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Faculty of Engineering and Physical Sciences
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Supervisor: Dr. Tom Blount
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Open-Source Stereo Video Camera System and Software Implementation for Virtual Reality Lifelogging and Content Creation

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ABSTRACT

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES
SCHOOL OF ELECTRONICS AND COMPUTER SCIENCE

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REDO SOON In the realm of virtual reality (VR) and lifelogging, this project endeavors to overcome barriers of exclusivity and cost by developing an open-source, low-cost, and modular stereo video camera system. Designed to be modular with the first design to stay on top of a cap, this system integrates lightweight cameras and a microphone with the Raspberry Pi Pico microcontroller. It offers efficient stereoscopic (3D) video capture and immersive surround sound recording. Complementing the hardware, the project entails the development of lifelogging VR software using the Godot game engine. This includes a side-by-side (SBS) video player and intelligent metadata auto-tagging through scene and object detection. The primary objective is to democratize VR content creation, making it accessible to a broad audience, from VR enthusiasts to content creators, encouraging innovation in VR and lifelogging. Challenges, such as technical complexities and power management, are addressed through rigorous prototyping and optimization, ensuring project success and fostering inclusivity, innovation, and the advancement of VR content creation technology in the field of lifelogging.

Contents

Chapter 1

Introduction

1.1 Problem Statement

The surge in Virtual Reality (VR) Head Mounted Display (HMD) technologies has opened new creative avenues, offering users immersive experiences [1], [2]. However, the challenges of exclusivity and high costs in existing solutions for recording stereoscopic/3D/spatial video limit their potential [3]. This holds significance for VR's broader adoption, as low user retention is often linked to a lack of exclusive content maximizing the medium's advantages [4]. Viewing 2D content on VR headsets, despite superior displays elsewhere, underlines the need to empower users to effortlessly create their stereoscopic content, enhancing the appeal of VR [4]. Traditional VR content creation's focus on factors like Field of View (FOV) and 3 Degrees of Freedom (3DoF) often results in visually uninteresting videos lacking depth [4], [5]. The exclusive depth perception feature on VR HMDs and certain autostereoscopic displays has the potential to revive lifelogging, offering individuals an immersive experience to relive memories [6].

1.2 Goals

This project endeavors to surmount these challenges by:

1. Developing an Open-Source, Cost-Efficient, and Modular Stereo Video Camera Hardware System:

- Introducing a hardware solution that is accessible to a broader audience, mitigating the cost barrier associated with existing options.
- Programming simple lifelogging algorithm for the system.

2. Implementing a Video Processing Pipeline:
   - Mixing two 2D videos into the correct stereoscopic Side-By-Side (SBS) format to achieve an authentic depth effect.
   - Synchronizing audio files with the correct channels to create an immersive surround soundscape.
   - Incorporating metadata tagging through object and scene detection, facilitating streamlined browsing and organization of content.
3. Creating Intuitive VR Software for Content Management:
   - Designing software that enables seamless file browsing and content viewing within the VR environment.

This project not only addresses the critical gaps in hardware accessibility and the video processing pipeline but also represents a significant enhancement to existing methodologies. By fostering an open-source, modular, and cost-effective approach, this initiative strives to democratize VR content creation, making it more widely accessible and fostering innovation in the field.

Chapter 2

Background

2.1 Lifelogging

Lifelogging, a contemporary term encapsulating habitual documentation of one life akin to social media practices, distinguishes itself through its methodical and routine nature. The motivation for lifelogging extends beyond sporadic capturing of moments to a deliberate effort to systematically record and preserve lifetime memories.[7] From the definition itself, the Lifelog data can be in any format such as texts from diaries, health sensor data or even digital footprint from application use. However, in this project, I will be focusing on visual lifelogging which obviously consists of images and videos.[8]

