Gaming System

Final Report

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2025

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ABSTRACT

The Gaming System is a portable handheld console designed to emulate original Nintendo Gameboy games while integrating modern enhancements. Built around the Raspberry Pi Pico microcontroller, the system uses the open-source Pico-GB Gameboy emulator [1] as its software backbone. Additional features such as a variable volume knob and analog joystick input expand the functionality beyond the original Gameboy interface, offering a more modern and user-friendly interface. The hardware consists of 3 custom-designed printed circuit boards (PCBs), which support a modular electronics layout. This modularity simplifies assembly, maintenance, and potentially future upgrades. The PCBs integrate the microcontroller, input/output components, and power management systems. The physical enclosure is a custom 3D-printed housing with an articulating screen, 8 tactile buttons, a power switch, 2 AA removal batteries, an analog stick, a volume knob, an audio amplifier, a speaker, and a removable top shell for ease of access. Ergonomics and portability were key design drivers, ensuring the device fits comfortably in the user's hands while remaining compact enough for easy travel. The final product met all 10 of our engineering specifications (refer to Appendix A-House of Quality). It delivers 50 minutes of continuous gameplay on 2 AA batteries and maintains seamless emulation performance across various different games. The joystick provides a versatile input option for future game compatibility, while the volume knob enables fine-tuned audio control. The Gaming System successfully combines retro gaming with modern usability, resulting in a robust and modular handheld device.

ACKNOWLEDGEMENTS

We would like to thank the Embedded Systems Design Club for sponsoring our project and providing valuable resources and support throughout the development. We are especially grateful to Sami Aljabery and Dr. Renato Figueiredo for their guidance on refining the software scope and ensuring feasibility within our timeline. We also extend our sincere thanks to Dr. John Greeven and Christopher Holm for their continuous advising on PCB design, hardware implementation, and the overall project direction, as well as for their support throughout the Capstone course.

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1 BACKGROUND

1.1 Introduction

The Gaming System Capstone project aims to develop a modern, handheld gaming system capable of playing the original Nintendo Gameboy games while enhancing the functionality through contemporary hardware features. The interdisciplinary team was composed of 2 Electrical and Computer Engineering (ECE) students and 3 Mechanical, Industrial, and Manufacturing Engineering (MIME) students, who collaborated to integrate a custom PCB, an ergonomic industrial design, and a modified open-source emulation software into a cohesive product. The primary objectives of this project are to create a modular, ergonomic, and user-friendly device that replicates the nostalgic Gameboy experience while introducing modern controls such as an analog joystick. These improvements reflect modern user expectations and broaden the system's potential applications in education, prototyping, and entertainment. This project is important because it addresses contemporary issues in sustainable product development, hardware modularity, and cross disciplinary design. In a new era where electronic waste and planned obsolescence are growing concerns, the Gaming System promotes longevity through its repairable design and replaceable power source. The use of the open-source software and custom PCBs encourages low-cost development and potential scalability. For the project sponsor and stakeholders, including engineering faculty and future capstone teams, this gaming system serves as a demonstrator of what is achievable through coordinated multidisciplinary collaboration. It provides a foundation for further innovation in embedded systems, custom electronics, and human centered product design. This Gaming System delivers not just a product, but a platform for continued learning and development.

1.2 Project Scope

The Gaming System is a fully functional gaming system capable of playing original Gameboy games. The purpose of the Gaming System Capstone project is to provide a valuable learning experience for the project's team members. This value comes from the experience of collaborating with a team of interdisciplinary engineers and the technical expertise acquired by building the Gaming System from scratch. To gain this expertise, the Capstone team members have added features to the original Gameboy system (and implemented a new PCB/physical design). For background, the original Gameboy came with a volume knob but no analog joystick. It was released in 1989 and has been one of the most iconic gaming systems ever created [2]. Existing Gameboy emulator systems (such as Pico-GB) do not support all original Gameboy features (such as a volume knob) and do not add more features to the original Gameboy system (such as an analog joystick). The Gaming System capstone project aims to add a volume knob and an analog joystick to the Pico-GB project (this includes writing software and integrating these two pieces of hardware onto the PCB). Lastly, the Gaming System aims to create a comfortable physical design (and custom PCB) that is significantly different from any previous 3rd party Gameboy systems [3]. See Figure 1 for an example of a 3rd party Gameboy system.

