

SIDHARTH SHANMUGAM

*Final Project Report*

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**Machine Vision-Based Anti-Backscatter  
Lighting System for Unmanned Underwater  
Vehicles**

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4<sup>th</sup> Year Project Final Report for the Degree of  
MEng in Electronic and Computer Engineering

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# Abstract

Underwater imaging is critical for various applications such as marine biology, underwater archaeology, and pipeline inspection. However, backscatter from suspended particles significantly degrades image quality. This paper addresses the challenge of mitigating underwater backscatter in real-time imaging by developing a backscatter cancellation system using a Raspberry Pi Single Board Computer. The paper proposes a solution that leverages a combination of image processing techniques, including and revolving around the Canny edge detection algorithm, to accurately detect and segment backscatter particles. To evaluate the system, the paper develops a bubble backscatter simulator, and a lossless video recorder for controlled testing and real-world footage analysis. Performance tests revealed an average frame processing latency of 2.6 ms, outperforming systems in previous work that operate on more powerful hardware. Attempts to enhance performance using multiprocessing and a real-time operating system (RTOS) patch, however, resulted in increased latency due to the overhead of Inter-Process Communication (IPC) and frequent kernel context switching. These findings suggest that simpler single-core implementations may offer superior performance for I/O-bound tasks. The results demonstrate significant progress in reducing underwater backscatter, with potential applications across various underwater imaging tasks. Future work will focus on hardware improvements and further software optimisation to refine system performance.

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## Ethical Statement

After consideration of the University of York's code of practice and principles for good ethical governance, I have identified no related issues in this project.

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# 1 Introduction

Underwater imaging capabilities are of great importance across a wide spectrum of disciplines, for instance, marine research and environmental analysis, where scientists dive to several reef locations with waterproof camera systems and quadrats to audit the abundance of coral over time [1]. Unmanned Underwater Vehicles (UUVs), a class of submersible vehicles, are pivotal in advancing these capabilities. With vast arrays of sensors and often remote-controlled or completely autonomous, UUVs enable the end user to conduct exploration missions of extended duration to analyse underwater environments with utmost accuracy even in the most hazardous conditions, impossible for direct human access. These benefits have caused UUVs to become common as a safer and cheaper alternative to manned vehicular operations in almost all underwater imaging-related applications, such as intelligence surveillance and reconnaissance in defence, defect and foreign object inspection in maritime, and oceanography and hydrography in marine research [2].

When capturing images or recording video underwater, one would instantly notice the lack of light at greater sea depths. Coupling a high-power light source next to the camera resolves this issue to ensure a well-lit scene. However, this produces an adverse side-effect called backscatter, as Figure 1 illustrates, where suspended particles in water scatter light in an inhomogeneous manner, reflecting the light emitted by the light source back into the camera, creating exceptionally bright spots and often saturating the image and degrading the quality [3]. Albeit the existence of a few simple and universal techniques to mitigate backscatter, such as bringing the camera closer to the subject, fine-tuning the headlight position such that only the edge of the light cone illuminates the subject, or achieving perfect buoyancy to minimise disrupting sand, debris, and bubbles [4], they all lack viability for UUVs due the continuous and arbitrary propellor motion and the constant existence of debris floating throughout water bodies.



(a)



(b)

Figure 1: (a) Backscatter appears as the particles of sand drift between the aquatic animal and the camera [4]. (b) A frame from GoPro footage showing backscatter from a UUV.

With a specialised camera sensor to capture fast-moving backscatter particles, a single-board computer processing frames using advanced machine vision technologies to detect backscatter, and a specialised projector to selectively illuminate the scene, the project’s ultimate goal is to develop a novel backscatter-cancelling light source to aid the generation of high-quality underwater images in real-time, thus eliminating the requirement for a camera with better dynamic range compatibility to compensate for the bright regions from backscatter and lens flares. The first objective is to research architectures to develop a reliable backscatter detection system, interlinking with the second objective of researching methodologies to optimise for real-time to ensure predictability and stability, ensuring the projection of backscatter-cancelling light patterns with minimal and consistent latency.

## 2 Background Information

An accurate and real-time backscatter-cancelling lighting system must consider five main factors: (a) precise backscatter particle segmentation even in varying environmental conditions by mapping the exact backscatter positions to aid in (b), the accurate projection of the backscatter cancelling light patterns, ensuring the whole scene except backscatter is lit, (c) low system latency by minimising the time it takes between frame capture and the light pattern projection, ensuring the projection is still correct even with fast-moving backscatter, integrating with (d), adequate system throughput with parallel processing to increase system responsiveness for reaching the low latency goal, and finally, (e) the ability to control and establish the system frame rate to ensure system predictability.

This section, gathers background information on the five system factors, beginning with an investigation of previous work on this project. Then exploring work related to underwater imaging for precise environmental analysis. Finally, a study on computer systems and architectures for this project and a summary of all aspects concludes the section.

### 2.1 Previous Work in Underwater Anti-Backscatter Lighting Systems

Previous work on this project in [5] by Shepherd introduces a backscatter-cancelling lighting system with goals similar to what this paper proposes. Shepherd presents a two-stage process, which is fundamental to their system, as Figure 2 illustrates. The first stage is ‘detection’, where the specialised projector illuminates the whole scene with a low-brightness, solid white output intending to forcefully induce backscatter particles for detection with machine vision techniques. The second stage is ‘pattern projection’, where the system overlays black ellipses called ‘holes’ at the positions of detected backscatter particles over a full-brightness, solid white projection to eliminate backscatter.

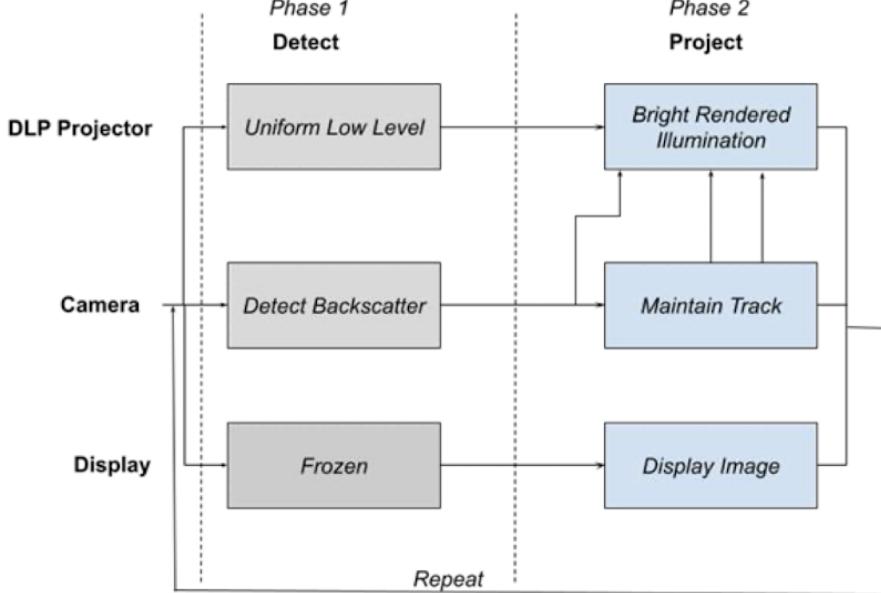


Figure 2: The high-level system stages from [5].

Shepherd designs the backscatter segmentation system based on a simple blob detection algorithm [6], where the term ‘blob’ denotes a group of connected pixels in a binary image. By applying several thresholds, the algorithm first converts the input image into a binary representation to then extract connected pixels and calculate the centre positions of each. After grouping the centre positions from the binary images, the algorithm finally estimates the final centroid and radii for each ‘blob’. While this blob detection algorithm benefits from a computationally simple approach, it suffers from a drastic drawback as Shepherd describes: “at least one property needs to be shared between the blobs such as size or shape to allow for the isolation of these blobs”. The underwater environment is unpredictable, where backscatter particles can never share the same characteristics, making this approach unviable.

## 2.2 Automotive Headlights for Illumination Through Rain and Snow

Similar to the underwater backscatter that this paper explores and attempts to eliminate, the work in [7] by De Charette et al. outlines an automotive headlight system to illuminate around the backscatter caused by rain and snow whilst driving. De Charette et al. resolves the parallax issue that Shepherd observed, where the displacement between the camera’s and projector’s viewpoint causes a perceived offset in object positioning, using a beamsplitter as Figure 3a illustrates, such that the incident visual beam is split 50:50 between the projector and camera, thus eliminating parallax displacement by co-location.

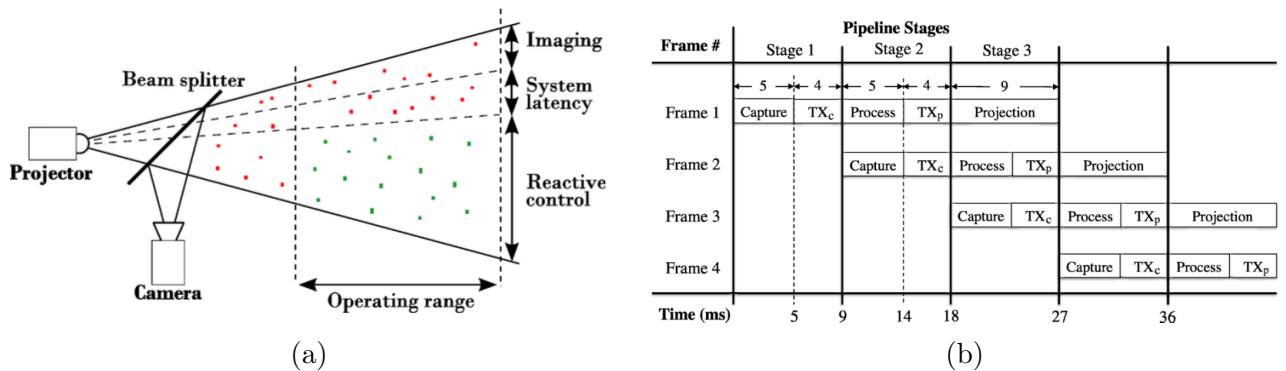


Figure 3: From [7]: (a) The system configuration including a beamsplitter for parallax elimination through co-location, (b) the parallel pipeline stages for their system.

The automotive backscatter-cancelling headlight system utilises an image processing pipeline that applies a background subtraction, albeit not specifying the exact method, followed by blurring and thresholding to isolate the bright water spots. The system employs the connected-components algorithm to segment the backscatter particles, this algorithm scans an image to group its pixels into components based on pixel connectivity, i.e., all pixels in a connected component share similar pixel intensity values and are in some way connected [8]. Unlike Shepherd's system which employs a blob detection algorithm, this system is resilient to unique backscatter particle characteristics, allowing for segmentation regardless of fixed parameters despite also being a computationally simple approach. However, the connected-components algorithm may be inherently limited when given low-quality input images as it may not correctly connect pixels due to distortion and noise.

Although not specifying the exact methods, the automotive system in De Charette et al. employs backscatter particle tracking with a predictive algorithm to project backscatter-cancelling light patterns by accounting for the movement during the system processing period, denoted by the system latency time. Due to the linear and vertical movement of rain and snowfall, one can assume they are using a simple linear interpolative approach with the assumption the particles are moving at a constant speed, to predict the future particle position. To increase system throughput, the work in De Charette et al. proposes a three-stage parallel processing pipeline, illustrated in Figure 3b. Stage 1 represents the task of capturing the frame from the camera, with  $TX_c$  denoting the image data transfer from the camera to the computer. Stage 2 represents the image processing steps, with drop detection, prediction, and projection pattern generation, with  $TX_p$  denoting the computer-to-projector data transfer. The third and final stage represents the refresh time of the projector. This system, after startup, will run with a three-frame latency: as the  $n^{th}$  frame is being captured, the  $n^{th} - 1$  frame is being processed, and the  $n^{th} - 2$  frame is being projected. With this constant latency mitigated by the predictive functionality.

