Leveling Up Emulation:

The Benefits of Field-Programmable Gate Arrays in Video Game Preservation

by

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Abstract

It is worthwhile for cultural institutions to stay in tune with hardware emulation to accurately preserve video games. Gaming culture is deeply entrenched in nostalgia, specifically, how games looked and played when gamers were younger. This “feel” of a game is something the gaming community holds dearly and any alteration to game-feel is normally met with animosity. Many quirks of early console games were found within how the original hardware ran them, and so the preservation of game-feel could be a task well suited for hardware emulation, notably Field-Programmable Gate Arrays. Many retro enthusiasts have turned to these malleable integrated circuit boards to reproduce original gaming console components and run their games as they did decades ago, stating they are more accurate than current software emulators. To investigate the benefits of hardware emulation, this paper conducts an experiment, utilizing the Sega Genesis and an FPGA from the MiSTer Project as a case study. The history of both the original console and the FPGA are examined, metrics are established for which to judge the MiSTer’s emulation against, and results are presented, detailing how well the MiSTer can emulate the original hardware.

Introduction

"Your Beloved Games Console Is Slowly But Surely Dying," written by Damien McFerran in late 2019 for NintendoLife.com details McFerran's troubles with his personal Sega Mega CD, which, by his own accounts, was well taken care of. Despite the care with which he handled his console, it failed to work and so he began to investigate probable causes for the failure. He reached out to Simon Lock, a retro console repair hobbyist to hopefully find the root of his problem.

According to Lock, "how well you look after something doesn't always mean that internally you have a system absent of perishable components; via age, humidity or design longevity/manufacturer component quality of that era."[1] He further explains that, "The di-electric fluid [found in capacitors] is prone to becoming more volatile over time, leak protection was not as reliable as it is today, and the design does not allow for top venting in the event of component failure. This causes the fluid to leak out onto the printed circuit board directly where it reacts with metals – such as copper traces or brass screws – resulting in damage."[2] In addition to leaking capacitors, oxidation, corrosion, and faulty power supplies are among many other problems that plague these consoles. Lock believes these problems will only get worse as modern consoles age (PlayStation 5, Xbox Series X, Switch, etc.), as their components are much more intricate than McFerran's Sega Mega CD.[3]

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[1] Damien McFerran, "Your Beloved Games Console is Slowly but Surely Dying," https://www.nintendolife.com/news/2019/12/feature_your_beloved_games_console_is_slowly_but_surely_dying (accessed Oct 22, 2021).
[2] McFerran, "Your Beloved Games Console is Slowly but Surely Dying."
[3] McFerran, "Your Beloved Games Console is Slowly but Surely Dying."

While Lock's observations of aging hardware are alarming, they are nothing new in the field of video game preservation. Hardware obsolescence and scarcity are key hurdles in preserving video games, which is why software emulation has become an incredibly prominent practice. Giovanni Carta defines emulation as a "digital process that aims at simulating either specific software applications or hardware architectures (or even both); an emulator, running in a so-called host system, is generally employed to perform this task."[4] The capability for software to replicate a different device[5] (like a video game console) or other software provides the benefit of preserving the work on newer machines should original software or hardware become obsolete or irreparably damaged, something the video game community is constantly battling as seen in McFerran's article. This coupled with the fact that many emulators are developed and tested by a large community, make them readily available on many modern platforms for both hobbyist and professional preservation use. Software emulation, while key in the preservation of these works, is not without its problems.

As recently as 2021, one can see the challenges faced in accurately representing a video game through an emulated environment. YouTuber Modern Vintage Gamer (MVG), real name Dimitris Giannakis, is a retro game and hardware enthusiast who provides a look into Nintendo's own Nintendo 64 emulation service through their Nintendo Online Platform. Boasting users can "Party like it's 1996," Nintendo's service offers access to a "library of

[4] Giovanni Carta, "Metadata and Video Games Emulation: An Effective Bond to Achieve Authentic Preservation?" *Records Management Journal (London, England)* 27, no. 2 (Jul 17, 2017)193. doi:10.1108/RMJ-10-2016-0037. https://www.emerald.com/insight/content/doi/10.1108/RMJ-10-2016-0037/full/html.
[5] Mark Guttenbrunner, "Digital Preservation of Console Video Games" (Vienna University of Technology), 31.

Nintendo 64 games."[6] Unfortunately, as Giannakis explains, Nintendo's own Nintendo 64 emulator hosts a plethora of problems in terms of emulating their games accurately.

Giannakis provides an in-depth explanation into the issues first noting, "When textures are filtered on any modern GPU, four sample points are used. But on the Nintendo 64 it uses three sample points and unfortunately it does not appear that the N64 implementation here uses three sample points. And this can be very easily demonstrated if we look at the character select screen on Mario Kart 64. You can clearly see the lines where the textures are stitched together, and if we compare that with a popular Nintendo 64 emulator, known as Project 64, with the three-point filtering option applied, it's completely eliminated"[7]

Figure 1. Example of improper texture stitching (2021). (Modern Vintage Gamer).

[6] Nintendo, "Nintendo 64 - Nintendo Switch Online - Nintendo - Official Site," https://www.nintendo.com/switch/online-service/nintendo-64-nintendo-switch-online-switch/ (accessed Dec 18, 2021).
[7] Modern Vintage Gamer, "Nintendo 64 Emulation on the Nintendo Switch is Not Good.... | MVG," https://www.youtube.com/watch?v=jSyBMSOfPxg (accessed November 19, 2021).

Figure 2. Example of proper texture stitching (2021). (Modern Vintage Gamer).

The problems Giannakis lists goes beyond the graphics citing input lag, poor fog rendering, and bad online multiplayer implementation, all problematic from an archival perspective.[8]

The purpose of this paper is not to contradict the work done with regards to software emulation, as there are communities dedicated to high accuracy representation for preservation standards. Giannakis's video is meant to highlight how this implementation can go wrong, and that there is an alternative to software emulation if need be.

Looking back at McFerran's Nintendo Life article, Lock highlights that, "we're seeing a significant rise in cycle-accurate or emulated systems being produced to fill the void created by the lack of working systems available or those seeking for modern creature comforts/improvements on hardware original designs."[9] What Lock is detailing here is not

[8] Modern Vintage Gamer, "Nintendo 64 Emulation on the Nintendo Switch is Not Good.... | MVG."
[9] McFerran, "Your Beloved Games Console is Slowly but Surely Dying."

software emulators, but newer circuit boards that are meant to replace the old parts that are deteriorated beyond repair. One method for this "cycle-accurate" emulation utilizing a hardware environment is through the use of Field-programmable gate arrays, or FPGAs.

FPGAs are "digital integrated circuits (ICs) that contain configurable (programmable) blocks of logic along with configurable interconnects between these blocks."[10] While this type or hardware was not developed with video game hardware emulation in mind, it does provide exciting opportunities to recreate the original console circuitry utilizing these programmable arrays to make the aforementioned cycle-accurate emulation. Unfortunately, there is little academic research into the use of FPGAs in video game preservation, although there are gaming-centric media outlets and communities that have praised their use. As of right now, there appear to be two key players in the field of hardware emulation, MiSTer, an open-source platform developed by enthusiasts, and Analog, a retro gaming company dedicated to creating hardware accurate consoles capable of playing original cartridges.

In 2019, Bijan Stephen wrote an article for The Verge, detailed the benefits of utilizing Analog's Mega Sg (a Sega Genesis/Megadrive console emulator) saying "Because Analogue has re-created consoles on a hardware level, the Mega Sg and the rest of Analogue's products are more accurate than just about any software emulators. Sega has its own line of remake Genesis consoles, which come with many games preloaded. But they're re-creating the Genesis experience on the level of software, which means that they're not quite as good as what

[10] Clive Maxfield, *The Design Warrior's Guide to FPGAs* (Burlington: Newnes, 2004) 1.

Analogue has to offer."[11] Mirroring Giannakis's video, Stephen details Sega's own failings utilizing software emulation and highlighting the benefits of hardware emulation.

In 2021, Mike Fahey of Kotaku praised the open-source MiSTer project saying, "MiSTer is the right-damn-now of retro gaming. By many metrics, FPGA hardware simulation surpassed software emulation a few years back."[12] Like Stephen, Fahey notes that "software emulation can be great. It can also be flawed. Some games run poorly, graphics get distorted, sound gets garbled. The games can exhibit slowdown and input lag not present on original hardware. Software emulation can be kind of a crapshoot."[13]

Due to hardware emulation's growing praise within the gaming community, the purpose of this paper is twofold. First, it is meant to detail why it is worthwhile for cultural institutions to stay in tune with hardware emulation to accurately preserve video games. In the early stages of researching this paper, the Museum of Modern Art, the Library of Congress, The National Video Game Museum in Frisco Texas, and The Strong Museum of Play were contacted to see if they were aware or utilizing FPGAs. Of the four organizations, only the Strong had said they began using them, while the others were aware of the technology but had not begun to implement them in their conservation efforts. This paper is meant to convince them to consider hardware emulation should they not already be investigating these resources. Secondly, emulation, both software and hardware, is difficult to understand without a

[11] Bijan Stephen, "Analogue's Console Clones are a Way to Preserve Gaming's Past," https://www.theverge.com/2019/5/6/18513025/analogue-console-clones-gaming-history-preservation-code-hardware (accessed Dec 15, 2021).
[12] Mike Fahey, "And Now, the Ultimate Retro Gaming Device," https://kotaku.com/and-now-the-ultimate-retro-gaming-device-1847608362 (accessed Dec 15, 2021).
[13] Fahey, "And Now, the Ultimate Retro Gaming Device."

background in computer programming and computer engineering so this paper will take technical jargon and translate it to be easily understood by video game archivists, who are not as well versed in physical computing.

In order to maintain scope, this paper will investigate the benefits of hardware emulation utilizing the Sega Genesis/Mega Drive as a case study. The Genesis was selected because the original console has some hardware quirks that are difficult to emulate through just software, as well as multiple hardware revisions that are worth exploring. First, this paper will provide both an explanation into how 16-bit console components work, a history of the development of the SEGA Genesis, and detail how a retro console such as this operates, focusing primarily on the parts that must be emulated. This chapter will utilize and review oral histories, journals, technical manuals, and community guides surrounding the topic.

Next, this paper will present a brief overview of software emulation, as well as a more in depth look at the short fallings of running old software in a newly emulated environment. Because software emulation is the norm in game preservation, it will be important to establish what hardware emulation must do better to be considered a complementary strategy.

Next, this paper will aim to define game feel and significant properties of video games, and what is essential to preserve when emulating a game. Gaming culture is deeply entrenched in nostalgia, specifically how games looked and played when gamers were younger. This “feel” of the game is something the gaming community takes very seriously and any alteration to game-feel is normally met with animosity, as seen in MVG’s criticism of Nintendo’s recent attempt at access to its older catalog. Many quirks of early console games were found within how the original hardware ran them, and so the preservation of game-feel could be a task well suited for hardware due to the cycle-accurate programming of the FPGA.

This paper will also provide a history of FPGAs, how they are currently being used in video game preservation, the development of these projects, and take a closer look at how they emulate older hardware.

The final chapter of this paper will provide a comparison between hardware emulation against an original console. Because the field of FPGA use in video game preservation is relatively new, its developers have only just begun to experiment with 32-bit console emulation, something that will be covered later in this paper a detailed list of equipment used will be provided, as well as the metrics being used to measure accuracy, which will be based off the previously detailed game feel and significant properties.

Chapter 1: Basics of 16-bit Consoles

1.1 CISC Basics

A CISC microprocessor utilizes CISC architecture which stands for "complex instruction set computer." CISC architecture's goal is to "complete a task in a few lines of assembly as possible," which is achieved by "building processor hardware that is capable of understanding and executing a series of operations."[14]

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[14] Crystal Chen, Greg Novick and Kirk Shimano, "RISC Vs. CISC," https://cs.stanford.edu/people/eroberts/courses/soco/projects/risc/risccisc/ (accessed December 12, 2021).

1.2 History of Sega Genesis Development

The Sega Mega Drive was released on October 29th, 1988, in Japan, and would reach the US on August 14th, 1989, renamed the Genesis for the US market.

