09	38.469	31.455	31.935	33.831
144.18	38.484	31.464	31.940	33.735
146.33	38.468	31.467	31.939	33.742
148.54	38.470	31.465	31.937	33.719
150.83	38.475	31.464	31.937	33.739
153.19	38.473	31.452	31.940	33.806
155.62	38.471	31.463	31.940	33.737
158.13	38.475	31.458	31.948	33.709
160.72	38.479	31.453	31.937	33.695
163.40	38.481	31.469	31.938	33.731
166.17	38.476	31.457	31.942	33.829
169.03	38.482	31.470	31.949	33.764
172.00	38.476	31.460	31.949	33.715

No. of timeouts per second	Absolute	Immediate	Zero Page	Mixed
175.07	38.486	31.464	31.945	33.724
178.25	38.482	31.462	31.943	33.710
181.55	38.486	31.480	31.942	33.787
184.98	38.491	31.462	31.941	33.783
188.54	38.489	31.464	31.944	33.741
192.23	38.483	31.483	31.951	33.720
196.08	38.495	31.473	31.955	33.702
200.08	38.485	31.476	31.937	33.773
204.25	38.489	31.479	31.946	33.819
208.59	38.488	31.476	31.945	33.763
213.13	38.486	31.470	31.951	33.740
217.86	38.479	31.472	31.933	33.729
222.82	38.490	31.478	31.952	33.730
228.00	38.491	31.469	31.942	33.820
233.43	38.494	31.464	31.951	33.795
239.12	38.500	31.468	31.958	33.742
245.10	38.500	31.484	31.953	33.730
251.38	38.493	31.471	31.954	33.743
258.00	38.495	31.488	31.952	33.791
264.97	38.498	31.470	31.955	33.815
272.33	38.500	31.475	31.954	33.748
280.11	38.508	31.493	31.955	33.721
288.35	38.505	31.465	31.961	33.747
297.09	38.506	31.483	31.958	33.750
306.37	38.510	31.497	31.953	33.824
316.26	38.508	31.493	31.955	33.782
326.80	38.503	31.510	31.955	33.752
338.07	38.515	31.502	31.961	33.733
350.14	38.515	31.496	31.960	33.743
363.11	38.514	31.484	31.979	33.840
377.07	38.528	31.493	31.969	33.826
392.16	38.522	31.492	31.963	33.742
408.50	38.527	31.495	31.971	33.746
426.26	38.531	31.514	31.970	33.766
445.63	38.518	31.490	31.979	33.811
466.85	38.540	31.520	31.978	33.836
490.20	38.544	31.506	31.979	33.792
516.00	38.542	31.514	31.993	33.776
544.66	38.557	31.536	31.979	33.762
576.70	38.563	31.538	32.001	33.811
612.75	38.565	31.518	31.999	33.868
653.59	38.569	31.531	32.005	33.831
700.28	38.582	31.548	32.020	33.790
754.15	38.600	31.522	32.013	33.805
816.99	38.612	31.504	32.037	33.782
891.27	38.613	31.561	32.041	33.874
980.39	38.641	31.608	32.050	33.929
1089.32	38.646	31.603	32.075	33.849
1225.49	38.676	31.618	32.085	33.883
1400.56	38.716	31.644	32.110	33.913

No. of timeouts per second	Absolute	Immediate	Zero Page	Mixed
1633.99	38.755	31.680	32.129	33.986
1960.78	38.810	31.761	32.192	34.069
2450.98	38.906	31.874	32.260	34.047
3267.97	39.067	31.912	32.386	34.162
4901.96	39.401	32.180	32.592	34.312