The system in De Charette et al. takes, on average across 5500 frames, 4.214 ms to transfer data from the camera to the host computer, a 3.2 GHz Intel Xeon processor with 8 GB of RAM

running Windows Vista 64-bit, 4.081 ms to process the image, 4.214 ms to send the data to the projector, and 9 ms for the projector to output. Thus, total system latency is 21.51 ms, with an accuracy of 68.9% for rain. The work in [9] by Tamburo et al. expands on the system by De Charette et al. with a more powerful desktop PC for image processing and an FPGA-based controller for the specialised projector. This system achieves an average frame processing time of 0.3 ms, with a total response time ranging between 1 ms to 2.5 ms.

## 2.3 Underwater Gas Seepage Bubble Quantification for Environmental Analysis

Aside from the work by Shepherd, De Charette et al., and Tamburo et al., public documentation of research related to real-time efforts for underwater backscatter-cancelling lighting systems is non-existent. However, numerous environmental analysis fields rely on highly specialised and precise systems for quantifying underwater bubbles to investigate gas seepages from the sea floor. As underwater backscatter can comprise a mixture of compositions, ranging from bubbles and sand to all sorts of marine debris, it will be beneficial to explore gas escape measurement and monitoring systems as they require high precision, extensive range, strong anti-interference, and low cost under complex underwater conditions [10].

The work in [11] by Thomanek et al. presents a novel approach for a highly precise and automated gas bubble imaging system that employs the Canny edge detection algorithm. The Canny algorithm, which prefers a single channel (greyscale) input, first smoothens the input using Gaussian convolution before comparing each pixel's values relative to its neighbours such that when the gradient is above a certain threshold, it sets the bordering pixel a value of '1', otherwise '0', resulting in the formation of edges around objects [12]. In contrast to the system by Shepherd, the Canny approach in Thomanek et al. works around the object characteristics limitation of the simple blob detection algorithm.

The paper compares the Canny algorithm approach with the simple image binary thresholding method, where only the pixels with intensities within a certain threshold are passed through, ultimately establishing Canny as the more accurate choice for segmentation, even in areas of uneven illumination, as Figure 4 illustrates. However, the drawbacks of the Canny approach, as Thomanek et al. highlight, include a significant increase in computing time, and the necessity for implementing morphological techniques to address bubble transformation issues such as expansion and contraction during segmentation. Nevertheless, considering the advancements in computing power over the past 14 years since this paper was published, modern computers should now be easily capable of handling this workload with relative ease.

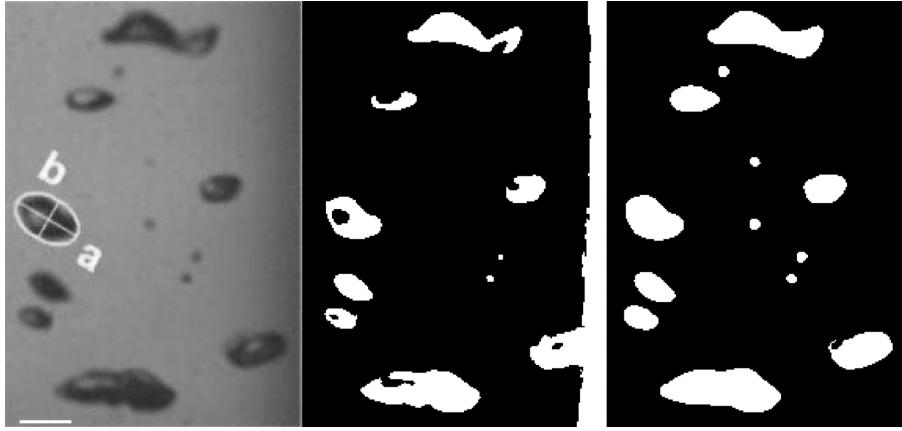
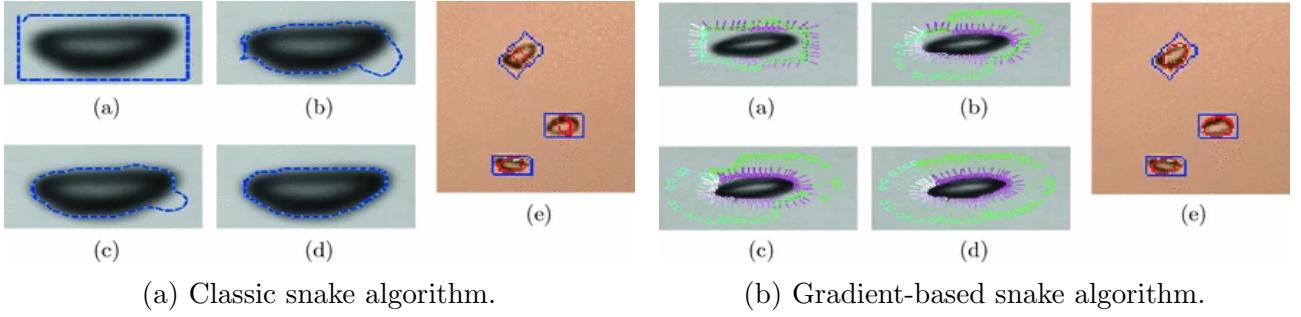


Figure 4: From [11], the original input frame in the left-most image, bubble segmentation using simple binary thresholding in the middle, and bubble segmentation using the Canny edge detection algorithm in the right-most image.

While this paper by Thomanek et al. provides valuable insight and serves as an excellent starting point, it primarily emphasises system construction and quantifying gas flux measurements. Consequently, certain crucial details, such as the precise methodology achieving the bubble highlighting post-Canny segmentation in Figure 4, receive less attention. However, one can infer that Thomanek et al. may have employed a logical algorithm to fill closed-loop edges. The study by Zelenka in [13] builds upon the foundational system by Thomanek et al. aiming to address the sporadic false detection issue that is inherent in the Canny edge detection algorithm, introducing robust algorithms capable of achieving precise bubble stream quantification with accurate bubble fitting.

Zelenka introduces the snake-based active contour model by Kass et al. in [14] for a more stable and precise method for bubble detection. As explained by Kass et al., a snake embodies an energy-minimising spline that's guided by external forces and influenced by image characteristics that collectively drive the snake towards prominent features within the image, such as lines and edges, all while the snake dynamically adheres to nearby edges due to the active contour model. The classic snake method, as Figure 5a illustrates, uses a bounding box from the baseline localisation for initialisation, shown in blue, from which the snake algorithm optimises with each iteration on a low-quality image sequence. The figure exemplifies the unreliability of the classic snake method due to light areas within the centre of the bubble, as the red outline borders this region instead of the bubble itself. Zelenka, therefore, introduces a novel enhancement to the classic snake method to improve performance in varying lighting conditions by utilising gradient information of an image to compute external energy terms that guide the snake.

Zelenka compares all of these bubble segmentation methods using a sequence of 20 GoPro-captured images, with circa 10 bubbles visible per frame and manual ground truth. The results, in Figure 6b, show a clear improvement across all methods compared to the baseline Canny approach, which achieved a detection rate of 77.3%. The classic snake approach achieved the best detection rate of 89.7% and the gradient-snake achieved 89.3%.



(a) Classic snake algorithm.

(b) Gradient-based snake algorithm.

Figure 5: The classic snake method in (a) and the gradient snake method in (a) from [13]. Sub-subfigures from (a) to (d) for both methods show every third step in the snake optimisation process, and (e) shows the final result.

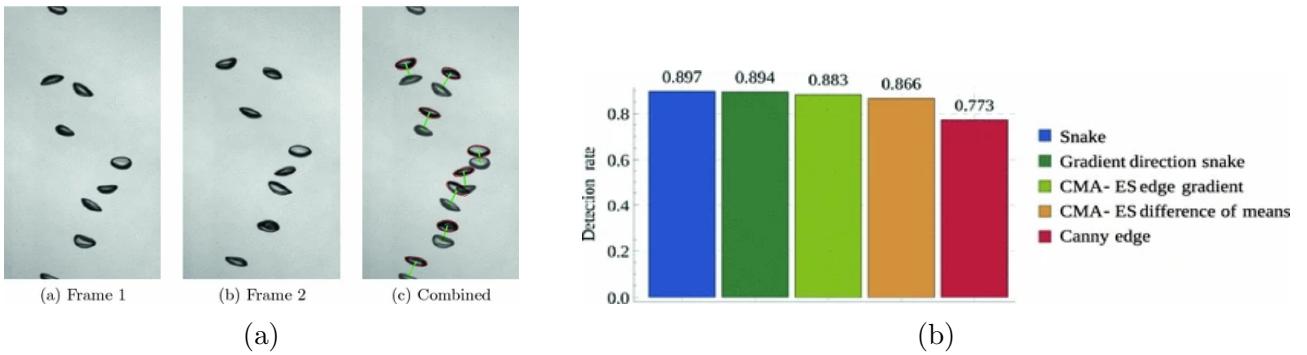


Figure 6: From [13]: (a) demonstration of the system across two subsequent frames at 100 FPS, with the red border denoting bubble detection and the green lines denoting bubble tracking, (b) a comparison of bubble detection rates for different segmentation approaches.

Thomanek et al. introduces a novel approach for bubble tracking, leveraging the ‘least distance assumption’. This assumption realises that the distance travelled by a bubble between two successive frames is typically smaller than the distance to its closest neighbouring bubble. While this assumption may not hold for scenarios involving overlapping bubbles, extremely high bubble concentrations, or cases where the travel distance exceeds the distances to neighbouring bubbles, it, however, facilitates a computationally straightforward method for determining bubble positions in successive frames and estimating the bubble rise velocity from the sea floor. Despite the computation simplicity, this method may not present a fair trade-off due to the backscatter originating from bubbles, which can be highly concentrated, overlapping, and subject to rapid movement, especially in the presence of UUV propellers. Zelenka’s paper introduces another novel approach for tracking bubbles by employing a Kalman filter [15] to predict bubble positions in subsequent frames based on initial detections. The Kalman filter utilises a recursive algorithm to estimate the state of a dynamic system, in this case, the bubble’s position, by incorporating both prediction and measurement update steps. Additionally utilising, the Hungarian method [16], which finds the optimal assignment in a weighted graph, for minimum weighted matching between predicted and newly detected bubble positions, optimising the association process. While it remains uncertain whether the Kalman filter-based method is immune to the limitations associated with the ‘least distance assumption’, Zelenka

does validate its capacity as a highly reliable tracking mechanism. Figure 6a illustrates the whole system's function, showing both bubble detection and tracking.

## 2.4 System Building Blocks

### 2.4.1 Real-Time Linux Kernel with the PREEMPT-RT Patch

Shepherd's work highlights the necessity of a Real-Time Operating System (RTOS) to mitigate jittering, the unpredictable bursts of reduced frame rates. An RTOS facilitates the compliance of a 'hard' real-time system, which can provide a guarantee of the maximum time a task requires for completion. Similar to Shepherd's system, in Linux, many sections in kernel space, where the kernel's code and data reside and execute, do not support preemption due to the presence of spinlocks. Spinlocks are non-blockable and non-sleepable programmatic loops that safeguard critical sections of code. Consequently, the preemption logic breaks down when a user space task invokes a kernel-specific function, thereby transitioning to kernel space upon receiving an interrupt.

Figure 7, from the material in [17] by Bootlin, highlights how kernel-based spinlocks contribute to unpredictable jitter, denoted with the green question mark. Apart from the kernel space incompatibility, Linux already facilitates user space preemption through task priority-based real-time scheduling, enabling RTOS functionality. The PREEMPT-RT kernel patch modifies all kernel-space code, allowing it to become preemptible and deterministic. While insufficient in transforming Linux into a 'hard' RTOS, the PREEMPT-RT patch minimises task-switching latencies. Using a test suite that contains programs to test various real-time Linux parameters, the material in [18] compares system latencies with the PREEMPT-RT patch. The results are in Figure 8, displaying the maximum latency measurements for the standard kernel, registering at 301  $\mu$ s, whereas the PREEMPT-RT kernel yields a significantly smaller latency of 83  $\mu$ s, a notable 3.63x reduction.