Issue 182 of Retro Gamer Magazine provides an "under the hood" of the Genesis, detailing each of the key components used in its creation. The Motorola 68000 (68K), a 16-bit CISC microprocessor,[15] was chosen as its main processor, due to the programming resources already available as it was used in Sega's arcade machines, and, according to Masami Ishiwaka, a lead developer at Sega's R&D division, "the hardware — bus components — and software — for coding — were relatively simple to get to grips with."[16] Developed in the 1980s, the 68000 was a popular choice for personal computers, found in Apple's Macintosh, Commodore's Amiga, and the Atari ST.[17]

For sound, Sega used two chips in tandem. First the Yamaha YM2612 sound chip was used, providing "six channels of FM (frequency modulation synthesis) sound," which also supported PCM sound "to support such effects such as drum beats and speech."[18] This choice was due to the same chip also being used in arcade cabinets, much like the 68K.[19] The other processor used was the Zilog Z80, an 8-bit CPU to help as a coprocessor, but was primarily used to maintain Sega Mark III/Master System[20] backwards compatibility[21]. Ishiwaka states, "When the Mega

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[15] Alan Clements, "The 68K Family," http://alanclements.org/68k.html (accessed April 16, 2022).
[16] Keith Stuart, *Sega Mega Drive/Genesis: Collected Works* (Read-Only Memory, 2014).
[17] John Harrison, "Overview of the Mega Drive's Hardware Architecture," https://rasterscroll.com/mdgraphics/mega-drive-architecture/ (accessed Dec 15, 2021).
[18] Nick Thorpe, "Inside the Mega Drive," *Retro Gamer,* June, 2018, 20.
[19] Stuart, *Sega Mega Drive/Genesis: Collected Works*.
[20] The Sega Mark III (Japan)/Master System (North America) was the previous console released by Sega.

Drive was in Mark III mode, it was mainly running on the Z80, but when it was in Mega Drive mode, the Z80 was used only for sound."[22]

Finally, the Sega 315-5313 (Yamaha YM7101) was used as a visual display processor (VDP), designed by Sega, tasked with handling graphics processing such as scrolling backgrounds and sprites.[23]

In terms of how each of these components communicate with each other, John Harrison of Raster Scroll Books provides a detailed look into their interactions. Although considered a console, the Genesis, like other game systems, is essentially a personal computer due to the aforementioned CPU, RAM, video, and sound chips.[24] The 68K, the CPU, is primarily in charge of moving data to the other components in the system, notably by loading information from the game cartridge.[25] Because, unlike many personal computers, the Genesis does not have a persistent operating system, the information on the cartridge is used to give the 68K game data as well as instructions as how to run it.[26] The Genesis was equipped with 64KB of RAM, which, just like a personal computer, was used to store temporary data like player health and score.[27] Information generated by the 68K and the RAM would be sent to the VDP, and when enough information had been sent, would be output to the monitor.[28]

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[21] Backwards compatibility is the ability for a current console to play games from a previous console generation.
[22] Stuart, *Sega Mega Drive/Genesis: Collected Works*.
[23] Thorpe, "Inside the Mega Drive," *Retro Gamer,* June, 2018, 20.
[24] Josh Harrison, "Overview of the Mega Drive's Hardware Architecture," https://rasterscroll.com/mdgraphics/mega-drive-architecture/ (accessed Dec 15, 2021).
[25] Harrison, "Overview of the Mega Drive's Hardware Architecture."
[26] Harrison, "Overview of the Mega Drive's Hardware Architecture."
[27] Harrison, "Overview of the Mega Drive's Hardware Architecture."
[28] Harrison, "Overview of the Mega Drive's Hardware Architecture."

With regards to audio, Rodrigo Copetti provides an in depth look at the Genesis architecture as well, detailing how the audio was processed. The Z80 was used to control the FM synthesizer, but received its instructions from the 68K, which would then process out and output the sound.[29] There is an additional sound chip found within the VDP, the Texas Instruments SN76489, which was also used in the Sega Master System to help process audio.[30]

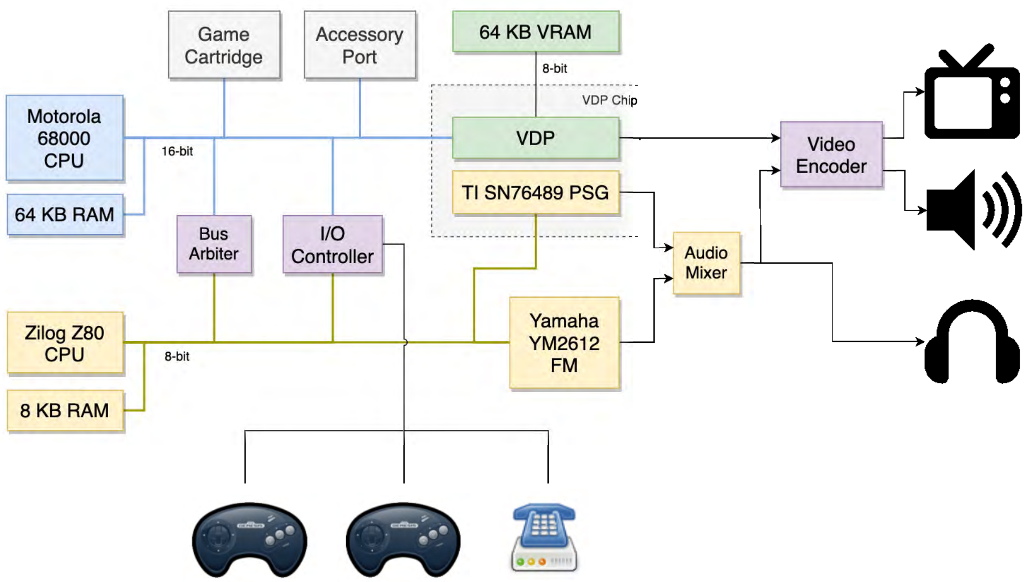

Figure 3. Main architecture diagram (2021). (Copetti, Rodrigo).

1.3 Hardware Revisions

It is not uncommon during a consoles lifecycle that it sees various hardware revisions. In 1994, the Genesis saw its first revision, the "Model 2", adjusting both its interior and exterior design.[31] This revision saw a change in the Genesis's power supply and removal of the headphone jack, channel select switch, and dedicated RF out.[32] The final revision arrived in

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[29] Rodrigo Copetti, "Mega Drive Architecture," https://www.copetti.org/writings/consoles/mega-drive-genesis/ (accessed Feb 20, 2022).
[30] Harrison, "Overview of the Mega Drive's Hardware Architecture."
[31] Bill Loguidice and Matt Barton, *Vintage Game Consoles : An Inside Look at Apple, Atari, Commodore, Nintendo, and the Greatest Gaming Platforms of all Time* (Burlington, MA: Burlington, MA : Focal Press, 2014).
[32]

1998, known as the Genesis 3, which also saw a change to the interior and exterior, making the console smaller, and eliminating the “expansion port” needed for a Sega peripheral known as the Sega CD.[33]

Figure 4. From Top Left Clockwise: Model 1, Model 2, Model 3 (2011) (2011) (2016). (Amos, Evan).

While these three console revisions are widely known, not all consoles within each revision cycle are created equal, with minor changes under the hood. These changes are not well documented, unfortunately, save for a few enthusiasts via forums.

A user of the Sega-16.com forum known as “Ace” provides a brief teardown of each console, noting differences between each one. The North American Model 1, for example, has

[33] Loguidice and Barton, *Vintage Game Consoles*, 174.

two different variants, one containing a TradeMark Security System (TMSS) and the other not.[34] Model 1s that boot straight into the game do not contain TMSS, while others that boot into a screen reading “Produced by or Under License from Sega Enterprises Ltd” do contain it.[35]

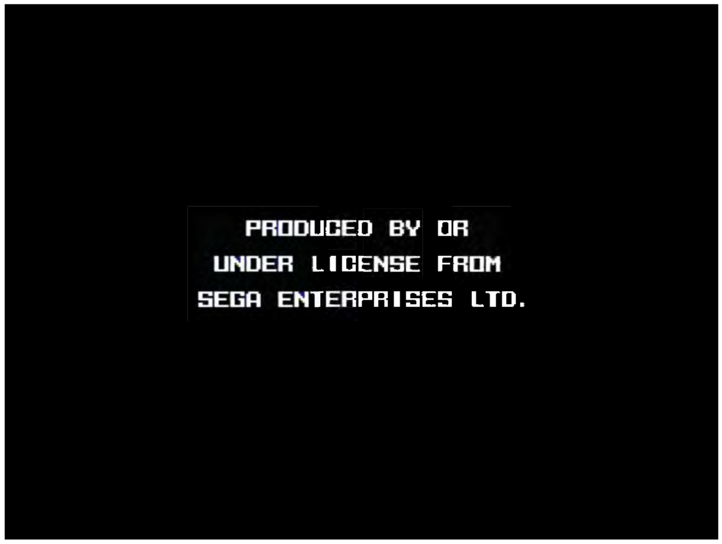

Figure 5: TMSS Screen

Within these variants, there are motherboard revisions, with slight alterations to the sound circuitry, which can affect the sound quality, with VA2 boards differing from VA3-VA6. The rest of the post continues to detail and explore the differences between each console, highlighting that the way a Genesis game was presented could differ from machine to machine.

Additionally, region specific hardware had an impact on the way games were presented and in turn, affected the way players experienced the game at the time. This is due to the PAL and NTSC standards having different refresh rates for their televisions. Sega made sure each console met the region’s standard, and outputting 50hz and 60hz respectively, but some game

[34] Sega-16, July 2, 2009, https://www.sega-16.com/forum/showthread.php?7796-GUIDE-Telling-apart-good-Genesis-1s-and-Genesis-2s-from-bad-ones.
[35] Sega-16, July 2, 2009, https://www.sega-16.com/forum/showthread.php?7796-GUIDE-Telling-apart-good-Genesis-1s-and-Genesis-2s-from-bad-ones.

developers did not take this change into consideration.[36] In their video *Why is Sonic Faster in America?*, Peter Leigh explains that the team behind *Sonic the Hedgehog*'s development did not account that the game would be running 17% slower in Europe as opposed to Japan and North America, which led to the game's controls feeling sluggish, and the music was slowed down.[37] While this phenomenon can be counteracted by developers by having the game play at different refresh rates, not all did, leading to different experiences of the same game depending on where it was being played. From a preservation standpoint, it is important to note when and how these differences affected a user's experiences, and if each scenario is possible to save.

Chapter 2: Software Emulation

When looking at FPGA's hardware emulation capabilities, it is important to understand how software emulation works. While there are a few levels of accuracy when looking at emulation[38], this paper, and video game emulators in general, are concerned with "cycle-accuracy." Arjan Tijms defines cycle accuracy as "instructions [completing] in the same relative amount of time compared to each other and to other components in the system."[39] Michael Steil expands upon this with relation to video games, and the importance of timing when carrying out these instructions:

> Cycle Accuracy means emulating the hardware including the "cycle exact" timing of all components. This type of emulators only implements the exact specification of hardware, but not its implementation. Many 1980s computer games (typically on 8 and 16 bit computers or gaming consoles) require this level

[36] Peter Leigh, "Why is Sonic Faster in America? NTSC Vs PAL/60Hz Vs 50Hz | Nostalgia Nerd," https://www.youtube.com/watch?v=cWSIhf8q9Ao (accessed December 3, 2021).
[37] Peter Leigh, "Why is Sonic Faster in America? NTSC Vs PAL/60Hz Vs 50Hz | Nostalgia Nerd."
[38] Arjan Tijms, *Binary Translation: Classification of Emulators*,[2000]).
[39] Arjan Tijms, *Binary Translation: Classification of Emulators*.

> of accuracy: Because it was easier to count on the timing of, for instance, CPU instructions as it is today, games could easily use timing-critical side effects of the machine for certain effects.[40]

Michael Steil points out that "modern processors depend on pipelining. While one instruction is being executed, the next one is already decoded, and another one is being fetched."[41] So while modern processors are inarguably faster than those found in 1990s video game consoles, they are still limited to running instructions from multiple processors that used to run in tandem, one after the other on a single CPU.