Figure 1. A 3rd party Gameboy system's physical design, by Vincent Mistler [3].

The Gaming System has three main design components. The first is the physical design; the three MIME members (Atom Rosseau, Justin Gonzalez, and Jaedo Oh) have created their own designs for a novel, 3D-printed controller. The Gaming System controller shell can be 3D printed by standard Fused Deposition Modeling (FDM) printers which use plastics such as Polylactic Acid (PLA) at high temps to replicate 3D objects. This makes the project easily accessible to anyone with an interest in the project, by having open-sourced files for those as well as the printed circuit boards (PCB) to match.The second is the PCB of the system, created by one of the ECE members (Mitchell Hopkins). The PCB contains (and connect) the following components, most of which were sourced from external manufacturers:

- 1 Raspberry Pi Pico development board (which consists of a PCB and an RP2040 microcontroller chip)
- 1 audio amplifier breakout board
- 1 analog to digital converter (ADC) breakout board
- 1 analog joystick breakout board
- 1 rotary encoder
- 8 push buttons
- 1 switch
- 1 LCD screen
- 1 speaker
- 2 AA batteries

The third is the software, which was written by the other ECE member (Gabriel Rodgers). The bulk of the software is provided by the open-source Pico-GB project [1], a Gameboy emulator that works for Raspberry Pi Pico development boards. Gabriel Rodgers has added functionality to the Pico-GB project to support an analog joystick and a rotary encoder by writing additional software for the Pico-GB project. Users can control Gameboy games on the Gaming System by using the analog joystick in the same manner as the push buttons. Users can change the volume of the Gaming System by rotating the rotary encoder. The Gaming System as presented during the Engineering Expo is based on a protoboard electronic system (i.e., one that is wired without a PCB). This is because the PCB was not manufactured in time for it to be integrated into a new controller shell design.

2 DESIGN PROCESS

2.1 General Process

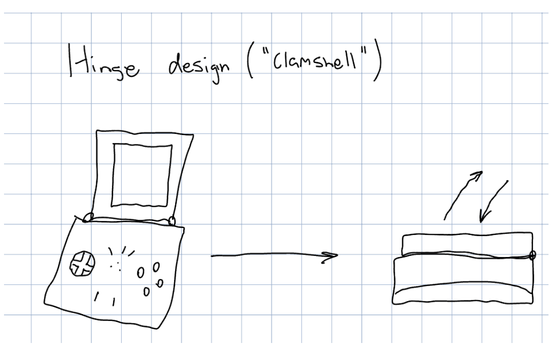
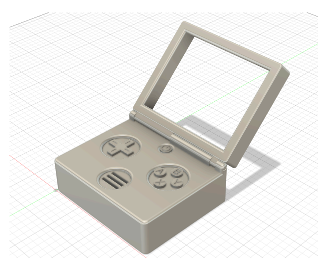
Our team began by collecting customer requirements to formulate what needed to be included in the creation of the gaming system. This process was carried out by the team, with the Embedded Systems Club serving as our sponsor and primary contributor to the project. This has led to our requirements to be well-defined, which helps with the overall design process. Our requirements are to be portable, have a standard layout of buttons and a directional pad, have a flexible hinge for the screen, and have easy access to the internals of the system. Our goal is to have this project be cost-effective and easy to assemble. Since the project will be using a Raspberry Pi Pico, the system will be power efficient, and we will be powering the whole system with AA batteries.

2.1.1 PCB Design Process

The original idea was just using one PCB and connecting everything directly on that PCB. With the change in outer shell design, the single PCB design was not sufficient. There are more moving parts, so the team decided to break up the PCB into three separate parts. The largest PCB was placed in the center and it is the main one with the microcontroller and the other PCBs connected to it and that will be where the power is connected. The other two PCBs will be for buttons, one is the classic video game d-pad used to move in four directions and the other is the symbol buttons classically used to advance the story of the game and perform functions that are not related to movement. The d-pad is implemented with the possibility of it becoming a joystick instead, which allows for more directional movement that is not just up, down, left or right.