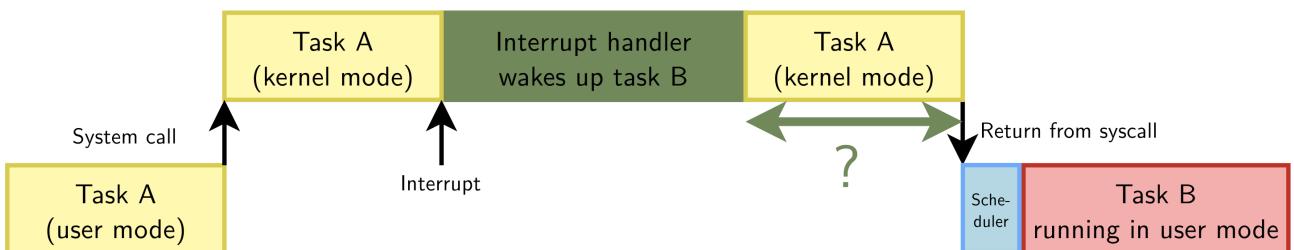


Figure 7: From [17], illustrating kernel-space latency from an interrupt in the Linux kernel with a green question mark.

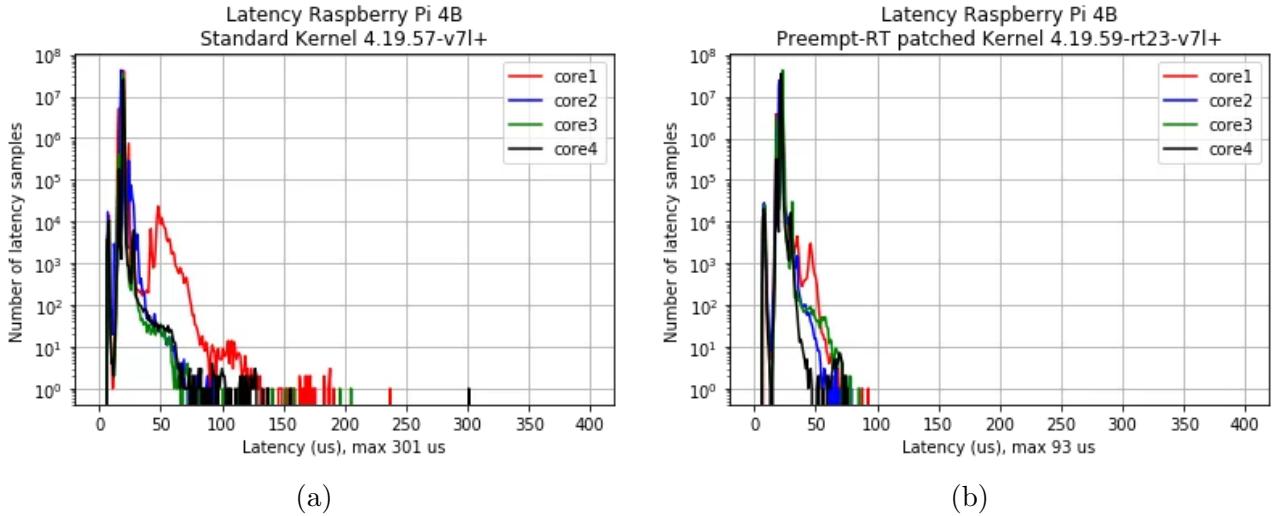


Figure 8: Latency measurements from [18] using Cyclictest from the RT-Tests suite. (a) The standard Linux RPi kernel, and (b) the PREEMPT-RT kernel.

#### 2.4.2 Computing Platforms

Field Programmable Gate Arrays (FPGAs), which are semiconductor devices structured around a matrix of configurable logic blocks (CLBs) interconnected via programmable interconnects [19], are ideal solutions for computationally demanding image processing tasks, owing to their inherent hardware parallelism and low latency characteristics. Despite the availability of highly efficient intellectual property (IP) cores for FPGA-based logic acceleration, development and prototyping times may increase due to the low-level hardware intricacies involved. Additionally, FPGAs typically incur higher costs compared to traditional CPU-based computing systems. On the other hand, the Raspberry Pi (RPi) company has been at the forefront of designing high-performance, cost-effective, single-board, and modular computers based on the Arm architecture and running the Linux operating system since 2012 [20]. The standard RPi product lineup provides an excellent non-FPGA, CPU-based route for swift and straightforward development and deployment.

#### 2.4.3 Specialised Light Source

A Digital Light Processing (DLP) projector plays a crucial role in projecting backscatter-cancelling light patterns. The DLP chipset comprises a Digital Micromirror Device (DMD), which houses millions of reflective aluminium mirrors, typically only a few microns wide. The DMD serves as a Micro-Opto-Electro-Mechanical System (MOEMS) Spatial Light Modulator (SLM), enabling the modulation and attenuation of an incident light beam with precision. As Figure 9 illustrates, a high-intensity white lamp directs a beam towards a rotating colour-tinted lens wheel. Subsequently, an internal lens diffracts the coloured beam onto the DMD. The angle and duration of each microscopic mirror's activation dictate the intensity of individual pixels, redirecting the desired beams of each pixel through a diffraction lens to exit the projector. Inactive DMD mirrors direct the beam into a light-absorbing region to prevent light leakage,

ensuring image integrity.

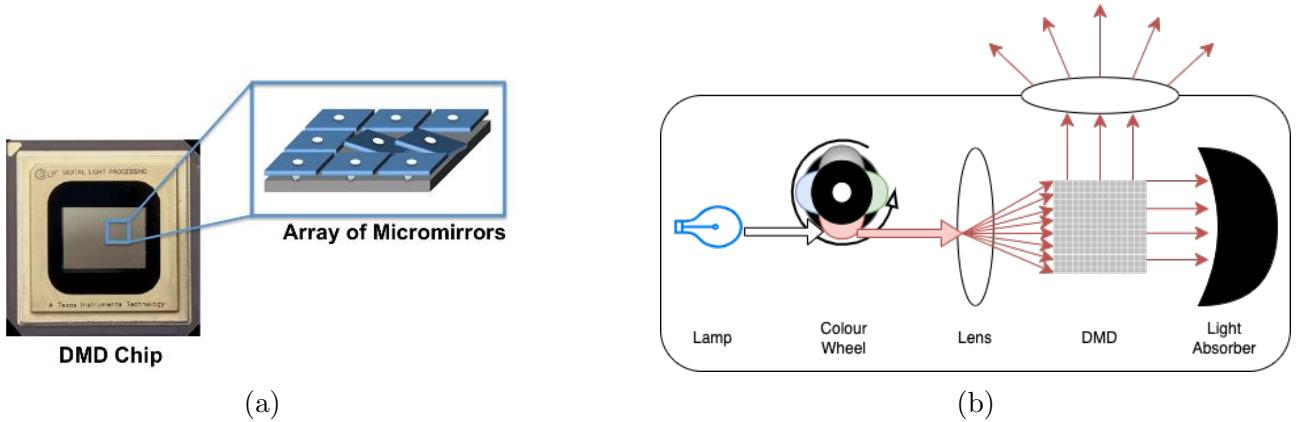


Figure 9: (a) The microscopic mirror array within a DMD chip [21]. (b) Cross-sectional view of an example projector employing DLP technology.

#### 2.4.4 Specialised Camera Sensor

The cameras found in many traditional and consumer-grade electronic devices, including smartphones, typically utilise a CMOS sensor equipped with a rolling shutter. These sensors introduce distortion effects when capturing fast-moving subjects, due to their line-by-line scan image-capturing characteristic. A global shutter sensor captures a snapshot of the scene using all pixels simultaneously, rather than line-by-line. Figures 10a and 10b depict the distinctions in image capture between a rolling shutter and a global shutter, and Figure 10c showcases output differences. The Raspberry Pi company offers a global shutter camera with plug-and-play compatibility with Raspberry Pi computers.

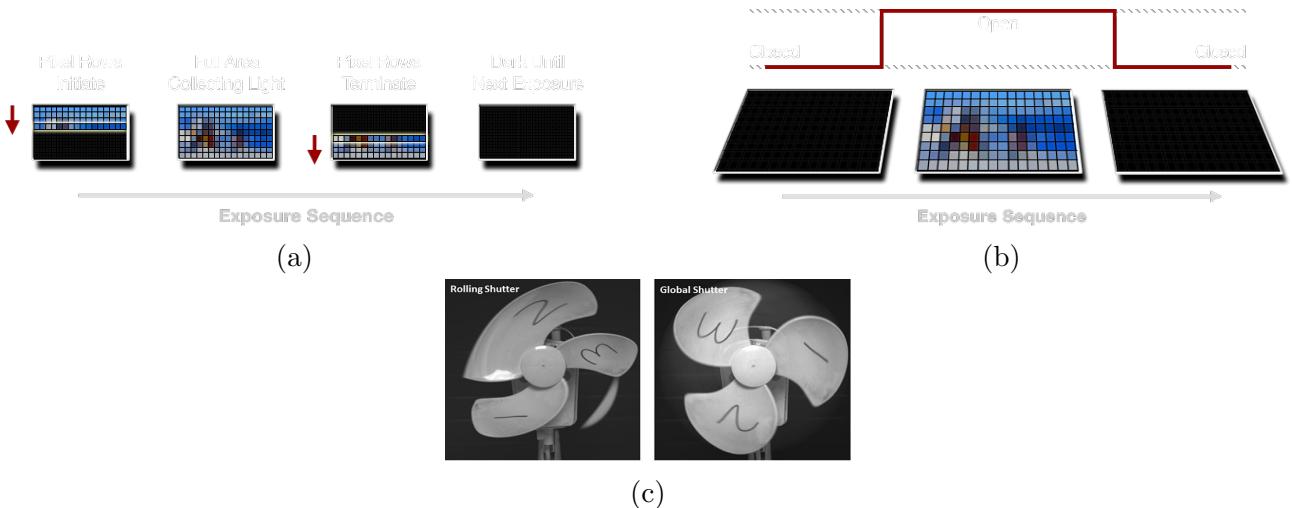


Figure 10: The image capture of a rolling shutter sensor in (a) and that of a global shutter in (b) [22], and (c), the comparison between the sensors when capturing a fast-moving target [23].

## 2.5 Summary

From the background research, the best methodology for precise backscatter segmentation is the Canny edge detection approach due to its resilience across varying particle appearances, a limitation of Shepherd's simple blob detection approach, and robustness in detecting edges even in uneven illumination conditions, as Thomanek et al. exemplifies, drawing comparisons with simple image thresholding. Zelenka's use of the gradient-based Snake method, despite its capability to segment bubbles with bright spots inside them, is unnecessary for this project's objective, as the focus lies on eliminating just the backscatter within sediments, the bright spot within bubbles, sand, and other marine debris, rather than the entire sedimentary particle.

When considering the computing platform, a Raspberry Pi single-board computer (SBC) running a Linux OS, and developing the system with Python and OpenCV, an open-source computer vision and machine learning software library with over 2500 optimised algorithms [24], is preferable over an FPGA for its cost-effectiveness, ease of development, and compatibility with a wide range of peripherals and software, aspects which are all essential for this project for prototyping in short time constraints. While a Raspberry Pi SBC that runs an ordinary Linux OS is not inherently a 'hard' real-time system like an FPGA implementation, implementing the PREEMPT-RT Linux kernel patch offers improved determinism and reduced latency compared to a standard Linux OS, crucial for ensuring timely and predictable response in the system.

A DLP projector is the preferred choice for projecting backscatter-cancelling light patterns due to its precise control and modulation capabilities, essential for accurately overlaying patterns to eliminate backscatter. Opting for a global shutter camera sensor over a rolling shutter sensor mitigates distortion effects caused by fast-moving subjects, ensuring accurate image capture in dynamic underwater environments.