Examples of existing wearable cameras specifics that used for visual lifelogging are as shown in Fig 2.1.[8] However, in recent years with rapid advancement in miniaturization of consumer products such as smartphones, camera sensors and storage devices, companies like Meta[9] and Snapchat also releases their version

FIGURE 2.1: Evolution of wearable camera technology. From left to right: Mann (1998), GoPro (2002), SenseCam (2005), Narrative Clip (2013), reproduced from [8]

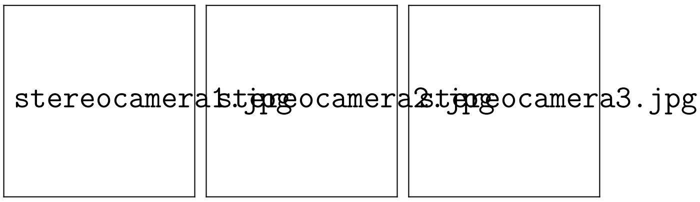

Figure 2.2: Commercially available consumer-level stereo cameras

of smart glasses, similar to Google Glass[10] released years prior. Although main appeal is for the smart features for convenience, this form factor and placement of camera is perfect for visual lifelogging aimed for VR userbase especially as already proven by Snapchat Spectacles 3[11] which can capture 3D photos and videos at 60fps.

2.2 Stereo Camera

Stereo camera refers to camera with stereoscopic imaging capabilities, this is simply achieved using 2 camera aligned side-by-side at a distance approximately the same as average human inter-pupilary distance (IPD) to mimic human vision.[12][13] This give the content viewed proper depth definition as in real life. This idea can also be extrapolated to higher Field Of View (FOV) content such as 180/360 degrees content but require either more complicated setup, computation or both.[14][15] Higher resolution is also needed as the content is stretched into larger area [4], this in turn increase storage and processing requirement.

Example of consumer-level stereo camera commercially available to buy right now as shown in Fig 2.2 are Snapchat Spectacles 3 [11], Kandao QooCam Ego [16] which includes integrated stereo/VR viewer and technically, iPhone 15 Pro/Pro Max [17] with version iOS 17.2 and above [18] which had Spatial Video recording enabled. This move is obviously to entice consumers using Apple products to buy their upcoming Apple Vision Pro VR HMD [2] which will make stereo camera and content more mainstream.

2.3 Virtual Reality (VR)

Virtual Reality (VR) transcends the conventional by offering a spatial computing platform, virtual 3D environment, and an immersive emulation of real life. The

FIGURE 2.3: Example of VR HMDs

emotional attachment fostered by VR content stems from its heightened realism, creating a sense of physical presence within the virtual space.[4] This emotional resonance distinguishes VR content from traditional media, providing a compelling reason for its adoption in content consumption including lifelog data.

Contrary to fully immersive FVV [19] or scene reconstruction [20], the adoption of SBS format is grounded in the current limitations of VR Head-Mounted Display (HMD) hardware. While FVV offers unparalleled immersion and depth perception through 6DoF [21], practical constraints dictate a compromise. This decision is further supported by the spatial video capabilities of the iPhone 15 Pro, which, despite being 1080p at 60fps, aligns with the current standards for windowed style viewing. The emphasis here is not on resolution but on perceived Pixel Per Degree (PPD) which is higher as the virtual window/screen is further, and lower FOV to stretch out. Choosing windowed viewing over panoramic alternatives (180/360 degrees) acknowledges the balance between realism and current technological constraints.

A poignant illustration of this concept is evident in the Black Mirror episode that explores the immersive preservation of memories in an eye-camera format.[22] This format aligns with human visual perception, eliminating the necessity for constant 3 Degrees of Freedom (3DoF) as our gaze isn't consistently omnidirectional. Although a higher FOV would enhance the lifelogging experience, it remains cost-prohibitive at present (full human FOV is approximately 220 degrees).[12]

2.4 User Interface in VR

Integrating VR software for content browsing amplifies the lifelogging experience. Leveraging the full potential of 6DoF through innovative UI design, expanded screen space, [23] and interactive features such as timeline shelves, this approach redefines how users engage with their memories. The incorporation of hand tracking and eye tracking further enhances the intuitive and immersive nature of content navigation within the VR environment as shown in Vision OS demo of Apple Vision Pro [2].