2.1.2 Shell Design Process

Through different prototyping phases as well as different brainstorming ideas we developed a few ideas that would help us determine the direction that we would want to take in the future. The designs and ideas for those designs through our early brainstorming phase is shown below.

Brainstorm	Prototype
	

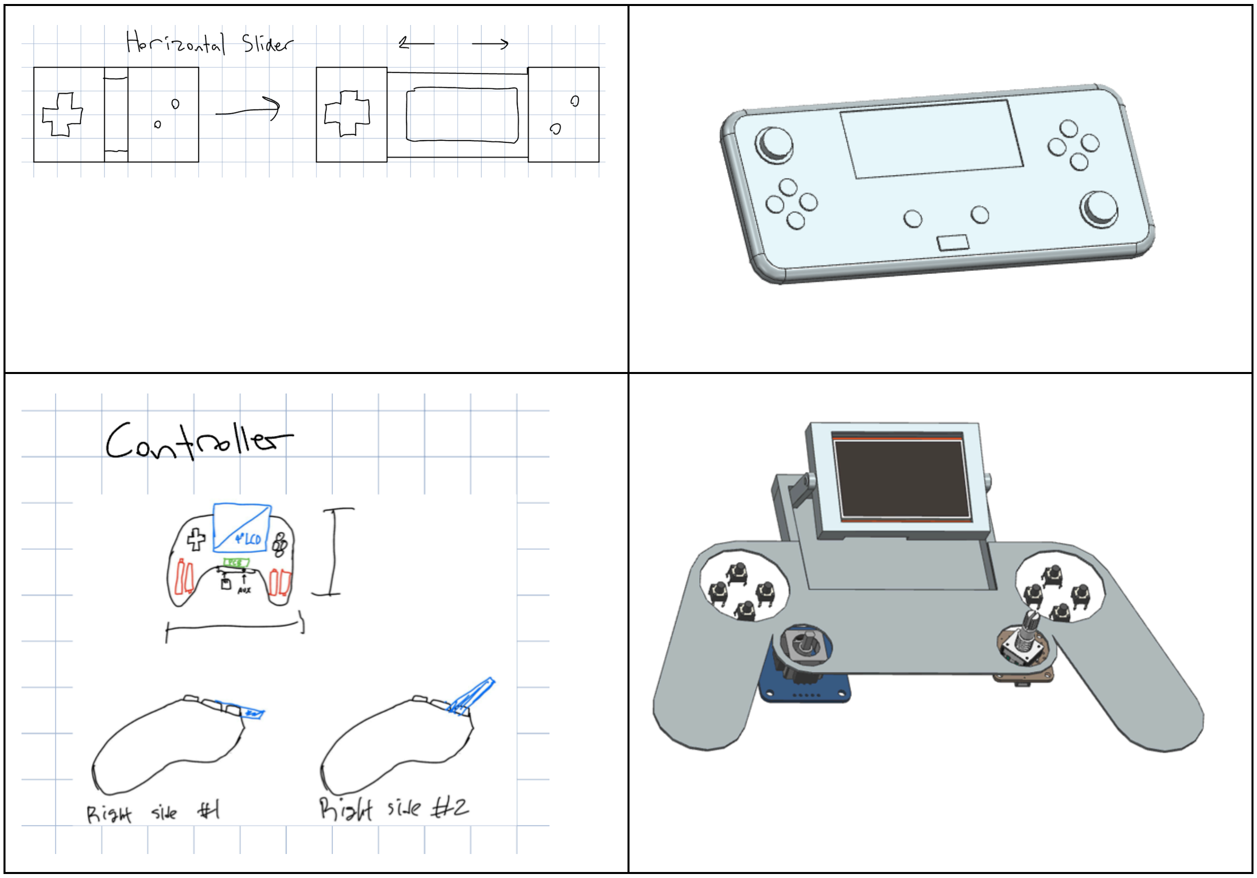


Figure 2. Brainstormed ideas and their resulting prototype.