## 3 Design

This section aims to explore the hardware setup and constraints, outlining key components and requirements for the system and toolsets, and concluding with a summary of the architectures and designs to aid in the subsequent implementation and testing phases.

### 3.1 System Equipment & Design Constraints

The system follows from the hardware constraints and assumptions that were set by Shepherd. In this prototype system, as Figure 11 illustrates, a plywood plate fastens the custom-fabricated and watertight tubes. The larger of the two tubes houses the Optoma ML550 projector, which features an LED lamp enabling a brightness capability of up to 500 lm, illuminating a 1 cm DLP for a native resolution of 1280x800, with a maximum 120 Hz vertical and 100 kHz horizontal scan rate capabilities. The smaller tube houses the RPi 5 (8 GB RAM variant) SBC, using a Broadcom BCM2712 2.4 GHz quad-core 64-bit Arm Cortex-A76 CPU to feature an advertised 2-3x performance upgrade from the RPi 4 that Shepherd used.

Connected to this RPi, via a 4-lane Mobile Industry Processor Interface (MIPI) transceiver, is an RPi global shutter (GS) camera, featuring the Sony IMX296LQR-C 1.58MP sensor. Instead of a GS sensor, Shepherd employed the RPi High-Quality (HQ) sensor, however, due to the reasons which Section 3.3 outlines, the GS sensor replaces this. The GS camera uses a PT361060M3MP12 lens, with an adjustable F1.2 aperture, a 6 mm adjustable focal length for a minimum object distance of 0.2 m, and a field of view of 63°. Mounting all components within their respective tubes with 3D-printed mounts, such that the separation between the camera and projector lenses is 12 cm. At the backside of each tube is a metallic cap with watertight cable couplers to pass through the RPi and projector power cables, and an ethernet cable for the RPi.

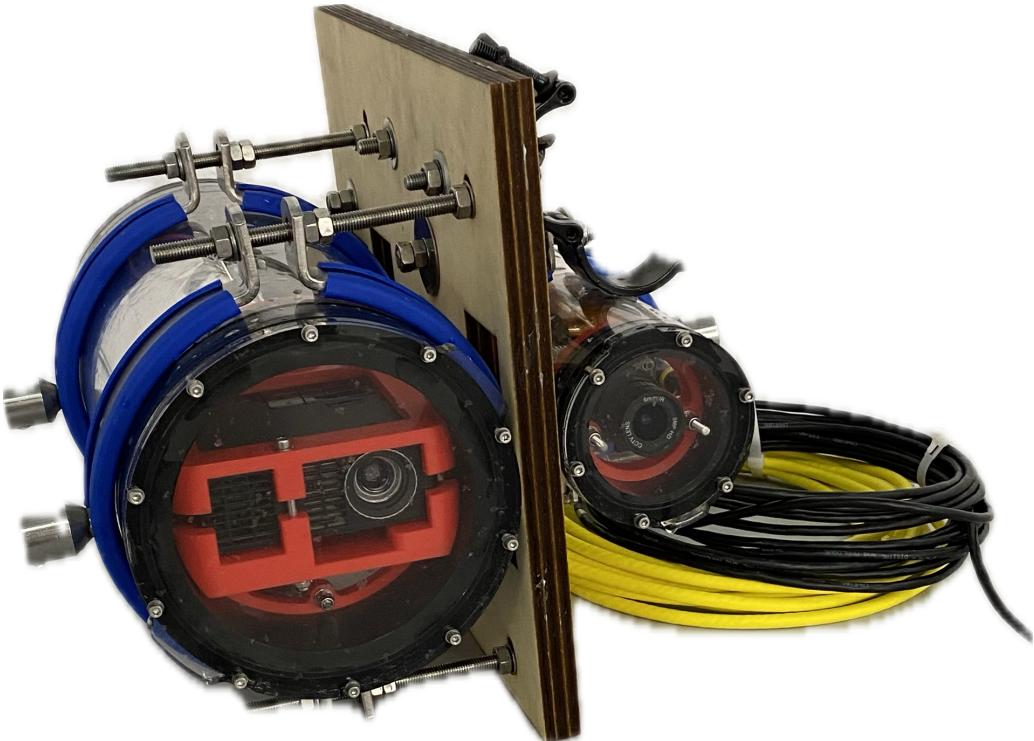


Figure 11: The submersible system.

The design relies on two assumptions: (a) the system is to run below the ocean twilight zone, which is approximately 200 m below the surface, ensuring the scene is only lit by the system and not other sources such as sunlight, and (b) there are no internal reflections from the housing, such as from the plastic tubes and tube lenses, ensuring all noticeable reflection to be backscatter particles. Due to its watertight construction, disassembling and reassembling the housing is a laborious process, often requiring the reapplication and testing of seals, which can extend the downtime to multiple days. Therefore, this project must prefer conducting tests using pre-recorded footage or synthetic simulations of backscatter to minimise disruptions and maintain operational efficiency.

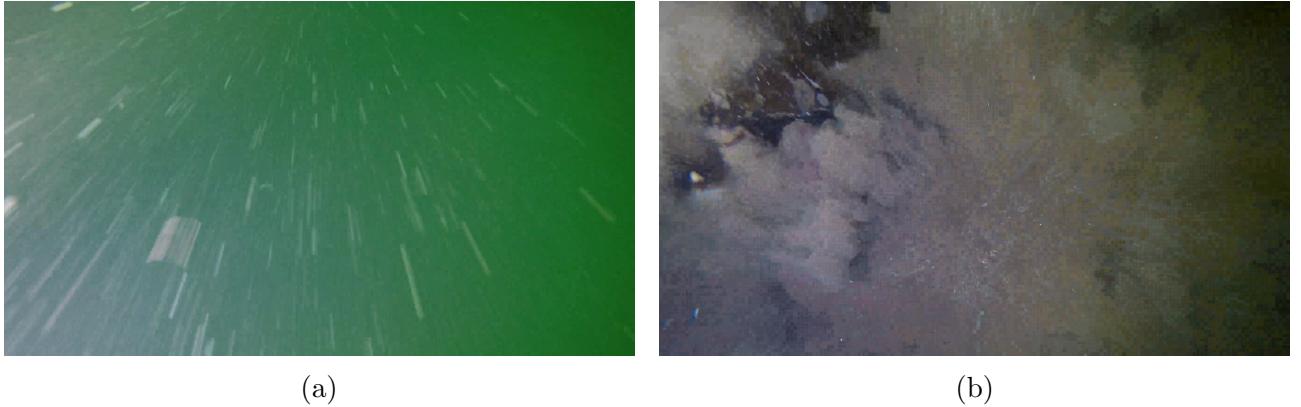
## 3.2 Simulating Backscatter for Synthetic Ground Truth

Given the substantial weight of the submersible, manoeuvring the system into position within an underwater testing tank presents significant challenges during testing. Moreover, the availability of the underwater testing tank at the Institute for Safe Autonomy wasn't fully realised until the later stages of this project. Consequently, there is a need for software capable of synthetically generating a simulation of backscatter particles. Since this simulation is entirely software-based, it must produce ground truth data comprising a dataset, assigning each backscatter particle with a unique ID, allowing for the tracking of coordinates across every frame of the simulation. Comparing the detected backscatter positions from the system with the true positions derived from the simulation ground truth enables the accurate assessment of the system's accuracy and performance.

Employing a straightforward model involving bubbles rising from the bottom of the screen can form a sufficient simulation of random backscatter particle movement in all axis directions: horizontal (x), vertical (y), and towards the camera (z). The simulation can depict backscatter particles as a white circle against a black background for simplicity, with user control over these exact colours. The model should also take into account the bubble expansion due to the pressure difference as they ascend from underwater. As a result, a separate model to simulate bubble distance from the camera location may not be necessary. It's also crucial to model horizontal bubble movement to capture the full range of particle motion.

## 3.3 Recording Lossless Video for Physical Testing

At the start of this project, Ben provided me with a GoPro recording from a submersible capturing the seabed, intending to use it as test material to develop the system. However, due to the GoPro's heavy video compression, coupled with its rolling shutter sensor, the video contains a large number of compression artefacts and significant motion blur, as Figure 12 illustrates. These issues significantly complicate the task of identifying individual backscatter particles for segmentation, with the system in Figure 11 originally, in Shepherd's work, employing an RPi HQ sensor, which is also a rolling-shutter sensor. The limitations posed by the GoPro footage proved the necessity for a GS sensor, prompting the exploration and subsequent implementation of the RPi GS camera. In order to capture test footage using this system, there must be a program in place to record the 'raw' footage from the camera, directly from the sensor inside the submersible without any lossy compression.



(a)

(b)

Figure 12: Frames from the GoPro footage: (a) showing the motion blur of backscatter particles, and (b) showing the pixelation artefacts (depending on your display, you may have to look closely to see the pixelation effect).

When recording in raw format, the RPi GS camera captures in full 1456x1088 sensor resolution at the maximum compatible framerate of 60 frames per second, using the native RAW10 SBGGR10 Bayer format, which utilises four channels, one red, one blue, and two green, with a 10-bit depth for each. Equation 1 calculates the total number of bytes per frame and Equation 2 calculates the total number of bytes per second when recording in this raw format, where  $R_w$  and  $R_h$  are the resolution width and height,  $D_b$  is the bit depth per channel,  $N_{ch}$  is the number of channels,  $F_b$  is the number of bits and  $F_B$  the number of bytes per frame,  $F_{rate}$  is the frame rate, and finally,  $S_b$  is the number of bits and  $S_B$  the number of bytes per second.

$$\begin{aligned}
 F_b &= (R_w \times R_h \times D_b \times N_{ch}) \\
 &= (1456 \times 1088 \times 10 \times 4) \\
 F_b &= 63\,365\,120 \text{ bit} = 63.365\,12 \text{ Mbit} \\
 F_B &= 7\,920\,640 \text{ B} = 7.920\,64 \text{ MB}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 S_b &= (F_b \times F_{rate}) \\
 &= (63365120 \times 60) \\
 S_b &= 3\,801\,907\,200 \text{ bit} = 3.801\,907\,2 \text{ Gbit} \\
 S_B &= 475\,238\,400 \text{ B} = 475.2384 \text{ MB}
 \end{aligned} \tag{2}$$

The calculations reveal an approximate transfer rate of 475 MB per second when recording the raw footage, presenting a significant data throughput requirement. It would be impossible to transfer at that data rate to the boot drive due to CPU bottlenecks, and most importantly, boot drive write-speed bottlenecks, with the drive being a USB 3.1 stick. To address this challenge, it is imperative to implement a memory buffer in RAM to temporarily store the recording data, offloading data to the boot drive only once the recording concludes ensuring the system solely

reserves the CPU for recording. Additionally, employing functionality to modify resolution for downscaling and to adjust the framerate, effectively further reducing the output filesize without introducing video artefacts.

### 3.4 Underwater Backscatter Cancellation System

The system must employ an image processing pipeline, Figure 13 illustrates this pipeline from a high-level perspective. The pipeline must begin with a greyscale filtering stage to reduce image dimensionality by categorising pixels by brightness, ensuring a single-channel output, reducing processing complexity for the subsequent pipeline stages. The next stage applies a Gaussian blur to reduce noise and small-scale variations in pixel intensities, to improve the edge detection performance such that the edge detection algorithm only detects regions of interest. Post-noise-smoothing, a histogram equalisation stage can improve the dynamic range, enhancing image contrast by redistributing pixel intensities to fully utilise the intensity range. The histogram equalisation stage can drastically improve the edge detection algorithm due to the improved contrast between objects of interest. Application of the Canny algorithm will extract all edges, ideally of the backscatter in isolation due to the previous stages, aiding in the next stage, which is backscatter segmentation. The segmentation stage will utilise a simple methodology, such as highlighting closed-loop edges, in order to isolate and pinpoint the backscatter particles.