The importance of timing is highlighted in community driven emulation development like the Nindtendo DS emulator, DeSmuMe. When developers tried to adjust timings for the game Final Fantasy III, the result would cause the title screen to lock up.[42] They were able to fix it by tightening up the synchronization between the two emulated CPUs found in the DS, which resulted in better accuracy, however this resulted in slower emulation.[43] Slower emulation can result in a multitude of things, most notably lag, although the community behind the RetroArch emulation project developed a system called Runahead to combat "baked-in latency" software emulators have by "running multiple instances of [an emulator] simultaneously, and quickly emulating multiple frames at a time if input changes."[44] As not to get mired in the technical details of their project, this is essentially a way for the emulator to adjust its latency to appear

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[40] Michael Steil, "Dynamic Re-Compilation of Binary RISC Code for RISC Architectures" (Technische Universität München), 19.
[41] Michael Steil, "Dynamic Re-Compilation of Binary RISC Code for RISC Architectures," 26.
[42] endrift, ""Holy Grail" Bugs in Emulation, Part 2," https://mgba.io/2017/07/31/holy-grail-bugs-2/ (accessed Feb 21, 2022).
[43] endrift, ""Holy Grail" Bugs in Emulation, Part 2."
[44] Libretro Team, "Beetle PSX Dynarec Update - Switch Alpha Port Plus Runahead Support - Lower Latency than Original Hardware! - Libretro," https://www.libretro.com/index.php/beetle-psx-dynarec-update-switch-alpha-port-plus-runahead-support-lower-latency-than-original-hardware/ (accessed Feb 21, 2022).

as accurate as possible when emulating a system. With this framework, it is important to highlight how the MiSTer differs in this regard to software emulators.

Birdybro, a developer on the MiSTer project states that “unlike software emulators which go through a cycle of executing, and then waiting for a screen refresh, FPGA cores run in real time, as the original hardware did. This means that cores don’t have CPU bottlenecks to slow them down arbitrarily or require additional large buffers to hold data under most circumstances.”[45] Instead of relying on coding CPU synchronizations and other component interactions into the software like in a traditional software emulator, the components programmed into the MiSTer, which will be explained in detail later in this paper, are all working in tandem just like the original consoles components did.

Chapter 3: Significant Properties of Video Games with Relation to Hardware

In order to determine the merits of hardware emulation, it is important to identify the significant properties of a game with relation to the original hardware. Significant properties of digital objects are defined as “those properties of digital objects that affect their quality, usability, rendering, and behavior.”[46] While significant properties of a digital object can extend to minute technical metadata such as file type, bit fields, and other “under the hood” elements, this paper is focused solely on the content’s relation to the hardware itself, which in turn focuses primarily on user interaction and presentation. This is akin to determining how a VHS deck plays a tape, rather than focusing on the elements and properties of the tape itself. When

[45] birdybro, "Lag Explained," https://github.com/MiSTer-devel/Main_MiSTer/wiki/Lag-Explained (accessed Feb 21, 2022).

[46] Margaret Hedstrom and Christopher A. Lee, "Significant Properties of Digital Objects: Definitions, Applications, Implications," *Proceedings of the DLM-Forum, Barcelona* 200 (2002)218.

looking at accurately emulating a video game using a software environment, Giovanni Carta highlights the importance of the "capacity to retain the gameplay and performance of a given object as close as possible to the original."[47] This definition of authentic emulation in software can be extended to hardware, and so it is important that the hardware presents these significant properties as accurately as possible.

A good framework for significant properties can be found in a 2007 paper by Mark Guttenbrunner at the Vienna University of Technology, in which they detail "Object Characteristics" of console video games. Guttenbrunner suggests that accurately representing the sound, graphics, network support, and interactivity of a video game are essential to preserving it, [48] stating "if the object is not displayed properly and the interactivity requirements are not met the preservation solution is not very useful, as the original look and feel is not recreated."[49] While network support is indeed important, especially with regards to PC gaming and consoles starting in the late 1990s, due to this paper's focus on the Sega Genesis, it will omit network support. Instead, it will define Control and Game Feel, Graphics, and Sound.

3.1 Control / Game Feel

One of Guttenbrunner's core significant properties is described as Interactivity, a key component to video games, and how one's chosen preservation strategy supports input

[47] Carta, "Metadata and Video Games Emulation: An Effective Bond to Achieve Authentic Preservation?" *Records Management Journal (London, England)* 27, no. 2 (Jul 17, 2017)194. doi:10.1108/RMJ-10-2016-0037. https://www.emerald.com/insight/content/doi/10.1108/RMJ-10-2016-0037/full/html.
[48] Guttenbrunner, "Digital Preservation of Console Video Games" Vienna University of Technology), 56-60.
[49] Mark Guttenbrunner, "Digital Preservation of Console Video Games" Vienna University of Technology), 80.

through “controllers, overlays, and additional items.”[50] Game controllers can vary from console to console, and it is important to note if the chosen emulation strategy supports either the original controller, or an accurate representation of the original controller. In the case of the Sega Genesis, companies such as Mayflash have created peripherals that allow an original Genesis controller to be read by a machine utilizing USB Type 2 or 3,[51] while companies such as Retro-Bit have created licensed Genesis replicas that support either USB, Blutooth, or 2.4 GHz Wireless out of the box.[52]

From a game design perspective, “game feel” is defined as “real time control of virtual objects in a simulated space, with interactions emphasized by polish.”[53] This definition provided by Steve Swink, by their own admission in their book games such as Starcraft and Civilization, which are from a top-down perspective with mouse button inputs.[54] True game feel consists of “precise, continuous control over a moving avatar, [combined with] active perception of literal space [coupled with] effects that artificially enhances interaction without changing the underlying simulation” which can range from particles effects, to sounds, to the camera shaking.[55] Swink’s definition of “true” game feel is somewhat limiting, and does not address the entire Genesis catalog, but each element of true game feel, precise control, perception of space, and polish, are each deemed essential to making a game feel like itself. It should be

[50] Mark Guttenbrunner, "Digital Preservation of Console Video Games," 59.
[51] Mayflash, "SEGA Genesis & Mega Drive Controller Adapter for Nintendo Switch/OLED Model, Windows," https://web.archive.org/web/20220418144408/https://www.mayflash.com/product/showproduct.php?id=25 (accessed April 07, 2022).
[52] Retro-Bit, "Retro-Bit X Sega Collaboration," https://retro-bit.com/sega-collaboration/ (accessed April 07, 2022).
[53] Steve Swink, *Game Feel : A Game Designer's Guide to Virtual Sensation* (Amsterdam ; Boston: Amsterdam; Boston : Morgan Kaufmann Publishers/Elsevier, 2009) 6.
[54] Steve Swink, *Game Feel : A Game Designer's Guide to Virtual Sensation*, 7.
[55] Steve Swink, *Game Feel : A Game Designer's Guide to Virtual Sensation*, 4.

noted that Swink's book focuses on game feel from a design perspective, highlighting what developers should do, but just because a game was poorly produced with critically panned controls such as *Slaughter Sport*, *Batman Forever*, or *Rise of the Robots*,[56] does not mean they do not possess feel, and it is up to the hardware emulation to retain the exact control as the original.

3.2 Graphics

It is no surprise graphics are deemed an essential element to preserve by emulation. Guttenbrunner provides key elements to the graphics, highlighting quality, frame rate, and 2D and 3D display characteristics as properties to consider when analyzing how well a game is being emulated.[57] While somewhat of a subjective task defining the quality of an image, it is easy to note if there are differences between the original image and emulated one. In an experiment performed by the CAMiLEON Project, researchers had users play the original version of a 1990s video game, *Chuckie Egg*, and compare it to both a software emulated version and a migrated version (a version recompiled to work on modern hardware without creating a virtualized environment). Their findings showed that the emulated version was "squished together," with some noting they preferred the original better, and that the migrated version looked "better" and that the "old version flickers more."[58] Neither of these results are good by a preservation standpoint in that, even if the user preferred a better-looking version, this was not an accurate representation of the original game, and in turn, is not a good strategy

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[56] Watch Mojo, "Top 10 Worst Sega Genesis Games," https://www.youtube.com/watch?v=7seiziPoEJM
[57] Guttenbrunner, "Digital Preservation of Console Video Games," 56-58.
[58] Margaret L. Hedstrom et al., ""The Old Version Flickers More": Digital Preservation from the User's Perspective," *The American Archivist* 69, no. 1 (Apr 1, 2006)170. doi:10.17723/aarc.69.1.1765364485n41800. https://www.jstor.org/stable/40294315.

by the metrics defined by Guttenbrunner. That being said, while hard to quantify, this study shows that picture quality is something one can evaluate.

Figure 6. Super Mario 64 properly rendered in RetroArch at 4:3.

Figure 7. Super Mario 64 improperly rendered in RetroArch at 16:9.

It is important to note that the image can be dictated by not only the hardware, but the monitor and cables that are used to display the game. The Sega Dreamcast, for example, shipped with composite video cables outputting a 480i signal, but did support a VGA output to

480p utilizing a special cable.[59] Both are native to the hardware, but this emphasizes that users could be experiencing different images based on the Dreamcast outputting progressive or interlaced. This does highlight a shortcoming with the "Old Version Flickers More" study, as they failed to describe exactly what monitors they were utilizing when running their experiment. It is unsurprising there was a change in game feel, as their modern setup seems to have included a modern display. With all that said, it is easy to get lost in the weeds of cabling and monitors, but the important concept to highlight is that when comparing game feel between original hardware and its emulated solutions for preservation, there should be some parity within the setup of each. This methodology will become clearer later in this paper when examining the FPGA test.

Frame rate can vary from game to game and is determined by the console hardware, the graphics found within the game, and how well the code is optimized for graphical performance.[60] As detailed earlier in this paper, *Sonic the Hedgehog* ran at different speeds in different regions and so when looking at preservation strategies, one must take this into account, and acknowledge this delicate balance between software and hardware as even a slight modification of the elements involved, whether it is the emulated software or hardware, can drastically change the end result and affect the game's frame rate.[61]

[59] Mas Systems, "Dreamcast VGA Audio/Video Adapter," https://web.archive.org/web/20100405045834/http://www.massystems.com/DC-VGA.html (accessed April 7, 2022).

[60] Michael Klappenbach, "How to Optimize and Improve Graphics Performance and Frame Rates," https://www.lifewire.com/optimizing-video-game-frame-rates-811784 (accessed Jan 9, 2022).

[61] Carta, "Metadata and Video Games Emulation: An Effective Bond to Achieve Authentic Preservation?" *Records Management Journal (London, England)* 27, no. 2 (Jul 17, 2017)196. doi:10.1108/RMJ-10-2016-0037. https://www.emerald.com/insight/content/doi/10.1108/RMJ-10-2016-0037/full/html.

Guttenbrunner details that 2D and 3D display characteristics are essential when analyzing graphical emulation. 2D characteristics can be considered a variety of elements but Guttenbrunner cites collision detection, sprite placement, background objects, and text as examples, while 3D objects are considered object calculation, clipping, and texture quality.[62] While the rendering of these graphics will vary from game to game, it is important to look out for key graphical features of each title. *Vectorman*'s pre-rendered 3D models, *Gunstar Heroes'* use of scaling and multi-sprite bosses, *Panorama Cotton*'s 3D like effects without the use of polygons, and *Virtua Racing*'s fully 3D and widescreen support are all essential to the presentation of each respective title, and proper emulation should be able to represent them without any errors such as unintended flickering, incorrect sprite placement, or screen tearing.[63]

3.3 Sound

Finally, Guttenbrunner breaks sound into two key elements, the music being played throughout the game and the sound effects.[64] This is an easily definable element, and, much like the graphical analysis in the *Chuckie Egg*, users were quick to identify when it was not presented correctly. Users in the study found the migrated version “sloppier” and “more annoying.”[65] It is important to remember that the same game could perform differently from region to region (as in the case with *Sonic the Hedgehog*) or even across revisions. The blog

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[62] Guttenbrunner, "Digital Preservation of Console Video Games," 57.
[63] RetroGaming with racketboy, July 3, 2007, https://www.racketboy.com/retro/best-sega-genesis-graphics-sound.
[64] Guttenbrunner, "Digital Preservation of Console Video Games," 56.
[65] Hedstrom et al., ""The Old Version Flickers More": Digital Preservation from the User's Perspective," *The American Archivist* 69, no. 1 (Apr 1, 2006)170. doi:10.17723/aarc.69.1.1765364485n41800. https://www.jstor.org/stable/40294315.

“Nerdly Pleasures” provides a post detailing some compatibility issues across Genesis models, citing sound differences. They note that Sega switched from a discrete sound chip, the YM2612 to a YM3438 integrated into an ASIC, and they continued to make slight revisions to the sound chip layout across new models and motherboard revisions.[66] The blog compares music from the title *After Burner II* on a YM2612 and YM3438, providing audio recordings in the post, and one can hear a louder volume level with certain notes on the YM2612.[67] Because of these differences, it will be important to note that if an emulator is accurately recreating the sound of a game, and which model of the system is the target.