These prototypes were created based on our brainstormed ideas. The idea was to see physically if we preferred a type of direction from our brainstorming session and having a physical representation of the shape and feel would give us the best idea of what we could work around. Ultimately we ended up going in the direction of the last design where the shape and feel would be based more like a controller. This was because of its potential for better ergonomics and ability to be flexible when it comes to what parts we could add and where we would be able to put them.

2.1.3 Software Design Process

The software design process involved redefining the scope of the software (from writing code to manipulate registers to writing code that uses Pico Software Development Kit (SDK) function calls), figuring out how to implement functionalities, and testing. Because the Gaming System uses the Pico-GB emulator software as its base, the added functionality needed to be quick and to not impede the activities of the emulator. To do this, we pondered the use of Direct Memory Access (DMA) to move joystick data from the analog to digital converter (ADC) to the Pico without interrupting the emulator. Before implementing DMA functionality, however, we first wrote software to test whether non-DMA software would work fast enough to be unnoticeable from the existing emulator. We found that there was no need for a DMA version of the software as the emulator was not significantly slowed down by the added software. As for the rotary encoder, it was trivial to use the Pico SDK function calls and an interrupt to determine if the rotary encoder was being moved - and to correspondingly change the Gaming System's volume.

3 DESIGN PROPOSAL – First Term

3.1 Shell Design

The design for the shell shifted a lot from the previous term as nothing was set in stone as the only thing that had been created with any physicality to it was the hinge (refer to Appendix C-Hinge Drawing). This served to not only act as a proof of concept but to help guide some of the size requirements for later. Doing the proofs of concepts in the first term solidified the direction that we wanted to take the gaming console. This is helpful as we would need to spend a lot of time prototyping different shapes and designs. Instead we just did it for the few designs that we had in mind. The proof of concepts also allowed us to build the resulting shape around our main mechanism being the hinge. Since the hinge takes up a lot of space this defines the shape that would eventually become the shell.

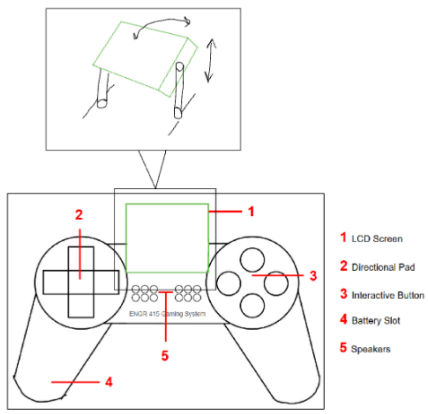


Figure 3. Original Proof of concept from first term

This is the basis of the shape that we decided on last term. As you can see the shape was built around the screen being able to move so the rest of the shape forms around the main mechanism. The idea for more of a controller shape is the largest thing that changed from the first term. This was due to the amount of space that was needed to house the electronics; the shape of the shell would be too large to incorporate the electronics while also remaining in a controller shape. As the prototype uses a protoboard the amount of space needed was a lot more than originally thought which led to the overall size of the shell being much larger than originally thought in the first term. The original thought, which is the prototype in the section above and the last figure in figure 2 was to keep the controller type shape while still being able to incorporate all of the electronics.

3.2 PCB Original Design

The original design was a single PCB that had all components soldered on the board. The only exception is that the LCD screen was on its own and connected to the board via wires. The design also had to work with curved areas and when connecting the line etches, they need to be lines and not curves. With the shell design not being fully integrated, the lab design was changed to be less rigid since the time to and money to change the PCB is much greater than that of the shell. The new design breaks up all of the original design into three separated PCBs that are connected directly to the main PCB. Also connected to the main PCB are all of the non button components to make it easier to move the components and make them fit in a way that is more comfortable for the user, which is our main goal.

3.3 Software Original Design

The original design for the software did not change from the first term to the second term.