Given Python’s high-level abstraction, there is a theoretical limit to how close to real-time the system can operate. For this system, I will be targeting a total processing duration, which is the time it takes to capture the frame, apply the image processing pipeline, and finally segment the backscatter particles, of 33.33 ms, which roughly equates to a framerate of 30 FPS. Employing a parallel processing pipeline, similar to the implementations by De Charette et al. and Tamburo et al., will increase system throughput to help achieve this target. Unfortunately, The Python interpreter is not fully thread-safe and thus utilises the Global Interpreter Lock (GIL), which prevents multiple processor threads from executing at once and causing race conditions. As a result, a Python-based processing pipeline will only ever process image frames sequentially, requiring the bypass of GIL to ensure parallel processing. Figure 14 illustrates the process distribution for the parallel image processing pipeline.

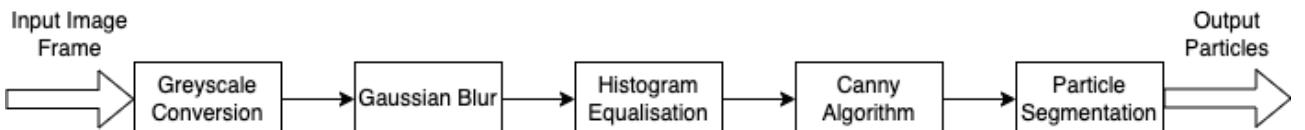


Figure 13: Design of the image processing pipeline for the system.

Parallel Image Processing Pipeline						
Time	Stage 1 Frame Capture	Stage 2 Grayscale	Stage 3 Gaussian Blur	Stage 4 Histogram Equalisation	Stage 5 Canny Algorithm	Stage 6 Particle Segmentation
t	Frame 1					
t + 1	Frame 2	Frame 1				
t + 2	Frame 3	Frame 2	Frame 1			
t + 3	Frame 4	Frame 3	Frame 2	Frame 1		
t + 4	Frame 5	Frame 4	Frame 3	Frame 2	Frame 1	
t + 5	Frame 6	Frame 5	Frame 4	Frame 3	Frame 2	Frame 1
t + 6	Frame 7	Frame 6	Frame 5	Frame 4	Frame 3	Frame 2
t + 7	Frame 8	Frame 7	Frame 6	Frame 5	Frame 4	Frame 3
t + 8	Frame 9	Frame 8	Frame 7	Frame 6	Frame 5	Frame 4
t + 9	Frame 10	Frame 9	Frame 8	Frame 7	Frame 6	Frame 5
...	...	...	...	...	...	...
t + n	Frame n + 5	Frame n + 4	Frame n + 3	Frame n + 2	Frame n + 1	Frame n

Figure 14: Design for parallel processing in the image processing pipeline for the system.

In addition to parallel multiprocessing, the system must implement a real-time kernel with the PREEMPT-RT patch. Shepherd's use of the fully-fledged Raspberry Pi OS, which includes a desktop environment and a full software suite, may have been the reason which led to its jitter, primarily due to the OS scheduler preemption type which prioritises a smoother graphical user interface over system latencies, and also due to the vast number of bundled software which could have been consuming CPU time. To ensure minimal OS and software overhead, I will be using the 64-bit Raspberry Pi OS Lite, which does not come with a desktop environment or any non-dependency software. Applying the PREEMPT-RT patch to the OS will reduce stage durations due to the reduction in system latency, and additionally, will also reduce latency randomness, ultimately improving system real-time and predictability. The final key factor is the ability to control the system frame rate, essentially by adding a delay to ensure processing at the established rate. For this design, the implementation must track the duration of each stage accurately to compute the necessary delay duration.

## 4 Implementation

Following Section 3, this section aims to implement the designs, starting with establishing remote communications with the RPi SBC, later developing toolset programs, and finally, the system itself.

### 4.1 Interfacing With Raspberry Pi SBC

Due to security reasons, also noted by Shepherd, it is not possible to connect the RPi SBC to the 'Eduroam' University network. This incurs a major roadblock, preventing remote communication to the RPi via SSH and communications to the internet from the RPi. Two aspects will ensure complete and seamless connectivity of the system: (a) SSH connection from the laptop to the RPi to enable remote connectivity for configuration and control, and (b) internet

connection from the RPi to a valid network to enable the installation and update of the OS and other software. The security policies in place across all University-owned networks block communication between devices. Therefore, there must be a separate link between the RPi and the device to initiate an SSH connection. As Figure 15 illustrates, SSH communications will occur over an Ethernet connection between the RPi and a personal computer, and internet communications will occur over Wi-Fi to a separate University of York-owned network called ‘mydevices’, which is intended for internet access from games consoles and specific smart home devices, and can be connected to by registering the RPi SBC’s MAC address via a web portal and then entering a default Wi-Fi WPA2 Personal password on the RPi.

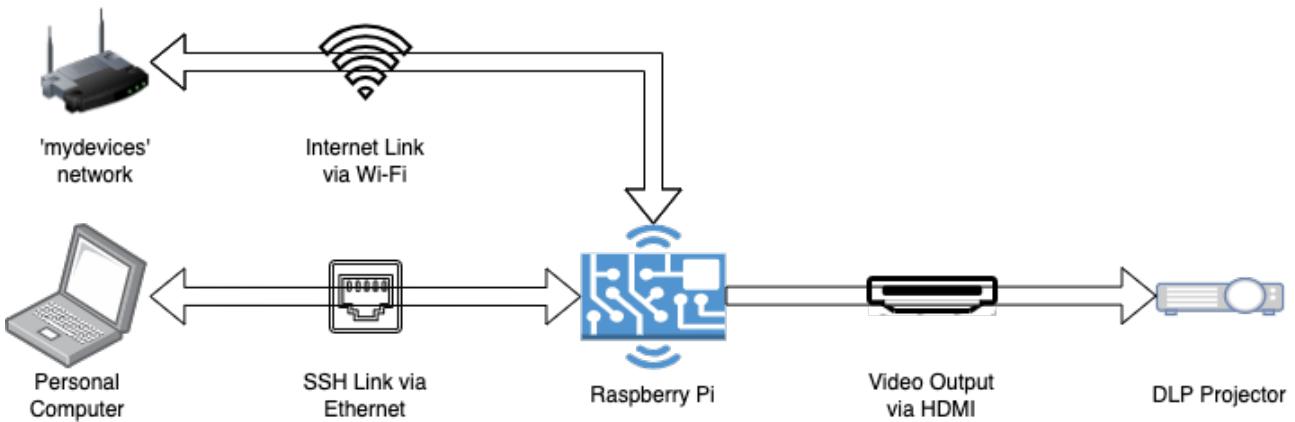


Figure 15: The Raspberry Pi SSH and Wi-Fi communication configuration, including video output interfacing with HDMI.

The RPi must have a set hostname for easy identification, and through NetworkManager, configuring ‘wlan0’ to connect to the ‘mydevices’ access point for internet access, and to prevent random and intermittent SSH disconnections and unresponsiveness, configuring ‘eth0’ to a static IP address in the format 192.168.0.xxx/24 and disabling IPv6. Creating a new network on the personal computer (PC) using the Ethernet interface with DCHP disabled, IP address set to 192.168.0.1/24, and subnet mask set to 255.255.255.0, ensures a bidirectional communication channel via Ethernet between the PC and RPi, essential for SSH. Unlike Shepherd’s system, which uses the Raspberry Pi OS, this system utilises the Raspberry Pi OS Lite which lacks a desktop environment. Using SSH with X11 forwarding with an X11 display server software, such as XQuartz, on the PC, graphical user interface windows will render on the PC, enabling quick system debugging. Due to the lack of a desktop environment, video output to the DLP projector will only be possible by directly writing to the Framebuffer, which is a portion of memory in RAM containing a bitmap that drives the video display output, ensuring display output rates quicker than through a GUI window such as in Shepherd’s system.

## 4.2 Backscatter Simulator for Synthetic Ground Truth

This software, code in Appendix A.2, utilises Python 3.11.2 just like the rest of the Python programs in this project, the ‘Pygame’ package, which is a game library, to render the graphical

user interface, the ‘random’ package to generate random particle velocities, the ‘uuid’ package to generate a unique ID for each particle in the simulation, and the ‘csv’ package to generate an export dataset consisting of the positions and radii of each particle for every simulation frame. Defining a set of constants at the start to control the simulation parameters, which Table 2 describes, the script also consists of a ‘Bubble’ class which denotes a backscatter particle, with the class fields in Table 3 and the class methods in Table 4, all tables in Appendix A.1.

The program flow, in Figure 16, begins by initialising the Pygame module and creating the graphical window and the simulation clock. If the program is not set to generate the bubble backscatter particles continuously, the program will initialise the bubble backscatter particles, ensuring that the bubble limit is reached before entering the simulation loop. Within the simulation loop, as each iteration denotes a new frame, the program initialises the simulation window background with the user-defined colour. Next, only if the user enables the constant particle generation feature, the program initialises the bubbles to the maximum count possible. Then, the program logs the position and radii of each backscatter particle in the frame before drawing every bubble and moving them. The program then runs a probability check, only if true will it randomise the velocities of every single bubble. The program then removes the particles that are outside of the simulation window before exporting an image capture of the frame. The reason behind exporting a PNG image file of each frame instead of a singular video file is to emulate the frame-by-frame capture logic of the Backscatter Cancellation System from the RPi GS Camera, Section 4.4 explains this in further detail. Finally, the Pygame-provided clock functionality limits the simulation to the user-defined constant and stores the time delta, which is the duration in seconds from the last frame, before iterating once again. When the user inputs a ‘quit’ signal by closing the window, the program creates a CSV file export, with the help of the ‘csv’ Python module, by offloading the metric data from each frame before the program gracefully terminates.

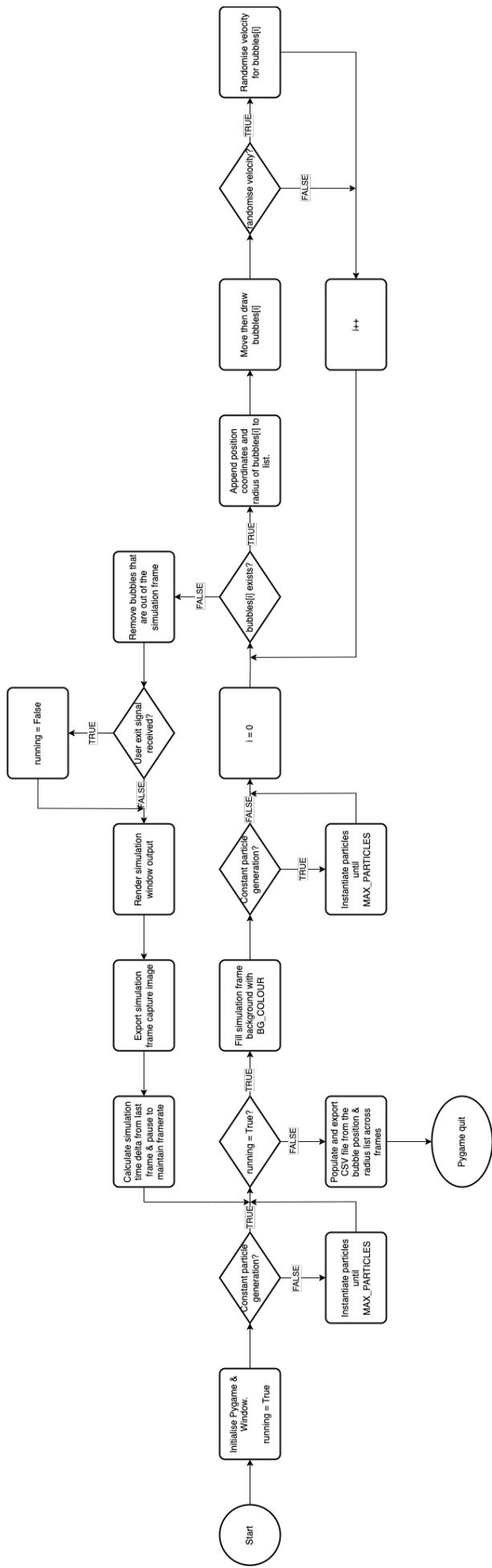


Figure 16: Backscatter simulation software process.