Chapter 4: History of FPGAs and Their Use in Video Game Preservation

4.1 History of FPGAs

The history of FPGAs begins in the in the mid-1980s, when the technology was developed by Zilog, a developer of microprocessors (as seen in the Sega Genesis and Mark III), and eventually purchased by Ross Freeman and his colleagues, founding their company Xilinx, with the goal of “targeting the ASIC emulation and education markets.”[68]

FPGA technology was developed due to a gap in integrated circuit technology at the time. Programmable logic devices (PLDs) are highly configurable ICs that were developed for fast design and modification but could not handle complex functions. On the other end of the spectrum there were application-specific integrated circuit ASICs which could support large and

[66] Nerdly pleasures, Sunday, September 23, 2018, https://nerdlypleasures.blogspot.com/2018/09/sega-genesis-compatibility-issues.html.
[67] Nerdly pleasures, Sunday, September 23, 2018, https://nerdlypleasures.blogspot.com/2018/09/sega-genesis-compatibility-issues.html.
[68] Oskar Mencer et al., "Hitting a Nerve with Field-Programmable Gate Arrays.
," *Communications of the ACM* 63 (2020), 36-39. https://cacm.acm.org/.

complex functions but were incredibly time consuming to design and not easy to modify.[69] FPGAs fit neatly along this spectrum as “a chip that is programmed by a circuit. It is said to “emulate” that circuit.”[70]

Because of this built-in plasticity, they were adopted by companies who made ASICs to emulate their circuits before committing to them an producing them. They also found much use in the telecom industry. Due to volatility of standards in telecom, they required their ICs to be more agile and reprogrammable to stay up to date, something for which an ASIC is suited.[71] It is this plasticity that makes FPGAs a perfect candidate for video game emulation.

4.2 Utilization in Video Game Community

Nick Recihart of the gaming website Racketboy conducted an interview with a lead community member named SmokeMonster, a pronounced voice of the MiSTer project. They detail the benefits of FPGAs citing what this paper has detailed previously with the number of components found in the Genesis stating, “Electronic PCBs [from original gaming hardware] are chock full of different chips and circuits operating in tandem at extremely precise timings. Perfectly emulating the real hardware of even simple consoles like the Nintendo NES requires an absolute monster of a traditional CPU to get similar results to low-end FPGAs,”[72] Because of the large amount of hardware needed to be emulated, FPGAs are beneficial in that they can be reprogrammed to emulate different ICs found on different consoles, and according to intel, the

[69] Maxfield, *The Design Warrior's Guide to FPGAs* (Burlington: Newnes, 2004), 1-8.
[70] Mencer et al., "Hitting a Nerve with Field-Programmable Gate Arrays," 36-39.
[71] Mencer et al., "Hitting a Nerve with Field-Programmable Gate Arrays," 36-39.
[72] RetroGaming with racketboy, February 20, 2019, https://www.racketboy.com/retro/mister-fpga-the-future-of-retro-game-emulation-and-preservation.

creator of the FPGA chip found on the DE-10 Nano, "there is no specific limit" to how many times it can be reprogrammed.[73]

Specific operations given to the FPGA are called "cores" in the MiSTer community. According to SmokeMonster, a core works by configuring the FPGA, emulating the console or computer by using physical logic gates instead of software code as seen in software emulated environments.[74]

In terms of development there appear to be two major ways in which community members program this FPGAs. The first is to utilize Verilogs and VHDLs which are "hardware description languages that were originally designed to document chips both for manufacture and research."[75] With this documentation in hand, one could reproduce the chip exactly as an ASIC in a factory, or, in the case MiSTer's development, program it to behave like said chip. However, this documentation can be sparse or incomplete, in which case the other method was taken by Kevin Horton, lead engineer at Analog.

In his Verge interview, Horton discusses how he was able to reverse engineer the Sega Genesis's 68K processor to "the cycle and sub cycle of its processor," consulting the actual semiconducting circuits on the CPU when designing the Mega Sg's (a commercial Genesis FPGA

[73] intel, "How Many Times can I Reprogram Or Reconfigure an Altera Device?," https://www.intel.com/content/www/us/en/support/programmable/articles/000075866.html (accessed April 02, 2022).
[74] RetroGaming with racketboy, February 20, 2019, https://www.racketboy.com/retro/mister-fpga-the-future-of-retro-game-emulation-and-preservation.
[75] RetroGaming with racketboy, February 20, 2019, https://www.racketboy.com/retro/mister-fpga-the-future-of-retro-game-emulation-and-preservation.

product) hardware board.[76] Their development went as far as connecting an “original 68k CPU to his emulated chip to test its relative accuracy and then left that test running for a week straight. (Any deviation would cause the test to fail.)”[77]

4.3 MiSTer

MiSTer began as a fork, i.e., an offshoot, of the MiST project.[78] MiST was designed to run older personal computers like the Amiga and Atari ST, from which the project was named (Mi from Amiga and ST from Atari ST).

In their interview with Racketboy, SmokeMonster details the MiSTer project:

> The objective of the MiSTer project is to create an open source, community driven, retro gaming console. In its current state, it is built on the Terasic DE10-Nano platform, which features a Cyclone V FPGA, DDR3 memory, an ARM processor to handle input and output, HDMI output, Ethernet, and a USB On-the-Go port, among other feature useful to development. The MiSTer has a menu, which allows the user to select cores, all of which are stored on a microSD card.[79]

According to the MiSTer GitHub repository’s FAQ, the DE10-Nano was chosen due to its large-scale production for its use in education.[80] The MiSTer community has also acknowledged that no board is produced forever, and there will be an effort to port all relevant software and cores to whatever new platform is chosen.[81] This dedication to future proofing the

[76] Stephen, "Analogue's Console Clones are a Way to Preserve Gaming's Past.”
[77] Stephen, "Analogue's Console Clones are a Way to Preserve Gaming's Past.”
[78] birdybro, "MiSTer Wiki," https://github.com/MiSTer-devel/Main_MiSTer/wiki (accessed Feb 1, 2022).
[79] RetroGaming with racketboy, February 20, 2019, https://www.racketboy.com/retro/mister-fpga-the-future-of-retro-game-emulation-and-preservation.
[80] missionfloyd, "Frequently Asked Questions," https://github.com/MiSTer-devel/Main_MiSTer/wiki/Frequently-Asked-Questions (accessed Feb 5, 2022).
[81] missionfloyd, "Frequently Asked Questions.”

development kit gives hope for a standardization of sorts which the preservation of video games needs.

In order to get the MiSTer running, only the DE10-Nano is needed, but there are recommended “daughter boards” (boards dependent on the main board that add functionality to the entire unit) that can be used. Notably, an expanded SDRAM board is needed to help run more RAM intensive cores, while an I/O board can be used to provide a VGA out, 3.5mm phone jack, interface buttons, and LEDs.[82]

Finally, the backbone of the MiSTer project are the previously mentioned cores. A core can be described as the software that makes the DE10-Nano run like a specific system, akin to how there are dedicated software emulators for different systems. RetroRGB describes the standard development of a core as:

> You essentially need to recreate the original hardware in HDL (Hardware Description Language), which is more similar to a schematic than traditional coding. To do this, you map out each component on the motherboard, trace all the lines and analyze how they “talk” to each other in real time. Some of the components on the board may be common off-the-shelf parts that offer datasheets about how they work. If not, someone else may have already reverse-engineered the ‘generic’ component and have FPGA data on it already. These modular parts are usually referred to as “soft cores” and can be ‘plugged’ (via software) into a core, almost like a socketed IC.[83]

Much like Analog’s development process, MiSTer developers reverse engineer specialty ASICs and other components, the soft cores RetroRGB mentioned, to make

[82] birdybro, "MiSTer Wiki.”
[83] RetroRGB, "MiSTer FPGA Hardware," https://www.retrorgb.com/mister.html (accessed Feb 5, 2022).

them as cycle accurate as possible.[84] Once all relevant components are assembled, they are released as the full core and are flashed onto the FPGA which will then emulate the desired core.[85]

It is this modularity that helped contribute to the Sega Genesis/Mega Drive FPGA core. In a 2018 YouTube video, SmokeMonster reported on the release of an Atari ST core utilizing a cycle accurate Motorola 68000 soft-core.[86] The soft-core, named FX68K, was developed by Jorge Cwik, or ijor on the Atari-Forum.com website, which was written in SystemVerilog.[87] Prior to the FX68K, there was a Sega Genesis core, named FPGA Gen that predated the MiSTer project, which was developed by Gregory Estrade for the Terasic Altera DE10 FPGA board.[88] FPGA Gen was then ported to MiST, then to the MiSTer by Alexey Melnikov, creator of the MiSTer project, which originally used a soft-core known as the TG68k, but was then replaced with Cwik's FX68K.[89]

In addition to the cycle accurate 68K soft core, a look at the SEGA Genesis core GitHub repository details that the core includes soft-cores for both the Yamaha YM2612

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84 RetroRGB, "MiSTer FPGA Hardware."
85 RetroRGB, "MiSTer FPGA Hardware."
86 SmokeMonster, "Why's the New MiSTer Atari ST Core so IMPORTANT? Cycle-Accurate 68000 FPGA!! | SmokeMonster," https://www.youtube.com/watch?v=VQiDpjVdtb4 (accessed February 7, 2022).
87 Jorge Cwik, "Fx68k," https://github.com/ijor/fx68k (accessed April 3, 2022).
88 SmokeMonster, "A New Sega Genesis Console: MiSTer FPGA - New Year Core Countdown #10 | SmokeMonster," https://www.youtube.com/watch?v=yBn60DrLWSA&list=PLsLxmNa35KdjEtsZb4wfnc4H2po84i0cf&index=12 (accessed December 19, 2021).
89 SmokeMonster, "A New Sega Genesis Console: MiSTer FPGA - New Year Core Countdown #10 | SmokeMonster."

and YM3438 sound chips, while also providing audio filters to emulate the Model 1, Model 2, with options for minimal and no filter.[90]

In addition to the SEGA Genesis, there is a plethora of cores ranging from classic computers such as the Apple II to the Commodore 64, consoles and handhelds such as the Game Boy, NeoGeo, and Atari 2600, as well as a number of arcade cores such as Asteroids, Centipede, and Donkey Kong.[91]

In terms of future development of cores for the DE10-Nano, the MiSTer community is presently working 32-bit consoles with the SEGA Saturn and Sony PlayStation,[92] however, hope for a Nintendo 64 core does not seem possible given the FPGA's specs.[93] It is also important to note, that many cores for the MiSTer project are still under active development with bugfixes for both graphics, sound, and stability, so while the theory, technology, and execution for the MiSTer project are solid, there are community members at work fixing any technical hiccups that might exist.[94]

4.4 Analogue

Because it is opensource, the documentation of MiSTer's development is much more easily accessible. That coupled with the fact that this experiment will be utilizing a MiSTer, this

[90] Alexey Melnikov, "SEGA Megadrive/Genesis for MiSTer Platform," https://github.com/MiSTer-devel/Genesis_MiSTer (accessed Feb 6, 2022).
[91] missionfloyd, "Frequently Asked Questions," https://github.com/MiSTer-devel/Main_MiSTer/wiki/Frequently-Asked-Questions (accessed Feb 5, 2022).
[92] Video Game Esoterica, "Sega Saturn and PS1 Core Updates + X68000 Progress & New Arcade Cores - MiSTer FPGA November News!" https://www.youtube.com/watch?v=lDI84_yV2a8 (accessed December 3, 2021).
[93] missionfloyd, "Frequently Asked Questions."
[94] MiSTer FPGA forum, April 13, 2022, https://misterfpga.org/viewtopic.php?t=147.

paper will only briefly cover the commercial semi-closed source option for FPGA's sold by Analogue.