4 Design Solution

This section outlines the final design implemented by our team for the Gaming System project. The mechanical and user interface components were developed with a focus on portability, ergonomics, and functionality, while ensuring ease of manufacturing and reproducibility for future users and developers. The system's final form reflects a balance between design simplicity and comprehensive input and display features.

The following subsections detail the physical design of the solution and the results from testing the system against the defined engineering specifications.

4.1 Description of Solution

The final implementation of our gaming system is a compact, handheld console designed with portability, usability, and modularity in mind. The outer housing was fabricated using 3D printing technology, utilizing PLA filament due to its accessibility, ease of printing, and sufficient mechanical properties for handheld device enclosure. The shell was designed with curvature to improve hand grip comfort and reduce fatigue during extended gameplay sessions.

The system features a 2.2 inch color LCD display, which is mounted on an articulating hinge structure. This hinge enables users to tilt the screen to their preferred viewing angle, improving visibility and usability in various lighting conditions and hand positions. The hinge was designed to maintain positional stability while allowing smooth adjustments, inspired by devices such as the Nintendo DS (figure 4).

Figure 4. The Nintendo DS, a dual-screen handheld gaming console, features a clamshell design with a central hinge allowing the top screen to be tilted for optimal viewing. This mechanism inspired the adjustable LCD screen hinge implemented in our Gaming System.

The user interface consists of a total of seven input controls: a directional D-pad, an analog joystick, two action buttons (A and B), Start and Select buttons, and a rotary volume knob. The joystick was added in addition to the D-pad to improve enhanced directional input and support for games or creatures that may benefit from analog movement. All buttons were chosen for their tactile response and were embedded securely into the front face of the housing.

Figure 5 shows the completed physical assembly of the Gaming System. The device's black PLA enclosure is contrasted with colored buttons for clear visual identification of input functions. The joystick is positioned for left-thumb use, while the D-pad is placed above it. The rotary knob, located in the lower left, provides analog volume control. The LED screen is seen mounted on a hinged section in the upper center of the device, enabling flexible screen positioning.

Power is supplied through two replaceable AA batteries, housed in a rear-mounted battery compartment. This design choice allows for convenient battery replacement without requiring tools. Based on empirical testing, the system can operate continuously for approximately 50 minutes under typical load conditions, which include active gameplay with screen brightness and audio at medium levels. Because the PCB was not manufactured in time for the Engineering Expo, we instead created a protoboard prototype of the system, soldering all of the components together on a protoboard and placing it within the custom shell design.

The software for the Gaming System is based on the Pico-GB emulator, with an additional ~hundred lines of C code to support volume control via a rotary encoder and game movements via an analog joystick and ADC. The added software includes Pico SDK function calls to operate the I2C (inter-integrated circuit) peripheral for the ADC, read the values of the GPIO pins connected to the rotary encoder, and to create interrupts to determine which way the rotary encoder is turnt. This added software does not impact the emulator's ability to run more than 5 original Gameboy games at low latency (more than 1 frame per second), which satisfies two of the engineering requirements.

In summary, the final design balances mechanical simplicity with user-oriented features, emphasizing ergonomic handling, screen adjustability, accessible power, and robust input methods, all packaged in a fully 3D-printed housing optimized for cost-effective assembly.

Figure 5. Assembled Gaming System showcasing LCD screen, joystick, buttons, and 3D-printed housing.

4.2 Project Results

To validate the design, the Gaming System was tested against the full set of engineering specifications established during the first term. These specifications focused on functionality, ergonomics, battery life, display usability and control responsiveness [4]. The system showed stable performance during gameplay, with all inputs registering correctly and without noticeable input lag. The D-pad and joystick were tested for responsiveness and accuracy in games that required both rapid button inputs and directional control. The volume knob demonstrated variable resistance control, smoothly adjusting the audio output without artifacts or noise glitches. Battery tests were conducted under typical use conditions - standard brightness, default speaker volume, and active gameplay. Under these settings, the system sustained operation for approximately 50 minutes using two AA batteries, meeting the target duration. The battery compartment design enabled seamless replacement, and the system rebooted correctly upon reinsertion of new batteries. Additionally, the articulating hinge mechanism for the LCD scream was tested across multiple tilt angles. It maintained its position during gameplay and did not show signs of mechanical fatigue or slippage after repeated adjustments. The shell also easily survived a drop onto concrete from a height of 1 meter, satisfying its associated engineering specification.All engineering specifications were tested and the Gaming System passed them all without issue.