### 4.3 Lossless Video Recorder for Physical Testing

As Section 3.3 introduces, this software, Python scripts in Appendix B.2, records test footage of bubbles from the underwater testing facility at the Institute for Safe Autonomy using an RPi 5 and an RPi GS Camera, from the submersible system itself. The software also drives a DLP projector to project a fully illuminated white light source, ensuring a well-lit scene and to induce backscatter, via HDMI using the Framebuffer to eliminate the need for a desktop environment. Aside from the main entry point script, the software consists of three self-built modules: (1) ProjectorManager, which interfaces the software with the DLP projector via the Framebuffer, (2) the CameraManager, which interfaces the RPi Camera with the software, and finally, (3) the PreviewManager, which produces the GUI window to output the recording previews and program status. The program uses the ‘Numpy’ Python package to generate bitmap arrays of pixel values to drive the DLP projector via the Framebuffer. The ‘Picamera2’ library, although only available as a beta release at the time of writing, provides the program with high-level access to the RPi Cameras and RPi SBC’s built-in imaging hardware. The ‘subprocess’ package spawns the FFmpeg process to encode the recording, with the assumption that FFmpeg is present on the system’s RPi SBC, and finally, the program uses the ‘OpenCV’ package to access machine-vision algorithms for image processing and to generate the preview GUI window. The tables in Appendix B.1 list and describe the program configuration constants, and the fields and methods for each class.

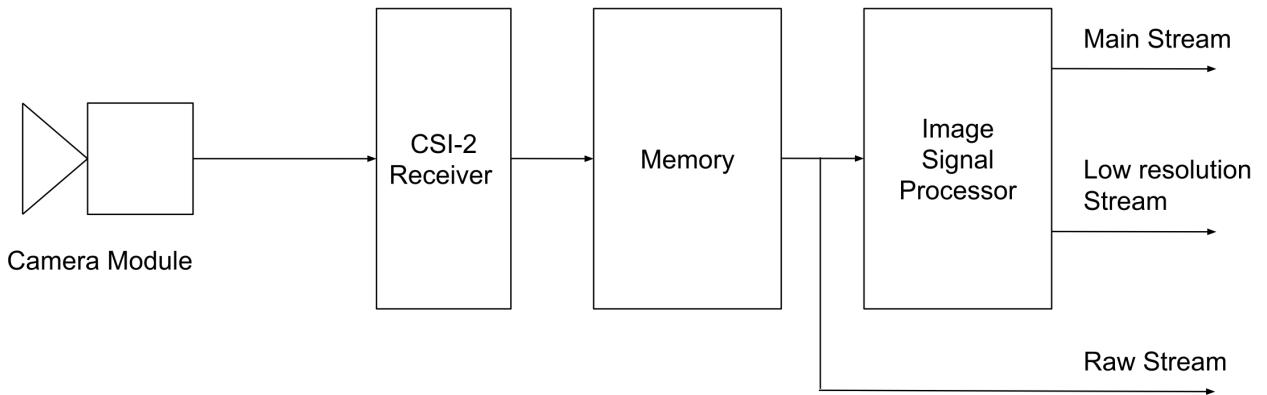


Figure 17: From [25], the Raspberry Pi camera system.

As the Picamera2 library manual from [25] illustrates in Figure 17, the RPi camera module delivers the output data stream, which is in native sensor format and not human-viewable, to the CSI-2 receiver hardware block onboard the RPi SBC via a ribbon cable. This hardware block transfers the incoming data into memory, ready for delivery to applications. In the initial prototyping stage for this system tool’s implementation, I was receiving and recording the ‘raw’ stream. However, this data required a lot of computationally intensive processing to convert to a human-viewable format, in addition to the high data throughput requirement of 475 MB per second, recording at a steady rate was impossible even with a memory buffer. The Image Signal Processor (ISP) onboard the RPi SBC reads the ‘raw’ stream from memory and

efficiently cleans and processes the pixel data stream, ultimately producing a human-viewable output in either, depending on user set configuration, the RGB or YUV format. Instead of parsing the ‘raw’ stream, I chose to process the ‘main’ output stream in the final version of the software, configuring the exact resolution and framerates, in addition to selecting the BGR888 output format such that the data is natively compatible with the OpenCV image processing libraries.

Figure 18 illustrates the flow of the software. The program begins with an initialisation, initialising the preview window, which passes through to the remote SSH connection on the PC via X11 forwarding, the projector via the Framebuffer, and the Picamera2 library, which applies a configuration to the RPi GS camera module and starts it. The main loop of the program then begins, retrieving the ISP-processed camera sensor array from the ‘main’ output stream, and also retrieving the statuses of whether the projector light is on and whether the camera is recording. The main loop sends the frame array, along with the statuses, to the preview window, which also logs any user keypress inputs. Using the Framebuffer, which is a memory location accessible through a directory, the program can toggle the light source by writing a bitmap array of white pixel values to turn on, and a bitmap array of black pixel values to turn off. If the program detects an ‘L’ keypress, the projector light source toggles. With an ‘R’ keypress, the program toggles the recording status. If the recording needs to start, the program initialises a memory buffer, configures the Picamera2 module to write to this Framebuffer along with a ‘Null’ encoder, which ensures that the output is unencoded and ‘raw’, and finally sends a signal to start recording. If the recording needs to stop, the program sends a signal to the Picamera2 module to stop the current recording, and using FFmpeg, which I have installed on the RPi SBC, the program applies lossless encoding using the FFV1 encoder to convert the bitstream into an ‘.MKV’ file, reducing the filesize and converting to a common video file format, for easy file transmission and so that any general-purpose software, such as VLC, can open and this footage for playback. When the program receives an ‘E’ key input, it will send the shutdown signal to the Picamera2 module, which gracefully terminates the camera module, it will turn off the projector light source by clearing the Framebuffer and sends a ‘destroy windows’ signal to OpenCV which will consequently close all windows gracefully, and finally, the program exits the main loop and quits. If the program does not detect a keypress, or if it has finished handling the keypress for all inputs except the exit signal, the main loop iterates such that the entire process repeats.

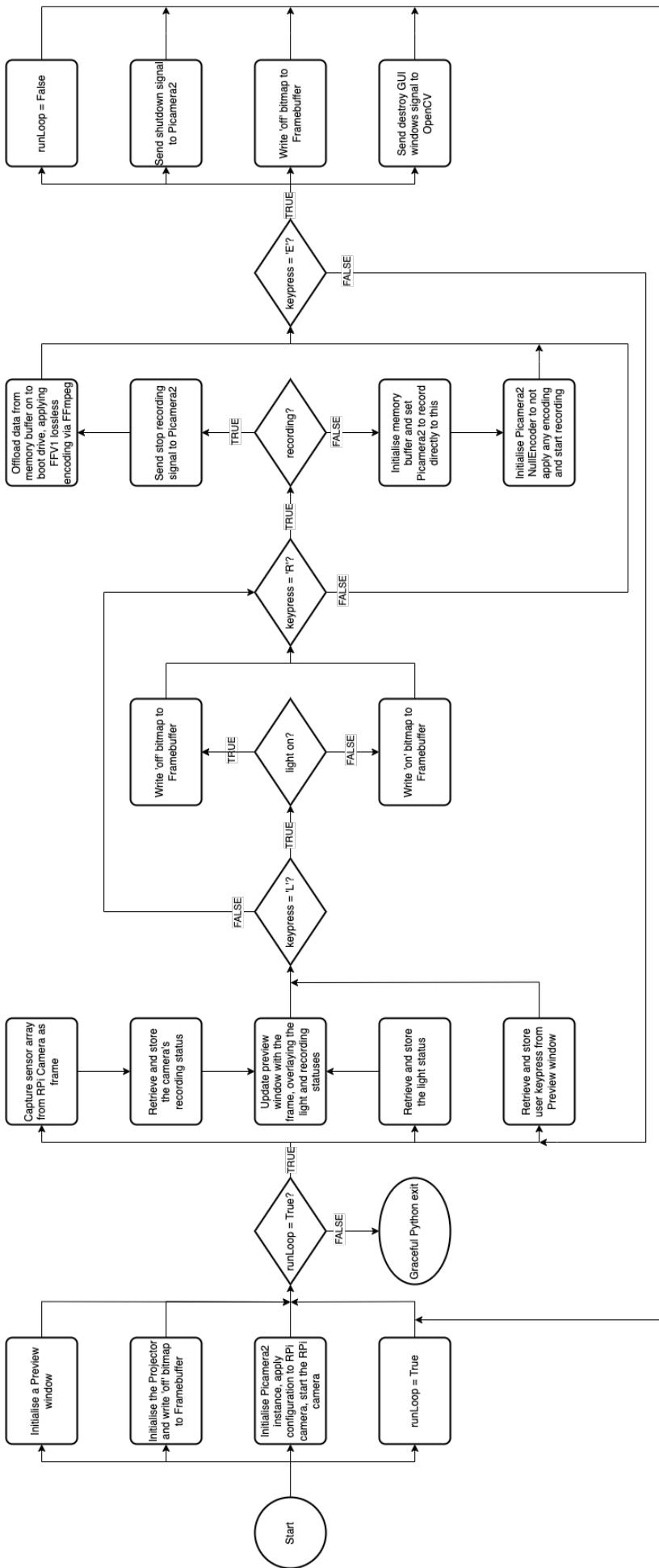


Figure 18: Lossless video recorder software process.

## 4.4 Underwater Backscatter Cancellation System

The backscatter cancellation software, as Section 3.4 describes, with code and references for methods and fields in Appendix C, applies an image processing pipeline to segment backscatter particle regions to then generate light patterns for selective illumination using the DLP projector. Similar to the Lossless Video Recorder implementation in Section 4.3, this system follows the object-oriented paradigm for modular code, breaking down the implementation into four self-built modules, aside from the entry point: (1) CaptureManager, which contains multiple different classes for input types, for example, a Raspberry Pi Camera interface similar to the CameraManager in Lossless Recorder, and a video file stream, which allows test footage inputs. (2) BSManager, which contains the image processing pipeline and backscatter segmentation functionalities, (3) TimeManager, which contains functionality to precisely time code, and finally, (4) WindowManager, very similar to PreviewManager in the Lossless Recorder program, contains functionality to output frames to a GUI for debugging. Instead of utilising Picamera2’s recording functionality for the RPi Camera Stream class, the system captures each frame individually at each iteration to enable fine control over framerates. Due to time constraints and issues with system offsets/parallax, which Section 5 will explain in further detail, I couldn’t implement functionality to output the light patterns by directly driving the DLP projector with parallax and offset mitigation, and therefore, skipping the implementation of logic to limit the framerates, such that this system outputs entirely via the GUI windows. Just like the Lossless Recorder program, this system uses the OpenCV package for both the image processing functions and for GUI windows. The program also uses the Numpy package for bitmap operations concerning the image frames, the Pandas package for large data set operations concerning the metrics that the system tracks, the ‘psutil’ package to set the program ‘nice’ value, which is the software priority for the OS scheduler, and finally, the ‘time’ package, where the system harnesses the performance counter, which is a system clock with the highest available resolution, to measure precise code execution durations.