Unlike the MiSTer, which can emulate a multitude of old game computers and consoles on the same hardware, Analogue focus on selling products tailored to specific systems. The Analogue Pocket emulates a variety of handheld systems, the Duo handles the PC Engine/TurboGrafx, the Mega Sg works with various 8 and 16-bit Sega consoles such as the Genesis and Master System, and the Super Nt and Nt Mini emulate the Super Nintendo and Nintendo Entertainment System, respectively.[95] Unlike the MiSTer project, which plays file-based ROMs and ISOs, Analogue supports playing original cartridges.[96]

Analogue's products are mostly closed source, save for the recently released Analogue Pocket, which had its development specifications released and utilizes an Altera Cyclone V FPGA[97], a chip in the same family as that used on the DE10-Nano board.[98]

In terms of interactivity, the Analogue products also allow connection of wireless devices as well as original controllers through their respective controller ports.[99]

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[95] Analogue, "Analogue," https://web.archive.org/web/20220219200123/https://www.analogue.co/ (accessed Feb 19, 2022).
[96] Analogue, "Analogue."
[97] Analogue, "Developer," https://web.archive.org/web/20220219210829/https://developer.analogue.co/ (accessed Feb 19, 2022).
[98] birdybro, "MiSTer Wiki."
[99] Analogue, "Super Nt," https://web.archive.org/web/20220219213036/https://www.analogue.co/super-nt (accessed Feb 19, 2022).

Finally, with regards to video and audio output, the Analog devices support an HDMI out, with the option of utilizing a proprietary digital to analog converter named the Analogue DAC, allowing users to output both a composite and RGB signal.[100]

4.5 Preservation of FPGA Documentation

It is important to note that just as these original consoles have several issues staying in working order, so too can any other piece of hardware. Because of this, it is important to look at the sustainability of FPGA's. Because of Analogue's mostly closed source nature as a company, one can only imagine that the longevity of their products will only last as long as the company will. The MiSTer project, due to its open-source nature, has been open about plans for futureproofing the project.

In their interview on RacketBoy, SmokeMonster details that "although it's currently based on the Terasic DE10-Nano, it will be relatively simple to port its cores to future devices. When all the original hardware and custom chips have died, FPGA recreations can be used to emulate or even produce physical replacements."[101] This practice of porting to new hardware has already been seen with the MiSTer project being a ported from MiST, which used a less powerful board. It is also interesting to note SmokerMonster's comment that physical replacements could be reproduced. RetroRGB.com delves further into this idea, detailing how chips are produced:

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[100] Analogue, "Say Hello to Analogue DAC," https://web.archive.org/web/20220219213927/https://www.analogue.co/dac (accessed Feb 19, 2022).
[101] RetroGaming with racketboy, February 20, 2019, https://www.racketboy.com/retro/mister-fpga-the-future-of-retro-game-emulation-and-preservation.

> Another bonus of HDL, is it's the actual blueprint that's sent to fabricate real chips for manufacturing. That means once all the original hardware is dead and gone, it can be recreated on a chip…provided it was recorded perfectly in HDL. Theoretically, you can model any digital circuit in HDL as a 1:1 exact copy, indistinguishable by human or machine, but few cores will ever reach that level of perfection.[102]

While the practicality and interest in creating new chips like the 68K could be up for debate, it is exciting to see that recreating original hardware years down the road is at least feasible.

Chapter 5: Hardware Comparison

5.1 ROM "Dumping" and md5 Checksums for Parity Across Platforms

Much like the consoles on which they are played, it was not uncommon for the games themselves to have multiple revisions. *Sonic the Hedgehog 2*, for instance, saw two different releases worldwide, each with minor differences in object placement, as well as a few bug fixes.[103] Because testing the hardware emulators against the original hardware should maintain parity, a commercially available project called a Flashkit Programmer MD was used to "dump" the ROM files (copying them from the cartridge), creating a file-based copy of the game, which is easily portable from the computer performing the dump to the MiSTer SD card.

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[102] RetroRGB, "MiSTer FPGA Hardware."
[103] The Cutting Room Floor, "Sonic the Hedgehog 2 (Genesis)/Revision Differences," https://tcrf.net/Sonic_the_Hedgehog_2_(Genesis)/Revision_Differences (accessed December 11, 2021).

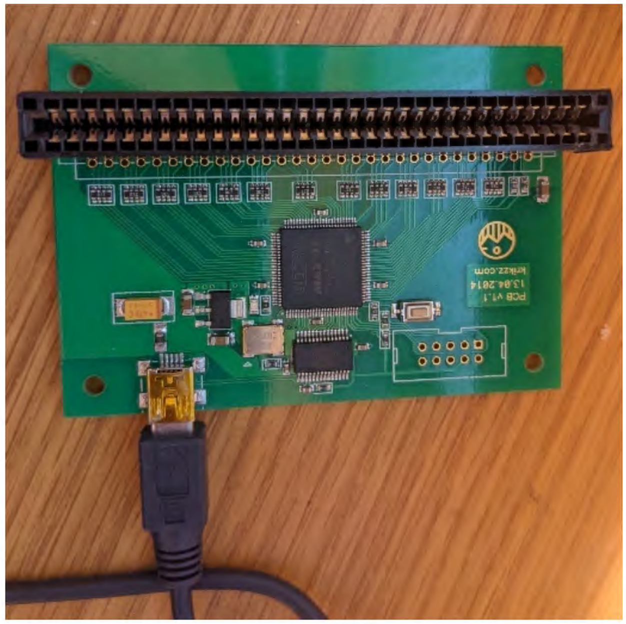

Figure 8. Flashkit Programmer MD.

As seen in Figure 9, the Flashkit Programmer MD utilizes pins that intake a Genesis cartridge, and then connects to a PC via a mini-USB cable as seen in Figure 9 below:

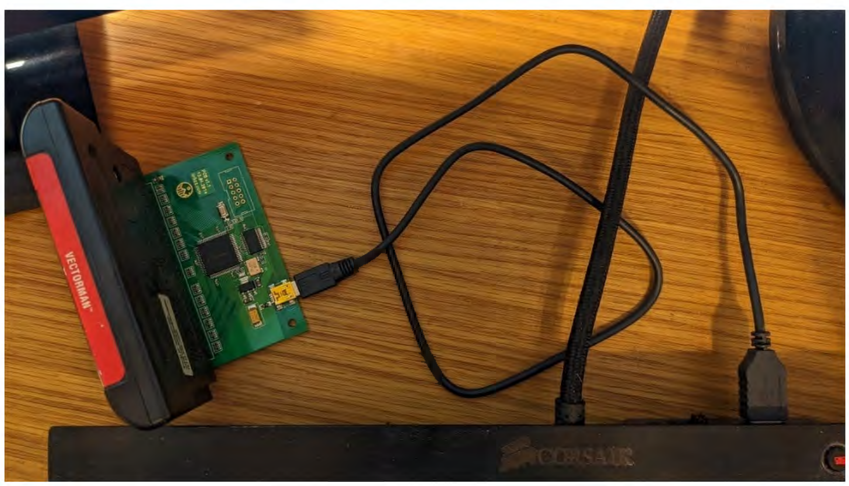

Figure 9. Cartridge, Flashkit, Computer Hook Up.

The Flashkit device utilizes proprietary software listing embedded metadata as well as generating an md5 hash specific to the cartridge. Figure 10 demonstrates the software used with the game *Vectorman*.

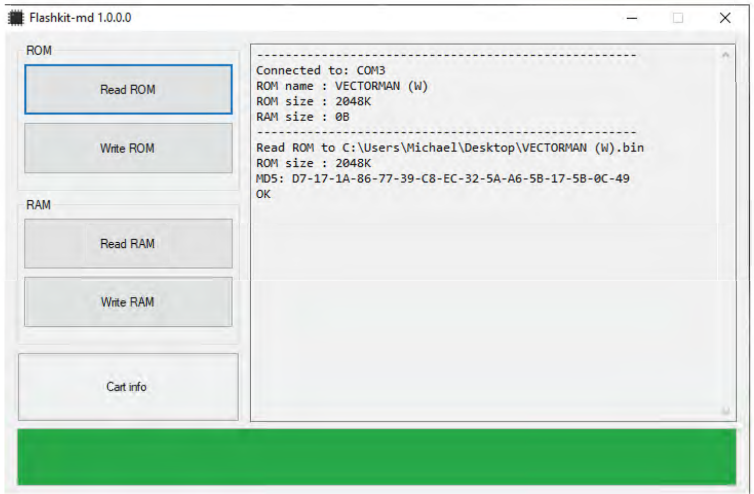

Figure 10. Flashkit MD Software Interface.

In order to verify the ROM was dumped accurately, an md5 checksum was run against both the dumped file and compared to a community-based video game preservation program, TOSEC (The Old School Emulation Center),[104] to verify that the dump of the game was performed correctly without any data corruption.

Game	md5 hash	Passed TOSEC Check?
Batman Forever	b04c06df1009c60182df902a4ec7c959	Yes
Golden Axe (Rev 1)	e4263c39487f0b55e8f33cbd5acd9b93	Yes
Sonic the Hedgehog 2 (Rev 1)	9feeb724052c39982d432a7851c98d3e	Yes
Streets of Rage 2	cb75d5a6919b61efe917bea5762c1cb7	Yes
Vectorman	d7171a867739c8ec325aa65b175b0c49	Yes

Finally, this paper understands the stringent copyright laws surrounding video games; however, physical copies of all games in this experiment were legally obtained from a local retro shop, dumped utilizing reverse engineered hardware, the digital files were not distributed, and were only used in a reserve engineered emulated environment. All these

[104] TOSEC, "Tosec," https://www.tosecdev.org/ (accessed Apr 17, 2022).

practices are considered legal to gray especially with regards to “making a backup copy of a game,” and so, there is no concern surrounding copyright issues with regards to an experiment such as this.[105]

5.2 Emulation Metrics

To test how well the MiSTer is emulating the original Genesis console, a few metrics must be established. Looking back to Guttenbrunner’s essential elements detailed earlier, image quality, audio, and input would be the best in terms of capturing the experience of playing on a console, as these three characteristics present themselves most notably to the user and make up the “authentic look and feel” noted by Guttenbrunner.[106]

For image quality, the elements that will be looked at are frame rate, color, aspect ratio, and a miscellaneous category. Frame rate is a less subjective metric to look as when measuring the difference to the original frame rate if the value is calculated in percent as deviation from the original frame rate, and any difference shows it is not being emulated as accurately as possible.[107] In order to measure frame rate, an open-source program “trdrop” (pronounced tear drop) will be used to measure the frame rate of uncompressed captured gameplay footage.[108] Color, a slightly more subjective metric, should be considered more critically if a color is wrong, i.e. blues appearing as red. Saturation and brightness, while important to note, can be adjusted depending on the cables used and settings on a video monitor. Aspect ratio

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[105] James Conley et al., "Use of a Game Over: Emulation and the Video Game Industry, A White Paper," *Northwestern Journal of Technology and Intellectual Property* 2, no. 2 (2004), 13-14. https://scholarlycommons.law.northwestern.edu/cgi/viewcontent.cgi?article=1022&context=njtip.
[106] Guttenbrunner, "Digital Preservation of Console Video Games," 53.
[107] Mark Guttenbrunner, "Digital Preservation of Console Video Games," 56.
[108] cirquit, "Trdrop - V1.1.1," https://github.com/cirquit/trdrop#readme (accessed Feb 19, 2022).

considers if the image is squished, stretched, or adheres to the original output. As for the miscellaneous criteria, this is an umbrella statement looking for any noticeable flickering of sprites, backgrounds tearing, or any other visual oddities not originally present on the original console.

In terms of sound, Guttenbrunner states that there are two different aspects to consider; the sound effects and the music.[109] When measuring how effective the sound is being emulated one must look at if the sound quality matches the original, and how well the sound is synchronized to the image.[110] Much like the framerate, any deviation from the original signals the game might not be accurately emulated.

Finally, Guttenbrunner details input measured in terms of delay, with considerable, short, and not noticeable.[111] While there are ways to measure input delay with cameras by filming user input and synchronizing it to the game play, that set up is beyond what this experiment's scope. Instead, it will be measured by the feel of the author when playing the game.

5.3 Software and Hardware Set Up

The below table provides all equipment that was used to test and capture footage of both an original Sega Genesis Model 1 and a Mister FPGA.

[109] Guttenbrunner, "Digital Preservation of Console Video Games," 56.
[110] Guttenbrunner, "Digital Preservation of Console Video Games," 56.
[111] Mark Guttenbrunner, "Digital Preservation of Console Video Games," 59.