Overall, the system was presented to the instructor, who validated the intended usability and design principles. All hardware components functioned as expected, and no critical failures occurred during extended demonstrations. Various members from ESDC tested the Gaming System for comfort, functionality, and usability. All were impressed with the system, with some stating how comfortable it was to use the analog joystick.

5 LOOKING FORWARD

5.1 Software Future Updates

Our future goal for the software is to modify it to be more modular, readable, and maintainable. The modularity would be used to allow for users to modify the source code to support Gaming Systems that have different combinations of analog joysticks/rotary encoders. The other two would be helpful for future Capstone projects that want to use a similar emulator. After updating the codebase, we would ideally merge our project with the original Pico-GB emulator, which would be a significant contribution towards open-source software.

For any future Capstone teams attempting something similar/continuing with this project, we would recommend trying to add additional functionality to an original Gameboy emulator, refactoring the existing emulator for performance, refactoring our code for performance (by using DMA for communications between the Pico and the ADC) [5], porting the emulator to a newer Pico model (such as the Pico 2), or using a more advanced emulator (such as for the Nintendo DS or Nintendo NES). One thing to be aware of is that when writing software, try the easiest solution first just to see if the functionality is even functional. One can always make the solution more efficient from there.

5.2 PCB Future Updates

In the future all three boards will be implemented into one because it will be easier to manufacture, but the current design is meant to be flexible and that makes it easier to fit in the outer shell. With the next iteration of the PCB, the wiring of the buttons will need to be re-worked because with the connection between boards the orientation of the buttons was flipped to avoid etched lines crossing. The etched lines on the PCB going to the encoder will need to be reorganized because when the encoder gets soldered into the board, the current connections will be wired incorrectly. Lastly, the connections between the boards used GH JST connectors that are 1.27mm apart, however, the actual components have differing widths, so using the standardized 1.27mm width between pins will make it so the components will not be able to be inserted into the board. The width of the holes between pins for the buttons and the microcontroller are correct.

5.3 Shell Design Updates

Looking ahead, we aim to significantly reduce the overall thickness and weight of the Gaming System shell to improve portability and ergonomics. With a planned integration of all electronic components onto a single custom PCB, we will have greater freedom to redesign the internal layout and optimize the form factory. A thinner shell will enhance the handheld feel of the device and make it more comfortable for extended gameplay sessions. The redesign will also address internal space constraints, allowing better alignment between the component and mounting features. We also plan to improve accessibility to internal components such as the batteries and the joystick.

6 CONCLUSIONS

The main goal of the Gaming System Capstone project was to create a valuable learning experience by collaboratively designing and integrating software, hardware, and a physical shell together. Through this project, the team successfully applied engineering including user-centered design, modularity, and manufacturability. By building a custom device from the ground up, the team gained heads-on experience in embedded systems, 3D design, open source firmware development, and rapid prototyping.

The Gaming System fulfilled all of its intended functional requirements. It was able to play original Gameboy ROMs using the Pico-GB emulator while incorporating new user features such as an analog joystick and rotary volume control. These additions enhanced the functionality beyond that of the original Gameboy system and reflected modern usability standards. The hinge-mounted LCD screen provided customizable viewing angles and improved ergonomics, and the use of replaceable AA batteries ensured that the device remained cost-effective and portable.

The Gaming System bridges nostalgia and modern usability, offering a new take on retro gaming. Educationally, it demonstrated the importance of interdisciplinary collaboration. Bringing together electrical engineering, mechanical engineering , software development, and systems integration.

In conclusion, the Gaming System stands as a testament to practical engineering application and cross-functional teamwork. The project not only delivered a working prototype that exceeded technical expectations, but also provided a foundation for future student teams or hobbyists interested in building and expanding upon the system.