As Figure 19 illustrates, the program begins by setting the software priority level, this priority level is also called the ‘niceness’, which has the lowest compatible value of -20, denoting the highest priority, and the highest compatible value of 0, denoting lowest priority, such that the lower priority processes demands less CPU processing time and are ‘nicer’ to other processes in the system. Next, the program sets the correct input stream type before initialising the graphical preview windows and entering the main system loop. Within this loop, the program captures a frame from the input stream at the start of each iteration, and for each frame, applies the image processing pipeline to segment bubbles. After a greyscale conversion, Gaussian blur, and histogram equalisation, all using OpenCV functions, the program configures the Canny edge detection algorithm following the zero-parameter approach by Rosebrock in [26]. Rosebrock’s approach simplifies the upper and lower Canny algorithm thresholds into a single parameter, sigma, which denotes a multiplier for the median pixel intensity of the input frame, such that the upper threshold is sigma above the median, and the lower threshold is sigma below the median. While not exactly zero-parameter as Rosebrock states as there is still a sigma parameter, this

approach ensures that the edge detection adapts to the specific characteristics of the input image even in different conditions, providing effective edge maps without manual parameter tuning. The system passes the Canny output, a bitmap of detected edges, to the segmentation method which then begins by finding contours, which are curves that join all the continuous points along a boundary, using OpenCV’s `findContours()` method. Next, the program sends each contour detection to OpenCV’s `minEnclosingCircles()` method, which calculates the smallest enclosing circle for a set of contour points, and returns the center and radii of each circle. These minimum enclosing circles (MECs) will be the black ‘holes’ in the white light patterns, ensuring the backscatter particles are dark whilst the system fully illuminates the surrounding environment. The program renders all of the output image frames, including those from the intermediate image processing pipeline stages if the debug window option is ‘True’, whilst logging the user-input keypresses. If the user enters the ‘E’ key, the program breaks from the main loop and enters the shutdown sequence. The program tracks the precise execution duration of each image processing stage with the performance counter for each frame, including metrics on the number of MEC detections, and the total frame processing time. When the program reaches the shutdown sequence, it extracts all of the metrics and generates a CSV export file, then exits all GUI windows, sends a shutdown signal to the RPi camera module, and finally exits completely.

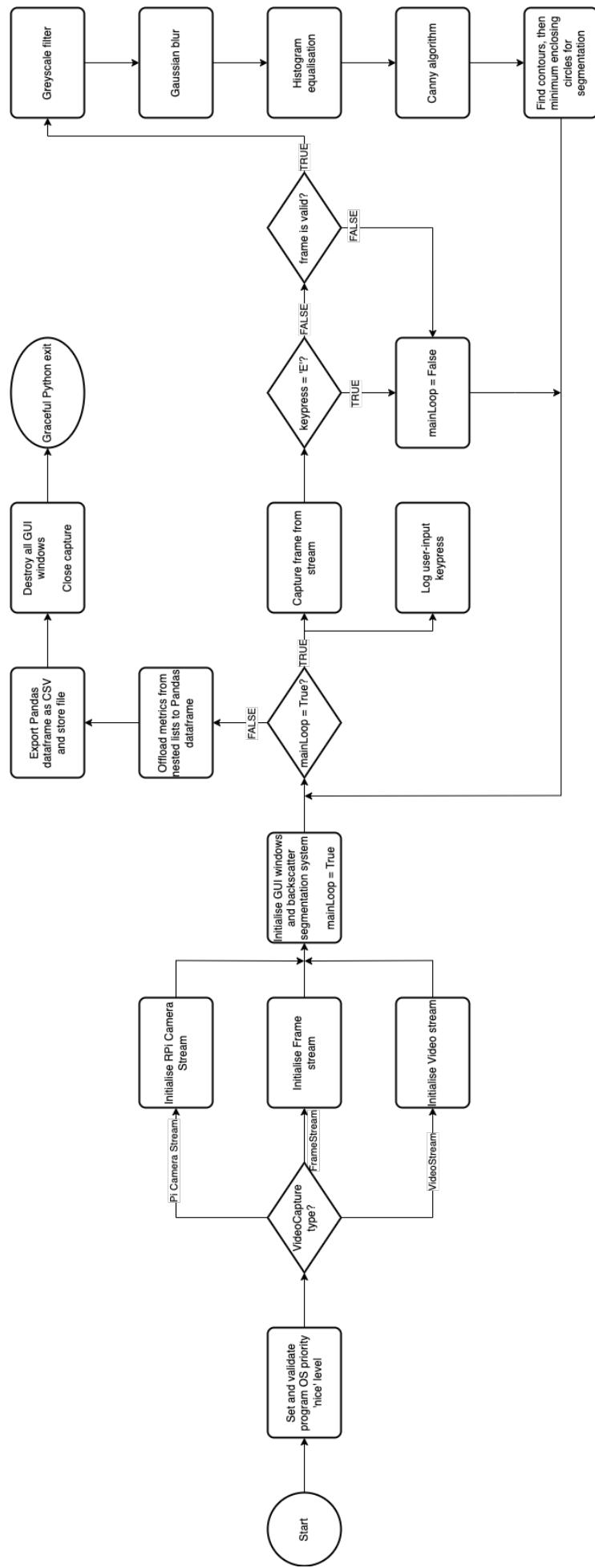


Figure 19: Backscatter cancellation system software process.

#### 4.4.1 Implementing Multiprocessing

The functionality of the multiprocessing system follows very closely to the aforementioned base system, which only utilises a single thread due to the Python GIL limitations. Appendix D contains the references for methods and fields as well as the code for this implementation. The ‘multiprocessing’ Python package provides an interface to support spawning subprocesses with concurrency, effectively side-stepping the GIL, and ultimately enabling the system to fully leverage multiple processors on a given machine, unlike Shepherd’s system which employs ‘multithreading’ and, therefore, is subject to the GIL for standard CPython execution. The single-thread version of the system is split into eight stages, denoted by classes that inherit the ‘multiprocessing’ Process, which is an object that spawns as a separate process: (1) Capture, which first initialises the input stream, then enters an infinite loop that iterates until the input stream ends whilst returning the capture frame and any user-input keypresses. (2) Greyscale, which simply applies the greyscale filter. (3) Histogram Equalisation, which also simply applies histogram equalisation. (4) Gaussian Blur, again simply applying a Gaussian blur. (5) Canny Algorithm, which applies the Canny edge detector using the ‘zero-parameter’ approach by Rosebrock. (6) Segmentation, which first finds the contours before applying the minimum enclosing circle function to segment the bubbles. (7) Project, which originally intended to output the light patterns to the Framebuffer, however due to the aforementioned constraints and limitations, instead outputs to a graphical preview window. Finally, (8) Logging, which exports the metrics into a Pandas DataFrame, then into a CSV document.

Due to the asynchronicity of the processes, the system employs queues to send data between stages in a thread-safe manner, preventing instances of data corruption with shared memory locations such as standard variables due to clobbering, where a process overwrites data while another was reading the data. The Capture stage will start filling its output queue with frames, and if no frames are left, or if the process receives a ‘quit’ signal from the user, it enqueues with a special code instead of a frame. This queue is input to the next stage, which is Greyscale, and this stage begins to dequeue, applying the greyscale filter, then enqueues to its output queue, and if it receives a quit code instead of a frame, it will shutdown itself after forwarding the code. This logic repeats across all the other stages.

### 4.5 Applying the PREEMPT-RT Patch

The latest version of Raspberry Pi OS Lite at the time I built the real-time kernel used the 6.6.20 Linux kernel version. Therefore, I applied the PREEMPT-RT patch with the corresponding version label of 6.6.20-rt25. While building, I selected the ‘Fully Preemptible Kernel (Real-Time)’ option, also enabling the RCU priority boosting with a 500 ms delay boosting for the RT kernel and enabled the ‘Multi-core scheduler support’ option for both RT and the non-RT kernels.

## 5 Testing & Evaluation

Due to the large offsets and parallax between the camera and projector, the project shifts its focus from physical testing to software testing and real-time performance analysis. Following the details on implementation in Section 4, this section aims to describe the testing process for testing both the system and the toolsets, including an evaluation of the backscatter cancellation system performance.

### 5.1 Bubble Backscatter Simulator

The bubble backscatter simulator program works very well as a simple backscatter simulation. As Figure 20 illustrates, the program successfully renders a preview graphical user interface, enabling the user to view the bubbles as they generate and move, and the program also correctly exports each frame of the simulation as a PNG file, emulating the frame-by-frame capture loop behaviour of the backscatter cancellation system. Furthermore, the program exports a CSV dataset of the individual backscatter particle positions and radii from each frame, classing each particle with a unique ID, for the first few particles in the dataset. Despite this, a major drawback that I found from this program is the fact that it doesn't simulate varying backscatter appearances, such as morphological transformations with shape warping, and colour changes, to verify if the system can detect varying backscatter parameters, as all particles are exactly circular and white. In addition, the program does not simulate varying background conditions as the background is exactly black, resulting in the inability to verify whether the system can correctly isolate and segment just the particles and not any regions of interest in the background.

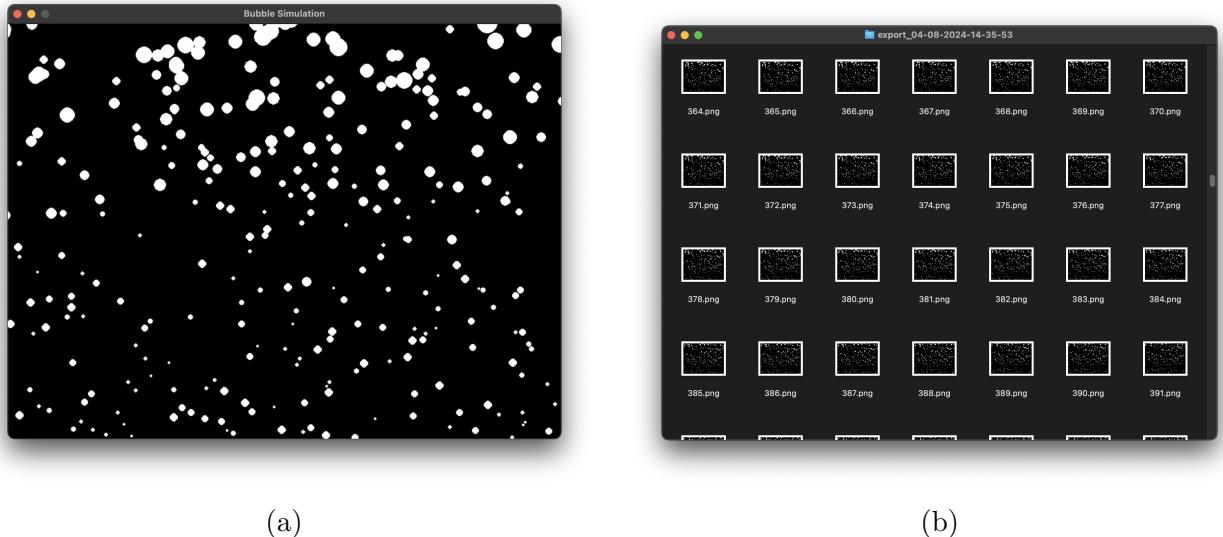
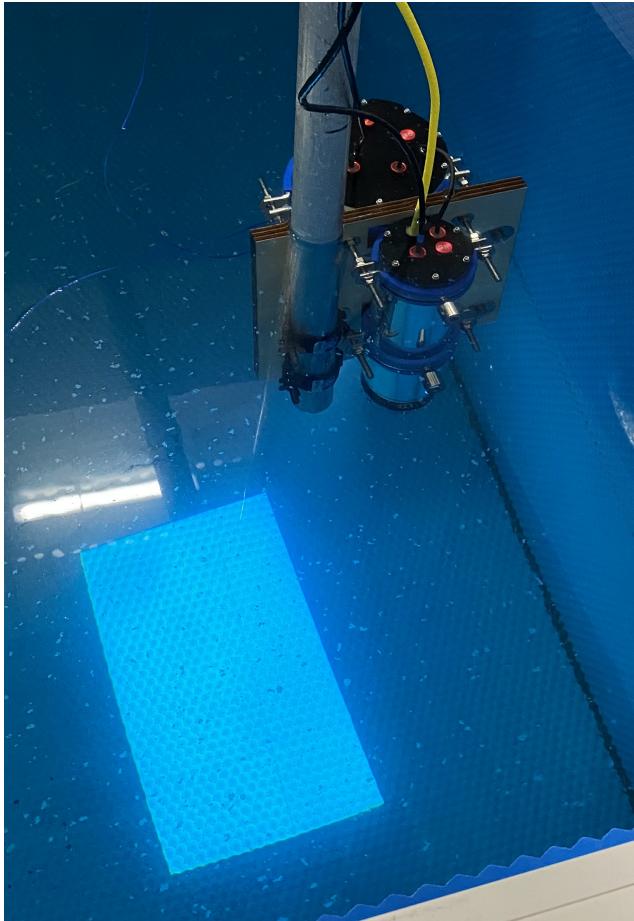


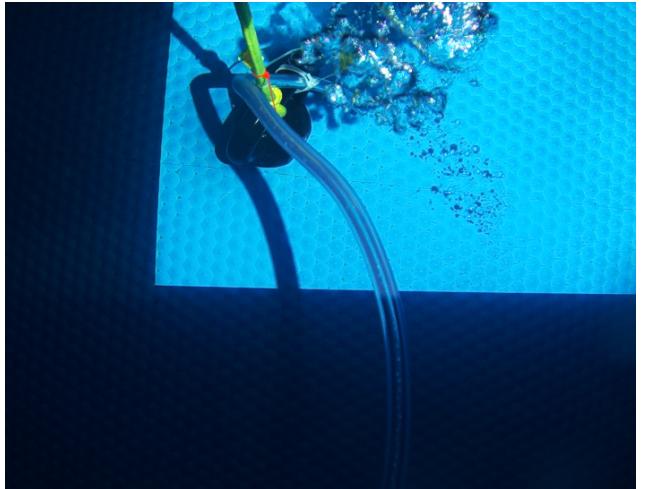
Figure 20: Screenshots validating the Bubble Backscatter Simulator program: (a) showing the preview GUI window, and (b) showing the list of frames in the output directory.