Item	Purpose	Source	Price
Consoles			
Sega Genesis Model 1 "High-Definition Graphics"	Original Hardware for use as a "control"	Video Games New York (local retro gaming store)	$76.20
Ultimate MiSTer PRO BlisSTer Edition	FPGA running MiSTer to test accuracy	Ultimatemister.com	$447.66 (includes shipping)
Cables			
Video Cable – VGA to YPbPr	Output YPbPr from MiSTer to try and match analog output of original console	MisterAddons.com	$24.15 (includes shipping)
HD Retrovision Genesis YPbPr Component Cable*	Match the color space the MiSTer is outputting on the Genesis	Retrostuff.ca	$10
HD Retrovision Model 2 to Model 1 Genesis A/V Port Adapter*	Needed to make HD Retrovision compatible with selected Genesis Model	Retrostuff.ca	$74
	Shipping*		$19
Controller			
Retro-Bit Sega Genesis 2.4 GHz Wireless Controller 8-Button Arcade Pad	Controller that is compatible with both original and emulated hardware	Amazon	$38.10 (includes shipping)
Capture Setup			
Mac Pro Mid 2012 (OS X El Capitan)	Capture Station	MIAP Lab	N/A
vrecord 2018-05-14	Capture Software	MIAP Lab	N/A
DPS-290 TBC	Used as input for Genesis and MiSTer	MIAP Lab	N/A
Kramer VM-1044 Distribution Amplifier	Split video signal	MIAP Lab	N/A
Rolls RA 163 Distribution Amplifier	Split audio signal	MIAP Lab	N/A
Sony PVM1954Q Monitor	Monitor analog picture quality	MIAP Lab	N/A

In terms of original hardware, a Sega Genesis Model 1 “High-Definition Graphics” version with TMSS was selected and obtained at a local New York City retro video game store. Based on Ace’s teardown guide on Sega-16.com, because of the FCC ID of FJ8USASEGA found on the back of this console, the sound chip used in this model is the Yamaha YM2612.[112] The original console selected will provide the baseline metrics for the MiSTer to be judged against.

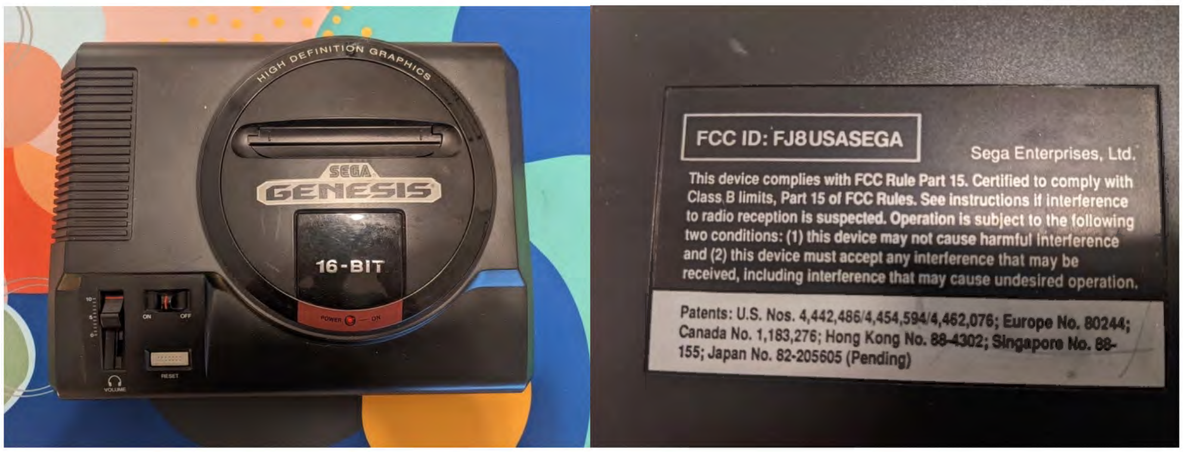

Figure 11. Sega Genesis Model 1 (Left), ID on back of console (Right).

Figure 12. Ultimate MiSTer PRO BlisSTer Edition.

For the FPGA, the Ultimate MiSTer PRO BlisSTer Edition was selected. While it does not affect the testing, this edition of the MiSTer comes with the additional SDRAM module,

[112] Sega-16, July 2, 2009, https://www.sega-16.com/forum/showthread.php?7796-GUIDE-Telling-apart-good-Genesis-1s-and-Genesis-2s-from-bad-ones.

normally required for emulating NeoGeo and other more powerful systems than the Genesis, as well as a Low Latency BlisSter Hub Board, which is said to decrease latency when utilizing USB devices with the MiSTer.[113] Both components are not essential with regards to emulating the Sega Genesis, but due to lack of availability of other models during the time of purchase, the BlisSter edition was selected. An element that is deemed optional[114] by the MiSTer GitHub, but necessary for this paper's purposes, is the I/O board. This board provides a VGA out port, which is capable of RGB, YPbPr, and standard VGA video signals, as well as a 3.5mm Audio Jack.[115]

Figure 13. MiSTer I/O Outputs.

Because the original Genesis utilizes a composite analog signal, for purposes of comparing the original experience between the two hardware, it is important for the MiSTer to output as close to the original signal as possible.

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[113] Ultimate MiSTer, "Ultimate MiSTer PRO BlisSTer Edition," https://ultimatemister.com/product/ultimate-mister-blisster/ (accessed Feb 18, 2022).
[114] birdybro, "MiSTer Wiki."
[115] Em K IronFist, "IO Board," https://github.com/MiSTer-devel/Main_MiSTer/wiki/IO-Board (accessed Feb 18, 2022).

With both the console and MiSTer selected, an important decision was made with regards to cabling. As previously noted, the MiSTer is capable of RGB, YPbPr, and VGA out, while the Model 1 Genesis originally shipped with an RF cable, and the option to buy a composite RCA cable.[116] Due to the need for parity between the two pieces of hardware, outputting to the same color space is helpful to provide an easy comparison. Unfortunately, none of the output signals provided by the MiSTer could exactly match the composite output of the Genesis, and so another solution had to be found. RetroRGB has a comprehensive list of RGB cable options, mostly utilizing SCART cables with an adapter.[117] Being in the US, however, made the proposition of utilizing SCART impractical, and would require a SCART to RGB adapter. Instead, RetroRGB recommends[118] a Genesis YPbPr component cable made by HD Retrovision, which processes the composite out into a YPbPr signal.[119] As a small note, this cable was made for the Genesis Model 2 video out port, and so a Model 2 to Model 1 adapter was required. To match the color space of the Genesis and HD Retrovision cable, a VGA to component cable was acquired from Mister Addons to use with the MiSTer.[120] With both video cables selected, an audio output solution was easily decided. The Model 1 Genesis's rear port provides mono out, but its headphone jack on the front provides a stereo output.[121] The HD Retrovision utilizes this stereo jack by allowing a 3.5mm cable to connect from the SEGA to a 3.5mm input found on the

[116] SEGA, *Sega Genesis Instruction Manual* (SEGA Enterprises, Ltd., 1991), 10.
[117] RetroRGB, "Genesis RGB Cables," https://www.retrorgb.com/genesisrgbcables.html (accessed Feb 18, 2022).
[118] RetroRGB, "Genesis RGB Cables."
[119] HD Retrovision, "Genesis YPbPr Component Cable," https://web.archive.org/web/20220417235926/https://www.hdretrovision.com/genesis (accessed March 16, 2021).
[120] MiSTer Addons, "Video Cables (HDMI, SCART, YPbPr)," https://web.archive.org/web/20220218192742/https://misteraddons.com/products/video-cables-hdmi-scart-ypbpr?variant=39633472225413 (accessed Feb 18, 2022).
[121] SEGA, *Sega Genesis Instruction Manual*, 13.

cable, which sends the audio signal to the audio RCA cables.[122] The MiSTer keeps its audio and video outputs separate with the aforementioned 3.5mm jack on the I/O board.

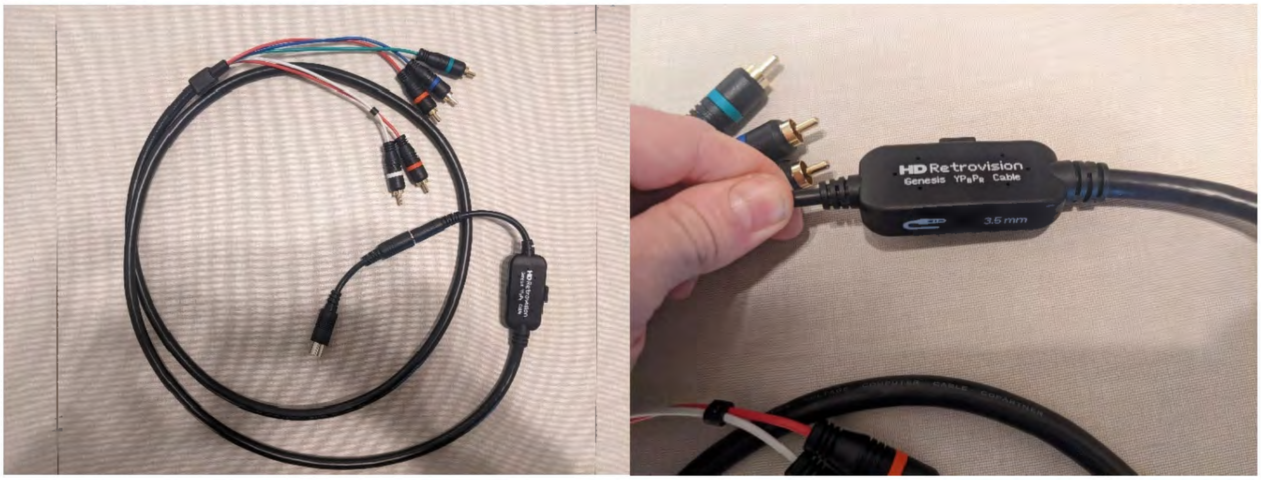


Figure 14. HD Retrovision YPbPr Cable with Model 1 Adapter (Left) HD Retrovision Cable 3.5mm Input (Right).

Figure 15. VGA to YPbPr Component Cable.

Much like the cables, parity is important when selecting a controller. There were various options available, including using an original Genesis controller with a USB adapter to use on both the console and the MiSTer; using aftermarket controllers with built in USB, (although this would require two separate controllers); or, the controller that was used for this experiment, a

[122] HD Retrovision, "Genesis YPbPr Component Cable."

2.4 GHz wireless Genesis controller licensed by SEGA manufactured by the company Retro-Bit. The controller comes with two wireless dongles, one can connect to the MiSTer by a USB 2.0 port, and one that can connect to the Genesis with a similar dongle that fits into the controller port via a D-sub connection.[123] This will act as a controlled variable as the same controller can be used on each system using the same type of wireless connection.

Figure 16. D-Sub (Left), USB (Middle), Controller (Left).

With the hardware components selected, the set up was brought to New York University's Moving Image Archival and Preservation lab which provided the equipment to record gameplay footage.

Normally used to digitize magnetic media, both the Genesis and the MiSTer were able to feed into the system via a switcher connected to a Leitch DPS-290, a device with a built-in processing amplifier to adjust color and light signals for analog video, utilizing RCA to BNC adapters, matching the inputs on the switcher. It is important to note that while the systems

[123] Retro-Bit, "Retro-Bit X SEGA® Collaboration - how Will You Play?" https://web.archive.org/web/20220219172127/https://retro-bit.com/sega-collaboration/ (accessed Feb 19, 2022).

were each connected to the Leitch, all levels were kept at 0 with no adjustments made. The Leitch was only the means for which to route the video signals into NYU's capture system, and any outside alteration to the signal introduced by the Leitch would be present in both the capture of the Genesis and MiSTer.

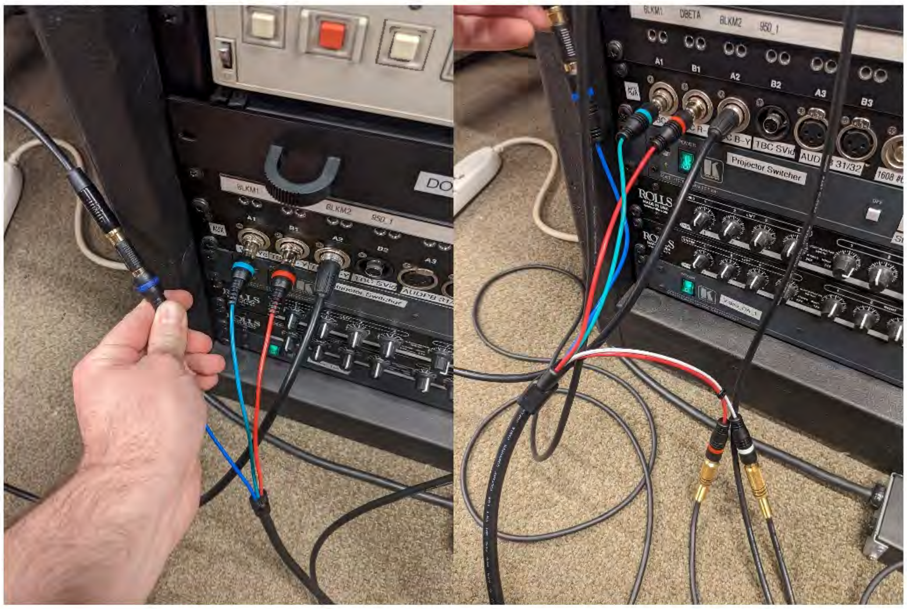


Figure 17. MiSTer Connection (Left), Genesi Connection (Right).