Other than that, the existence of window or virtual screen to host the content will cause less motion sickness as user have virtual anchor to the virtual space. [24][25] Lower FOV helps as the experience will be just like watching movies in 3D cinema.[26][27][28]

The combination of lifelogging and VR represents a novel and niche subset within both domains. As technology advances and user preferences evolve, this integrated approach is poised to become more mainstream, particularly in the realm of personal videos, memories, and photos. The synergy between lifelogging and VR anticipates a future where individuals seamlessly capture, relive, and share their most cherished moments in a more immersive and engaging manner.

Chapter 3

Technical Progress

The project is divided into 3 distinct parts, following the MoSCoW requirement framework (M: Must-Haves, S: Should-haves, C: Could-have, W: Wont-have).

3.1 MoSCoW Requirement

3.1.1 Hardware Development

- **M:** Develop an open-source, modular stereo video camera system with Raspberry Pi Pico microcontroller. Ensure it is low-cost and easily accessible.
- **S:** Consider additional features or improvements based on feasibility, such as using an onboard rechargeable Li-Po battery circuit instead of a power bank to power it.
- **C:** Explore advanced features like wireless connectivity or additional sensor integration, time permitting and if resources allow.
- **W:** Exclude features or components that are deemed impractical or beyond the scope of the project, such as higher resolution or different video format (180/360).

3.1.2 Video Processing Pipeline

- **M:** Implement a video processing pipeline for transforming mono stills and video into stereoscopic Side-By-Side (SBS) format. Synchronize audio files for an immersive surround soundscape.
- **S:** Explore additional video processing features, such as metadata tagging through object and scene detection using existing library and tools.
- **C:** Automated video stabilization or advanced filtering options, based on available resources and time constraints.
- **W:** Exclude overly complex video processing tasks that may hinder the project timeline or exceed available resources, such as 3D depth reconstruction.

3.1.3 VR Software Application

- **M:** Develop an intuitive VR software application for seamless file browsing and content viewing. Ensure compatibility with the stereo video format.
- **S:** Implement innovative UI designs for enhanced interaction within the VR environment.
- **C:** Explore the integration of hand tracking, and eye tracking, if resources and time allow.
- **W:** Exclude overly ambitious features that may compromise the core functionality or extend the project beyond feasible timelines, such as a personal AI assistant.

3.2 Hardware System

3.2.1 Cost Analysis

The budget provided for the project is £150, and the aim is to get all components under £100, making it a low-cost solution compared to alternatives that usually cost around £300 or more. The most expensive part, as expected, is the camera modules, which are around £35 each. However, they boast a 5MP sensor and are capable of taking 1080p60fps video, justifying their cost. The exact component details and costs can be seen in Appendix A.

3.2.2 Components

After comparing costs, availability, ease of use, and hardware constraints, the choice of microcontroller is Raspberry Pi Pico due to its cheap cost, cohesive documentation, compatible hardware, and, most importantly, buffer size, which is important to get high enough resolution images/video to prevent motion sickness.

To achieve an immersive experience, audio is also an important variable. Thus, the use of 2 independent electret microphone modules is added to work in tandem with the camera. This, in theory, should make it possible to achieve stereo sound channels for each ear.

An SD card extension board is also added to host the SD card that holds all the data. The circuit schematics can be seen in Figure 3.1

3.2.3 Constraints

The initial draft design is to have both cameras mounted on the side of eyeglasses, akin to Ray-Ban Meta and Snapchat Spectacles glasses. However, after getting the camera module and other components, it is deemed too unwieldy to fit the electronics into a small form factor. The main reason for this choice is to capture the footage as close as how humans see the world, and mounting the camera close to the eye would achieve that compared to a chest mount design.