7 REFERENCES

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[4] Kim, J., and Lee, S., 2021, “The Ergonomic Development of Video Game Controllers,” Longdom Publications, [Online]. from https://www.longdom.org/open-access/the-ergonomic-development-of-video-game-controllers-24556.html.

[5] osu-esdc., 2025, “osu-esdc/pico-gb-capstone: Fork of the original Pico-GB git repository, with added volume rocker and analog stick functionality.,” GitHub [Online], from https://github.com/osu-esdc/pico-gb-capstone

8 APPENDICES

8.1 Appendix A: House of Quality

Customer Requirements (CRs) to Engineering Specifications (ESs)				
CR#	CR description using complete sentences	Weight (100 total)	Matching Engineering Specification	Targets with Tolerances
1	System will be light weight	5	Final product mass will be 1 kg or less.	±0.2 kilograms
2	System will have adjustable display	5	Display can have its angle adjusted by 0 - 15 degrees.	±5 degrees
3	System will have good battery life	10	Will operate for at least 30 minutes while continuously playing games.	±10 minutes
4	System will have volume control	5	A volume knob will allow a user to decrease, increase, and turn off the volume.	Yes/No
5	System will play games with low latency	10	Screen will update from user input within 1 s	±500 milliseconds
6	System's physical housing will be durable	10	The shell of the system will survive 1m drop onto concrete with no cracks	±0.25 meters
7	System will run original Gameboy games	35	System will support 5 or more original Gameboy games	±4 games
8	System will have power on LED	2	Will have green LED turn on when powered on, and turn off when powered off.	Yes/No
9	System is easily fixed by the user	5	Will be able to access the electronic components in less than 20 seconds.	±5 seconds
10	System has multiple forms of input	8	A user can control a game with an analog joystick or a directional pad	Yes/No

8.2 Appendix B: Bill of Materials

Item Name	Item Price Per Unit	Item Count	Shipping Cost	Item Price Total	Vendor Link
LCD Screens	$12.49	3	$0.00	$37.47	https://www.amazon.com/HiLetgo-ILI9225-176x220-Support-Arduino/dp/B0
RP2040	$4.00	4	$0.00	$16.00	https://www.digikey.com/en/products/detail/raspberry-pi/SC0915/13684020
SD Card w/ Adapter	$7.99	2	$0.00	$15.98	https://www.amazon.com/SanDisk-microSDHC-Standard-Packaging-SDSC
Tactile Switches	$0.13	25	$9.00	$12.33	https://www.digikey.com/en/products/detail/same-sky-formerly-cui-devices/
Slide Switches	$4.99	1	$0.00	$4.99	https://www.amazon.com/Position-Breadboard-Electronic-Miniature-SlideSwitch/dp/B09R3ZWBBC?cor
Raspberry Pi Debug Pro	$12	2	$0.00	$24.00	https://www.digikey.com/en/products/detail/raspberry-pi/SC0889/17877576
Speakers (6x)	$9.99	1	$0.00	$9.99	https://www.amazon.com/Weewooday-Speakers-Internal-Speaker-Multime
Audio Amplifier (5x)	$12.88	1	$0.00	$12.88	https://www.amazon.com/MakerHawk-Amplifier-Amplifiers-Filterless-Raspb
Header pins	$7.99	1	$0.00	$7.99	https://www.amazon.com/Straight-Breakaway-Connector-Breadboard-Elec
Jumper Wires (5.9")	$7.49	1	$0.00	$7.49	https://www.amazon.com/EDGELEC-Breadboard-1pin-1pin-Connector-Mul
Button Covers	$1.00	4	$0.00	$1.00	3D printed
Top Half Shell	$10.00	1	$0.00	$10.00	3D printed
Bottom Half Shell	$9.00	1	$0.00	$9.00	3D printed
D-Pad Cover	$1.00	1	$0.00	$1.00	3D printed
Hinge Clips	$0.25	2	$0.00	$0.25	3D printed
Screen Cover	$0.75	1	$0.00	$0.75	3D printed
Total Cost:					
$171.12					

8.3 Appendix C: Hinge Drawing