The signal from the Leitch was then patched into a distribution amplifier, splitting the signal. One signal was sent to a Sony PVM1954Q CRT to monitor the picture, and the other signal was sent to the capture station, a Mid 2012 Mac Pro running OS X El Capitan.

The audio wiring was slightly different for each system. For the Genesis Model 1, the stereo sound from the front jack was hooked into the HD Retrovision cable via a 3.5mm to 3.5mm cable. The HD Retrovision cable has stereo RCA cables that were each plugged into RCA to bantam adapters, and then plugged into an audio distribution amplifier. The process into the DA was similar for the MiSTer, the difference being a 3.5mm to RCA stereo cable was used in the MiSTer's audio jack. Each RCA cable was then adapted to fit in the DA just like the Genesis.

Once input into the DA, the audio was split to an audio monitor, so it could be listened to along with the picture on the PVM, and the other signal was sent to the same capture station as the video.

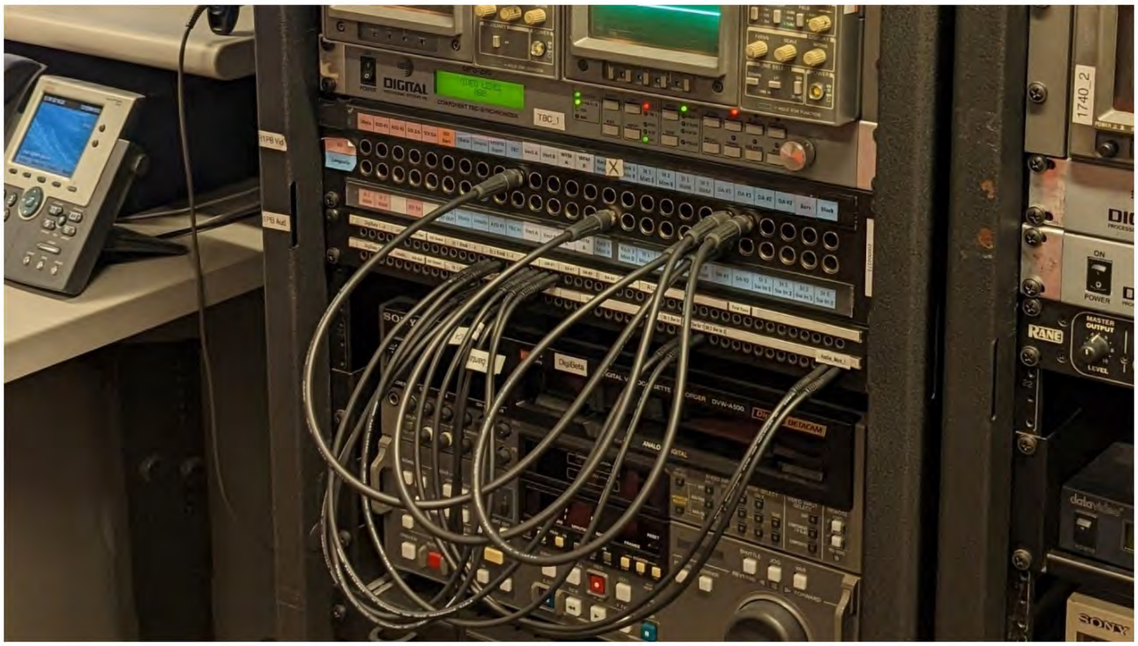
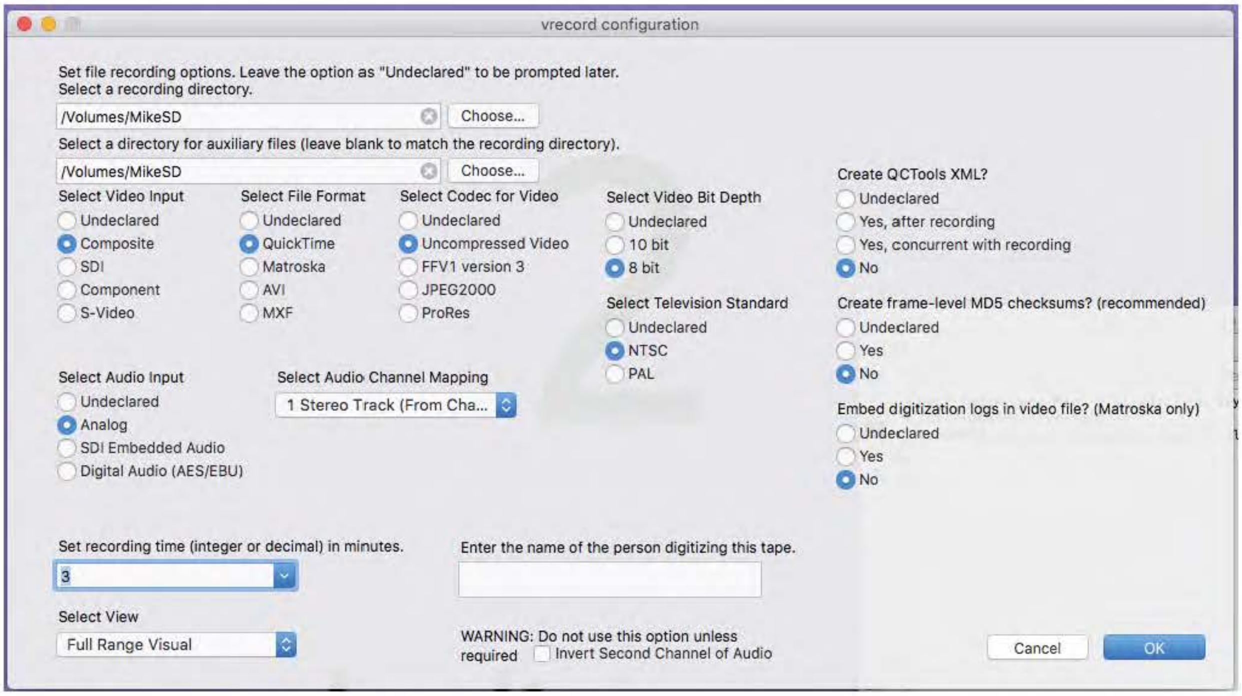


Figure 18. Patch bays for audio and video.

The capture software used was a version of vrecord from May 14, 2018. The captured footage was set to uncompressed and wrapped as a Quicktime .mov as to be compatible with trdrop, a frame rate analyzer.


vrecord configuration
Set file recording options. Leave the option as "Undeclared" to be prompted later.
Select a recording directory.
/Volumes/MikeSD
Choose...
Select a directory for auxiliary files (leave blank to match the recording directory).
/Volumes/MikeSD
Choose...
Select Video Input
Undeclared
Composite
SDI
Component
S-Video
Select File Format
Undeclared
QuickTime
Matroska
AVI
MXF
Select Codec for Video
Undeclared
Uncompressed Video
FFV1 version 3
JPEG2000
ProRes
Select Video Bit Depth
Undeclared
10 bit
8 bit
Select Television Standard
Undeclared
NTSC
PAL
Create QCTools XML?
Undeclared
Yes, after recording
Yes, concurrent with recording
No
Create frame-level MD5 checksums? (recommended)
Undeclared
Yes
No
Select Audio Input
Undeclared
Analog
SDI Embedded Audio
Digital Audio (AES/EBU)
Select Audio Channel Mapping
1 Stereo Track (From Cha...
Embed digitization logs in video file? (Matroska only)
Undeclared
Yes
No
Set recording time (integer or decimal) in minutes.
3
Enter the name of the person digitizing this tape.
Select View
Full Range Visual
WARNING: Do not use this option unless required
Invert Second Channel of Audio
Cancel
OK

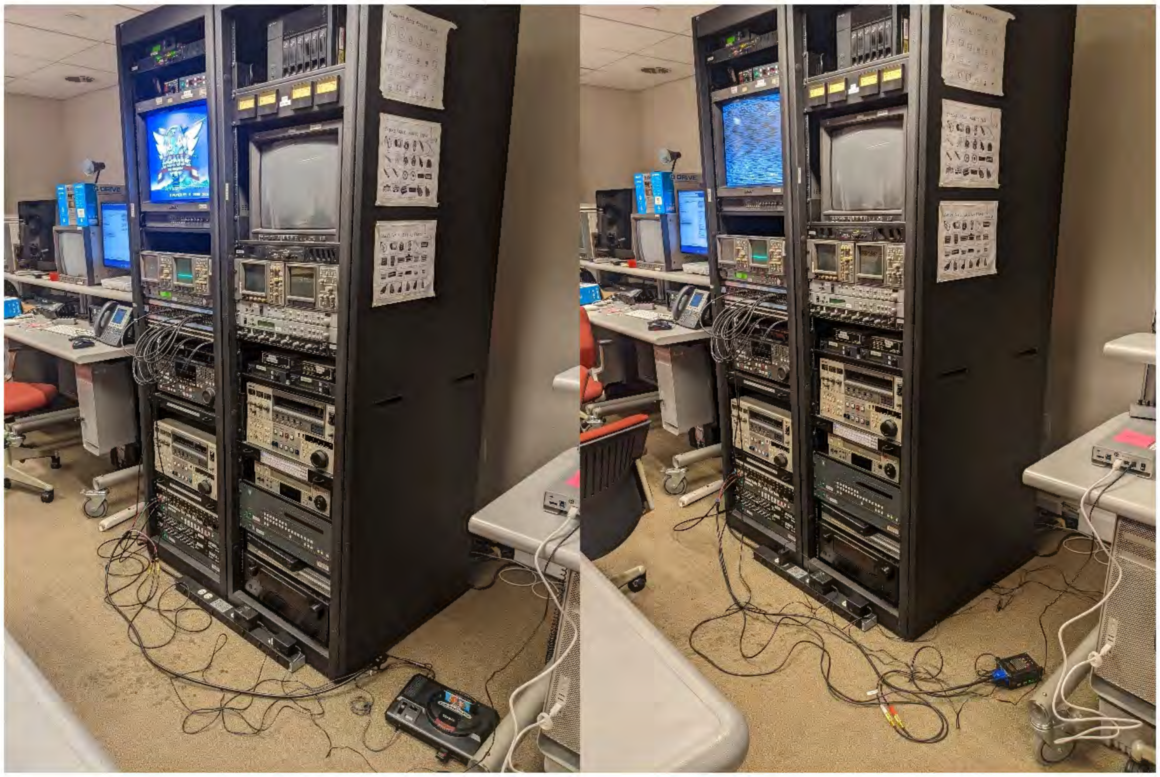


Figure 20. Genesis Capture Set Up (Left), MiSTer Capture Set Up (Right),

5.4 Results of Experiment

In terms of the input of the MiSTer, there seemed to be no discernable lag when compared against the original Genesis. Jumps, movement, and even the start menu presses all seemed equally responsive. This conclusion was made easier by monitoring the audio alongside the input. For example, when the jump button was pressed in *Sonic*, there was no delay in either movement or sound on the MiSTer, denoting no lag was present. Also, there was no improvement in game feel, especially with regards to *Batman Forever*, which was just as frustrating to play on the MiSTer as it was on the original console.

Sound is another area in which the MiSTer seemed to be accurately representing the original's output. The MiSTer Genesis's core was set to the YM2612 sound chip with a Model 1 filter, and the quality between the two matched well. Also, as stated in the input results, the sync on the sound and music on the MiSTer did not deviate from the original console. The one difference that was noticeably present, however, was the loudness. The Model 1 Genesis has a volume slider controlling its stereo output, and while it was set to 50%, it was still producing a much louder output than the MiSTer's audio, which could only be controlled by the output on the speakers. So, while different, volume can be easily adjusted on an external speaker.