To compromise, a hat/cap-mounted design is chosen, where the POV is higher than usual, but the camera movement/rotation will still follow head movement and should give a realistic enough POV as seen in Figure 3.2.

Trying to make it power-efficient might prove challenging and needing to deal with additional circuitry, so for now, the system will be powered with a power bank to the micro-USB on the main Pico board.

path/to/breadboard_prototype_circuit.png

FIGURE 3.1: Breadboard Prototype Circuit

3.2.4 Onboard Embedded Software Algorithm

The main idea is that in normal lifelogging mode, the cameras would take stereo still images every now and then on a timed interval, which will be decided through trial and error and optimization depending on how much storage the images occupy and the power efficiency of the algorithms. However, to get a more immersive experience, video is also needed, and a button can be used to manually start and stop recording, with an LED being an indicator when it's recording. The saved files should be aptly named for easier processing later, maybe in a standardized DATETIME-NUMBER format. The proposed algorithm can be seen as in Figure 3.3

path/to/designs_and_pov_example.png

FIGURE 3.2: Designs and POV Raycast Example

3.3 Video Processing Pipeline

3.3.1 Motivation

The motivation behind implementing a pipelined process for video processing stems from the acknowledgment that attempting to execute this intricate task directly on the Raspberry Pi Pico would introduce unnecessary complications and exceed its memory and processing power limitations. By adopting a pipelined approach, the processing burden is shifted to a more capable system, ensuring a more efficient and effective transformation of videos and images. This is particularly crucial for the generation of Side-By-Side (SBS)/3D format from two path/to/flow_chart_for_algorithm.png

FIGURE 3.3: Flow Chart for Onboard Embedded Software Algorithm

mono/2D stills using ffmpeg. While ffmpeg provides a baseline solution, the desire for a streamlined script or process is imperative to facilitate batch processing, ensuring accuracy and effectiveness. Additionally, the inclusion of a custom metadata tagging system for object and scene detection is pivotal. This customized metadata enhances the overall VR experience by enabling advanced filtering and indexing, thereby optimizing the video and image browsing experience within the VR application.

3.3.2 FFMPEG for Mono to Stereo Stitching

The utilization of FFMPEG for mono to stereo stitching serves as a cornerstone in the pre-processing pipeline. FFMPEG, a powerful multimedia processing tool, efficiently transforms mono/2D videos and images into the desired stereoscopic Side-By-Side (SBS)/3D format. This process is instrumental in creating a lifelike and immersive visual experience for VR content, aligning with the project's goal of democratizing VR content creation.

3.3.3 Object and Scene Detection

Incorporating object and scene detection algorithms further enriches the preprocessing pipeline. Leveraging advanced computer vision techniques, this step aims to automatically identify and tag objects and scenes within the videos and images. The integration of object and scene detection not only enhances the visual content but also lays the foundation for sophisticated filtering and indexing capabilities within the VR application. This ensures that users can seamlessly navigate and explore their lifelogging content with enhanced precision and relevance.

3.3.4 Custom Metadata Tagging

Custom metadata tagging is a pivotal aspect of the preprocessing pipeline, allowing for the incorporation of user-defined information related to object and scene detection. This bespoke metadata adds a layer of personalization to the content, enabling users to categorize and organize their lifelogging data according to individual preferences. The inclusion of custom metadata serves as a cornerstone for optimizing the VR content browsing experience, ensuring that users can easily locate and revisit specific moments within their immersive collection.

3.4 Video Player VR App

3.4.1 Game Engine – Godot 4.2

The selection of the Godot 4.2 game engine for the development of the video player VR app is rooted in the project's commitment to Free and Open Source Software (FOSS) principles. Unlike more established game engines such as Unity or Unreal Engine, Godot aligns with the FOSS ethos, making it the ideal choice for this project. Despite having fewer documentations and examples compared to its counterparts, this presented an opportunity for active participation in its development.

Consultation with the Godot community, particularly through their Discord channel, guided the decision-making process, revealing that utilizing shaders is the most straightforward approach for rendering stereo Side-By-Side (SBS) video playback.

3.4.2 Shaders

The implementation of shaders in the Godot 4.1 engine for stereo video playback is relatively uncomplicated. Given the SBS format of the video, the left-half is rendered for the left camera eye, and vice versa for the right-half. The gdshaders code utilized for this purpose adheres to this logic, facilitating an efficient rendering process.

3.4.3 User Interactions (UI)

The user interface (UI) for the video player VR app is designed within a 3D space, a standard practice for VR applications and games. However, a challenge arises as the video player itself operates as a 2D screen within this 3D environment. Initial attempts to follow a tutorial by MalcolmNixon on YouTube, supplemented by consultation with the Godot community, encountered difficulties in integrating the shader script within the same scene as the videostreamplayer node. Subsequent experimentation and development efforts proved inconclusive.

Fortunately, after seeking guidance from the Discord community, MalcolmNixon, the tutorial's author, provided a pivotal solution.**<empty citation>** Instead of employing the 2DScreenIn3D approach, the revised method involves instantiating a 2D screen videostreamplayer node in the main scene, where the shader is then applied. This modification successfully addresses the challenges encountered during the development process. Example or app running is seen Figure 3.4

3.4.4 File Browsing

While file browsing functionality has not been fully implemented, conceptualization has begun. Proposed ideas include leveraging metadata tagging for specific searches and employing bookshelves or 3D objects as interfaces for navigating between months or weeks, deviating from the conventional 2D screen approach to enhance interactivity.

`path/to/app_running_images.png`

FIGURE 3.4: Images of App Running

To optimize browsing efficiency, the screen space may be expanded to resemble an ultra-wide monitor or more, enabling users to view a greater number of files in a single window. This approach capitalizes on the immersive capabilities of VR, utilizing the 360-degree view and 6 Degrees of Freedom (6DoF). Additionally, the implementation of the depth axis remains contingent on contextual considerations and future developments.

Chapter 4

Plan of Remaining Work

This project is technically 3 different part, stripped to basic components to prove a minimum viable product prototype, thus require great detail in planning and initial design. This had been done thoroughly as demonstrated in previous section. However, the challenging part in which to actualize the bulk of the design into real working solution is where it matters, and what I will be spending my time perfecting.

As seen in the Gantt Chart in Appendix B and C, the proposed timeline is a bit late unfortunately due to risk happening such as microcontroller breaking due to short circuit from my testing from user error, the wires provided is not stable enough thus delaying testing. However, all 3 main part had preliminary testing and initial work done with great success as seen in previous section.

Appendix C shows actual gantt chart timeline executed together with planned with different colour density. From this, I realised I should make my gantt chart tasks more specific for future reference. Overall, the main idea of work to be done still remains the same.

Appendix A

Cost Table

Budget for 3rd Year IP = £150

Supplier: The Pi Hut

Refer Table A.1 for cost breakdown by components.

No.	Item	Function	Cost (£)	Quantity
1	Raspberry Pi Pico W	Signal/Control/Main Pico	6.3	1
2	Raspberry Pi Pico	Eye'/Camera Pico	3.9	2
3	5MP ArduCam Camera module, OV5642	Camera Module (SPI)	35	2
4	SD Card SPI Breakout Board	SD Card 'reader' (SPI)	3	2
5	32GB MicroSD Card	Storage	8	2
6	Electret Microphone Amplifier	Audio recorder	6.9	2
7	Breadboard for Pico	Prototyping	4.2	1
Shipping Fee			3.99	1
			Total	128.09