For image quality, the MiSTer accurately output the aspect ratio of the Genesis with no stretching or shrinking.

Figure 21. Genesis (Left), MiSTer (Right),

It is important to note that the MiSTer does not output YPbPr "out of the box" and had to be set via the .ini settings through an "Video/Audio" menu. Some trial and error with the settings was needed, but after some tinkering, the correct output was achieved.

As for the miscellaneous object characteristics discussed, all sprites and graphics were rendered accurately. Sonic's shield would flicker correctly, flashing lights in a bar in *Streets of Rage* were shown with no odd behavior, and the 3D-like graphics of *Vectorman* had no trouble rendering.

When looking at color, the hues were rendered correctly, with blues, greens, reds, etc., appearing where they should be. The saturation and brightness differed between the MiSTer and the Genesis, but also the Genesis could differ from itself based on specific settings. The differences here are unsurprising due to the many factors at play such as cabling, monitor settings, and various other interferences added in the signal path. One notable example is that the component cable acquired for the Genesis has a brightness switch on it, allowing the user to boost the brightness of the output.

Figure 22. Cable switched to Dark (Left), Light (Right) for Genesis,

So while the differences between the MiSTer and the Genesis are noticeable, as seen in games like *Golden Axe*, adjustments could have been made on a TBC, the output monitor, or cabling to achieve a near identical look.

Figure 23. Genesis (Left), MiSTer (Right)

Finally, the frame rate was analyzed using trdrop. Trdrop is an open-source tool to measure framerate within games to see if it is hitting their targets and can be used to compare different settings and setups. It analyzes uncompressed recordings by looking at it frame by frame, converting the video into a series of thousands of TIFF or JPEG files, and comparing them.[124] When looking at the framerates captured on the Genesis for *Vectorman* and *Streets of Rage 2*, there was odd behavior being in trdrop's analysis. *Vectorman* was showing a constant framerate of 6.9 fps and *Streets of Rage 2* was showing 2.8 fps, much lower than expected. There seemed to be an error with either the capture or how trdrop was measuring it, but after some investigation, it seems that framerate does not pertain to the way consoles like the Sega Genesis handled graphics. There are many in the community who explain that systems were tied to the refresh rate of the CRT it was playing on, and so the video output would match that, 60Hz for NTSC and 50Hz for PAL. [125] [126] [127] What the experiment was first interpreting as change in frame rate was actually the CPU being overloaded (notably from having too many sprites on screen such as Sonic losing a number of rings), resulting in perceivable slowdown of the sprites' movement and flickering.[128] So while the measurement of frame rate did not provide the results intended by the experiment, this was taken as a learning experience and created a new property that could be used in future analysis, "slowdown" or "CPU tax."

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[124] cirquit, "Trdrop - V1.1.1," https://github.com/cirquit/trdrop#readme (accessed Feb 19, 2022).
[125] R/truegaming, Nov 14, 2016, http://www.reddit.com/r/truegaming/comments/5cg345/60_fps_for_a_historical_reason/da04ldn/.
[126] Digital press, Jan 19, 2014, https://forum.digitpress.com/forum/showthread.php?170706-Retro-Games-are-they-30-FPS-60-FPS-Help!.
[127] MiSTer FPGA forum, May 04, 2021, https://misterfpga.org/viewtopic.php?t=2558.
[128] Digital press, Jan 19, 2014, https://forum.digitpress.com/forum/showthread.php?170706-Retro-Games-are-they-30-FPS-60-FPS-Help!.

There are too many factors (sprites on screen, position, timecode of the music being played) and not enough time to accurately recreate the same slowdown for this current experiment, but from passing observations, the MiSTer did seem to emulate the slowdown present in the Genesis. The aforementioned instance of Sonic getting hit with a large number of rings would cause many ring sprites to fly from his body, resulting in the whole game slowing down. This behavior is present in a lot of animations resulting from the player being hit, as also seen in *Streets of Rage 2* and *Golden Axe*. It appears as if the MiSTer is accurately emulating this tax on the hardware, which should come as no surprise due to its cycle-accurate function, emulating the original hardware and the way in which each chip communicates with each other.

Conclusion

After research into the inner workings of the MiSTer project and looking at the results of the experiment for this project, the claims made by the gaming community that FPGAs are a great solution for aging and broken hardware are well founded. Because of this, many cultural heritage institutions should keep FPGAs in mind as their collection of retro consoles break down and become more difficult to replace. However, based on the results of this paper, FPGA emulation is not the be-all end-all way to preserve video games, but more another great tool to add to the toolbox for conservators.

First, as far as this experiment is concerned, the MiSTer is emulating every aspect of the Genesis as it should. There is no difference in input lag between the FPGA and the original console, even when using a 3rd party wireless controller. Also, the variety of options one can select with regards to audio and video makes the device quite appealing. For research purposes, if one wanted to see how a game ran across different revisions of a Genesis, and they did not have access to the original consoles, having the ability to change which sound chip and filter is incredibly useful to have all on one device. Also, having multiple options for video output on the MiSTer is helpful when deciding how to exhibit the games as well. HDMI has temporarily "future-proofed" the device for the time being, allowing conservators and hobbyists to experience games on current day hardware, without having to worry about keeping a CRT operational. The RGB and YPbPr out also allow for the option of interlaced output, somewhat matching the look of what might have been experienced in the 1990s; however, it is interesting that the MiSTer project does not easily support composite out, which would have most certainly been used by many consumers at that time. The RGB output points to retro enthusiasts who are probably playing on broadcast grade monitors that support RGB input, something many people would not have had access to at the time, and the YPbPr is most likely still available on more recent consumer grade CRTs which enthusiasts might have held onto. The MiSTer project is not the only FPGA project though, and those interested in hardware emulation might want to investigate Analogue's DAC peripheral, which is said to support composite out.

Capturing the exact look and feel of how a game was originally experienced is a slippery slope of subjectivity, but the takeaway from this experiment is that, at least for the MiSTer, one can have the option to display and project audio with a variety of options that will rely on cables and settings outside of the FPGA itself. What matters here, is that for all intents and purposes, that the games are being run exactly as they were on original hardware, with the caveat stated earlier that this project is still under active development and bugs may occur across multiple platforms and games and will need to be fixed.

Outside of the presentation of the games, it is exciting to see the rise of documentation of both chip and hardware schematics. Learning about the reverse engineering of components, notably the Motorola 6800, proved to be incredibly enlightening, and these cycle-accurate schematics should be preserved. In their piece “Archaeology versus anthropology: what can truly be preserved?”, Richard Bartle discusses the importance of the preservation of digital objects for scholars, how their preservation allows them to learn more about technology and how it works.[129] Focusing on creating Verilogs and other hardware descriptive languages is the practice needed to complement software preservation. While migration and software emulation are great ways to preserve the games themselves, it leaves behind the original hardware, and over time the appreciation of the quirks and context in which the consoles and games were developed together might be lost. This coupled with the fact that FGPAs are running emulated components without any built-in latency like most software emulators makes it preferable in many situations when trying to accurately display a game.

However, where software emulation does have an FPGA beat is its portability and ease of wide scale use. A software emulator can be distributed across various operating systems or accessed online as seen with the EaaSI project, whereas with hardware emulation one is tied to the specific FPGA unit. Also, price should also be considered. At around $500 to get the system up and running for this project, if one wanted to present multiple games on different monitors,

[129] Richard A. Bartle, ""Archaeology Versus Anthropology: What can Truly be Preserved?"," *Preserving Complex Digital Objects* (2014), 13-20.

depending on the institution, the price could be prohibitive since you can set up a Raspberry Pi running a software emulator for a fraction of the price ($35) at the time of writing this paper.[130]

Finally, the other purpose of this paper was to decipher technical jargon and present it in a way easily understandable for those not as literate in physical computing. There was much information discovered that was outside the knowledgebase of the author, yet important facets were gleaned, notably how the FPGAs were emulating component interactions. Deeper familiarity with computer science would be needed to understand the granular details of what is going on, but it should not be deemed essential to using FPGAs as a resource for both conservators and curators. While much of the information presented in this paper was found in published journals, books, and articles, just as much was discovered on online forums and guides put together for free by the community behind projects such as MiSTer and Analogue. It is this community-based documentation that will help keep these projects alive and help the conservation of video games in the long term.

[130] Raspberry Pi, "Raspberry Pi 4," https://web.archive.org/web/20220417212848/https://www.raspberrypi.com/products/raspberry-pi-4-model-b/ (accessed April 2, 2022).

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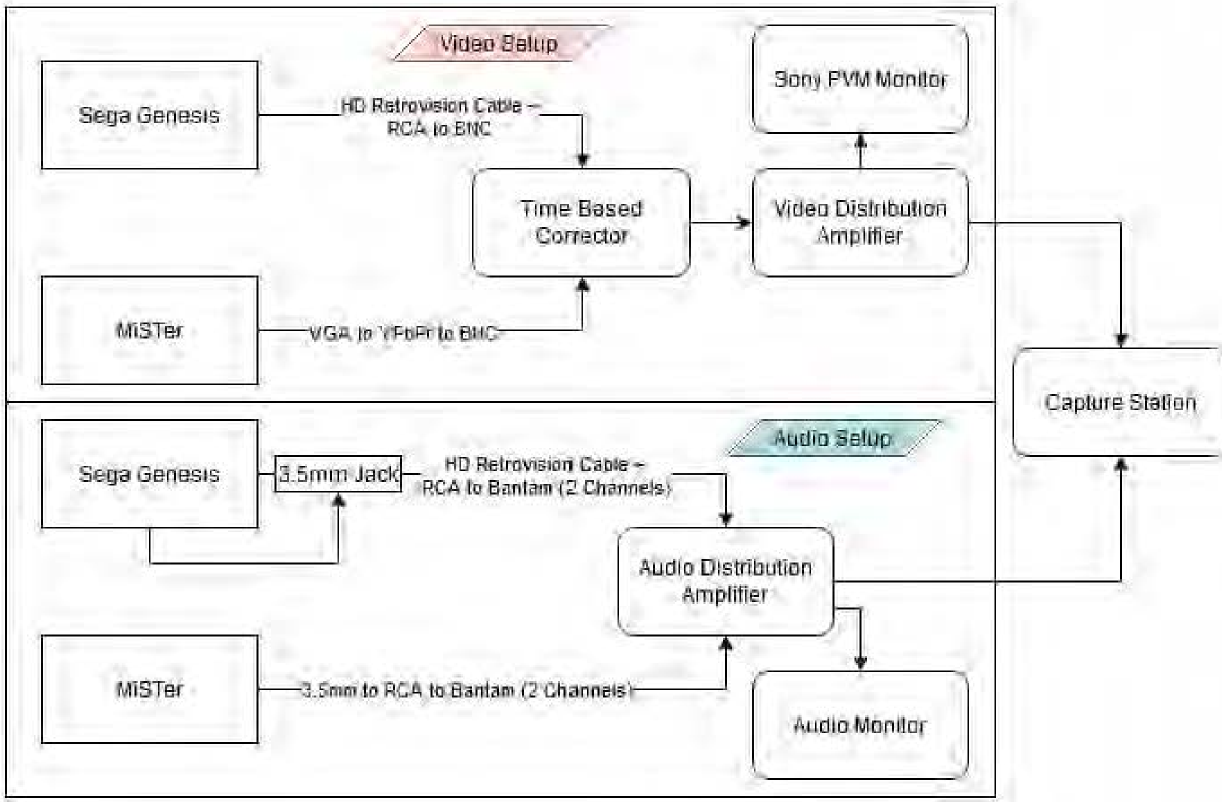
Video Setup
Sega Genesis
HD Retrovision Cable –
RCA to BNC
Sony PVM Monitor
Time Based
Corrector
Video Distribution
Amplifier
MiSTer
VGA to YPbPr to BNC
Capture Station
Audio Setup
Sega Genesis
3.5mm Jack
HD Retrovision Cable –
RCA to Bantam (2 Channels)
Audio Distribution
Amplifier
MiSTer
3.5mm to RCA to Bantam (2 Channels)
Audio Monitor

Appendix B:

Link to Lab Recordings

This appendix contains a link to the author's personal YouTube playlist, which hosts the results of his findings:

https://www.youtube.com/playlist?list=PLmxVyWJCb7c0pJCFGArWIwnpjOXk5uc9o

All uncompressed video was transcoded into mp4 files to upload them to YouTube. Although compressed, each video still demonstrates the capabilities of the MiSTer.