TABLE A.1: Cost Breakdown of Components

Appendix B

Planned Gantt Chart

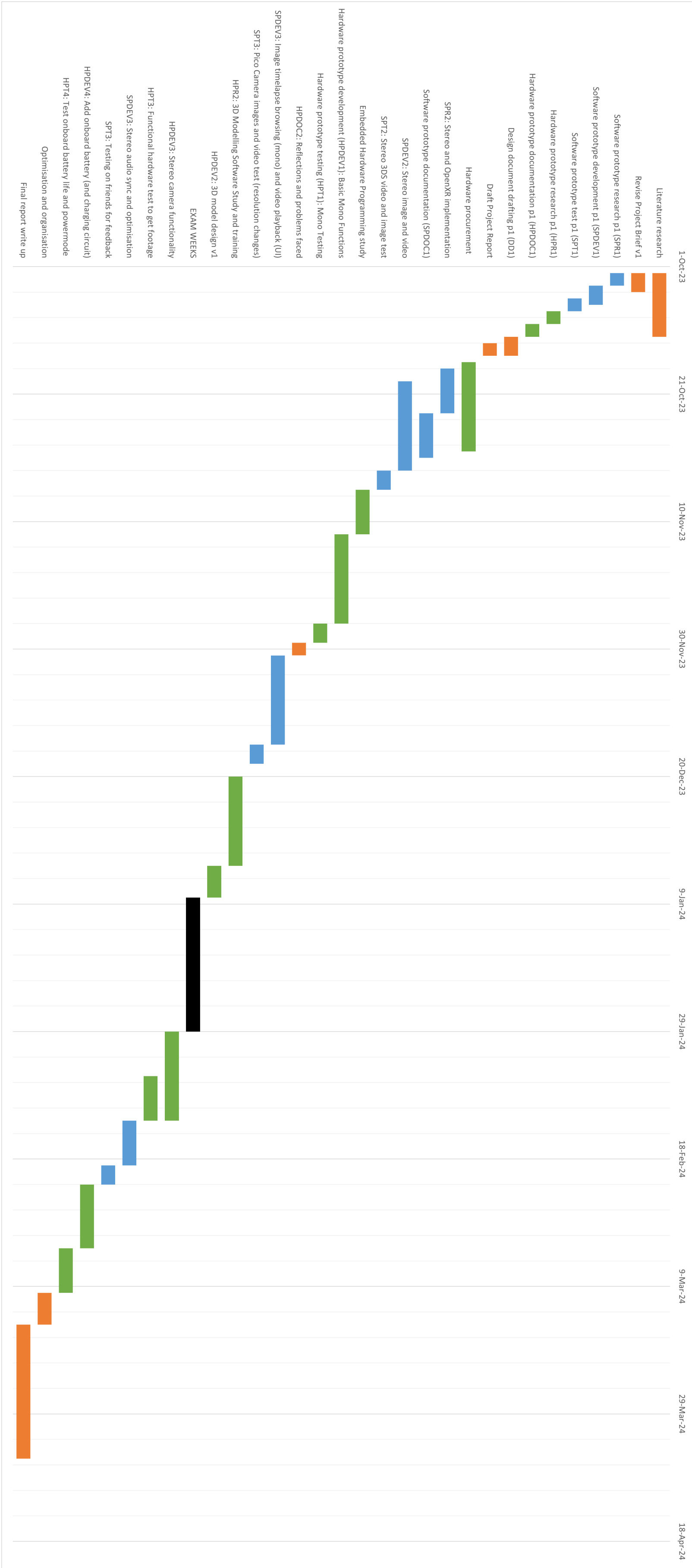

Figure B.1: Planned Gantt Chart

Appendix C

Combined Gantt Chart

Legends:

Orange: Report or writing related task
Blue: Software related task
Green: Hardware related task

Softer colour represents task over expected time or unexpected tasks compared to Appendix B.

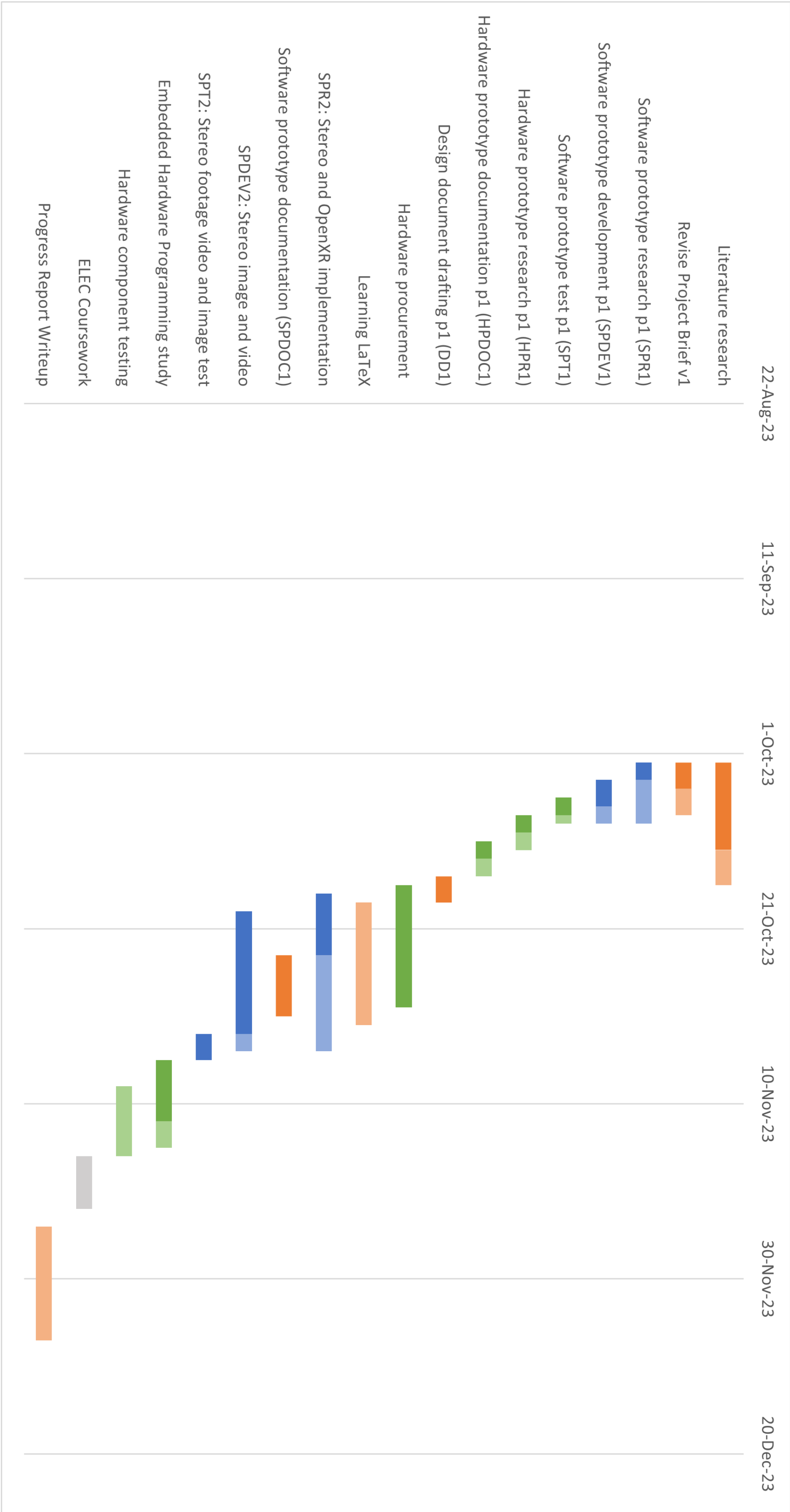

Figure C.1: Combined Gantt Chart

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