## 5.2 Lossless Video Recorder

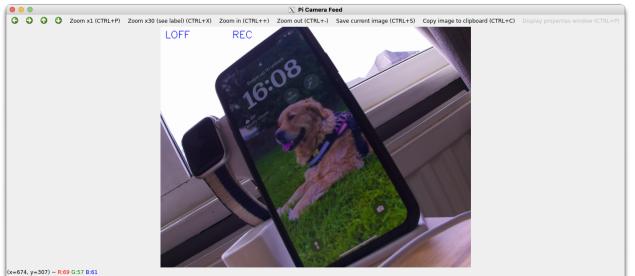
The lossless video recorder proved an invaluable tool that performed almost flawlessly, as Figure 21 illustrates. A change I had to make was to modify the OS to ensure the console would not output to the HDMI Framebuffer, as this was causing interference with my Framebuffer-driven light source. Unfortunately, as the figure also illustrates, there was a major misalignment issue, where the camera is only able to a small corner in the bottom-left of the projector-lit scene. While a simple cropping function can resolve most of this, which I have implemented in the backscatter cancellation system, albeit reducing the system's useable region, the system will still be affected by the camera's internal reflection, which reduces the field of view and adds distortion. Nevertheless, the recordings were very helpful in validating the system in a non-synthetic environment without requiring re-deployment underwater.



(a)



(b)



(c)

Figure 21: Figures validating the Lossless Video Recorder program: (a) showing the submersible recording underwater at the Institute for Safe Autonomy testing tank, (b) an extracted frame from recorded footage, and (c) showing the preview GUI window, rendered remotely with X11 forwarding.

## 5.3 Backscatter Cancellation System

I first verified the backscatter cancellation system using the output from the backscatter simulation and it worked flawlessly, identifying and segmenting the bubbles correctly using the min-

imum enclosing circle logic, as Figure 22a illustrates. However, when using the underwater test footage, the system started to incorrectly detect the background, mainly the textured padding of the testing tank, as Figure 22b illustrates. This was caused by the histogram equalisation stage as it increases the image frame's contrast substantially. I therefore replaced this stage with an OpenCV binary thresholding implementation, ensuring the system only passes certain pixel intensities. The results after this processing pipeline stage replacement were much better, as Figure 22c illustrates. Figure 23 illustrates the final system's image processing pipeline flow.

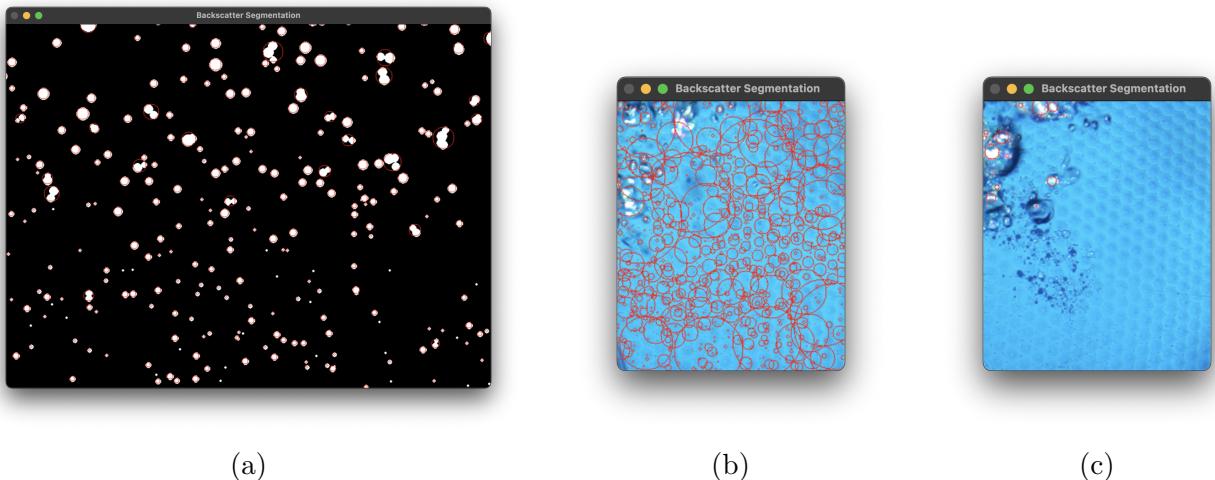


Figure 22: Backscatter Cancellation System program output: (a) showing the backscatter segmentation (red circles) from the Backscatter Simulator, (b) incorrect segmentation with histogram equalisation, and (c), correct segmentation with binary thresholding.

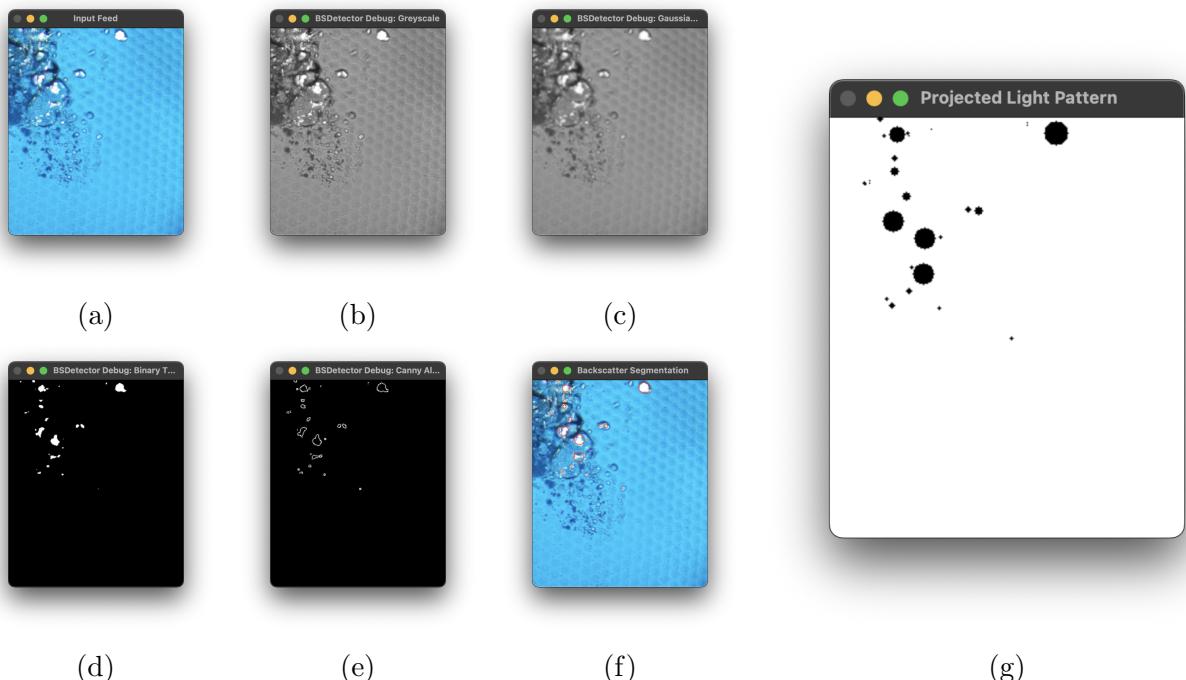


Figure 23: Backscatter Cancellation System program debug output: (a) the input, (b) greyscale filtering, (c) Gaussian blur, (d) binary thresholding, (e) the Canny algorithm, (f) segmentation with minimum enclosing circles, finally, (g), the projection.

## 5.4 System Performance Evaluation

Due to time constraints, I couldn't implement logic in the backscatter cancellation system which exports a dataset of detected backscatter particles, which I could've then used to compare with the simulation export, the synthetic ground truth, to quantify the accuracy performance of the system. Therefore, this section entirely focuses on the real-time performance, by analysing the execution time for each image processing pipeline, and the total execution time for each frame with the underwater testing tank footage input to the RPi SBC system with the system software 'nice' value set to the lowest value (-20), ensuring the highest process priority, ultimately quantifying the impact of multiprocessing and the PREEMPT-RT kernel patch.

Process	Avg. Duration (μs)				Std. Deviation (μs)			
	Std, SP	RT, SP	Std, MP	RT, MP	Std, SP	RT, SP	Std, MP	RT, MP
Frame Capture	1,480	20,100	12,120	27,730	3199	9629	14990	11600
Greyscale Filter	193.4	2370	220.2	212.0	31.19	57.67	91.02	80.16
Gaussian Blur	159.2	319.2	339.5	378.8	148.2	457.4	653.0	599.0
Binary Threshold	19.79	29.70	64.10	81.34	5.144	61.15	57.45	111.3
Canny Algorithm	601.9	795.3	879.20	975.3	95.46	550.3	724.4	1427
Find Contours	110.8	135.8	180.0	252.2	43.16	184.2	134.0	389.2
Find MECs	41.88	47.14	45.60	47.05	30.84	36.67	92.65	41.89
<b>Tot. Duration (μs)</b>	<b>2,607</b>	<b>21,620</b>	<b>13,850</b>	<b>29,670</b>	<b>3253</b>	<b>9732</b>	<b>15140</b>	<b>11920</b>

Table 1: Real-time system metrics using the standard (Std) and real-time (RT) kernel, in single-core (SP), and with multiprocessing (MP). Values rounded to the nearest 4 sig. figs.

Table 1 transcribes the real-time metrics for the system, across 402 frames of real test footage recorded from the testing tank, listing the execution duration for all the image processing pipeline stages using the standard kernel, real-time kernel, multiprocessing, and in the standard single-core mode under the GIL. The data shows a 431% increase in total latency from the single-core to the multi-core program with the standard kernel, and 37% increase of that in the real-time kernel, a 729% increase when moving from the standard to the real-time kernel with single-core, and a 114% increase when moving from that in the multiprocessing system. The data also contains the standard deviation of the individual processing stage and total system latencies to measure data variability, showing a 199% increase in fluctuations when moving from the standard to real-time kernel in the single-code environment, and a 21% decrease of that in the multiprocessing environment.

In contrast to the theory that previous sections cover regarding the reduction of latency with multiprocessing and a real-time OS, the data illustrates the complete opposite. The multiprocessing system employs queues, a form of Inter-Process Communication (IPC), to preserve data whilst processing asynchronously across multiple processes. These IPCs introduce vast computational overhead due to data serialisation and deserialisation when transmitting across processes and during OS context switching. Furthermore, while multiprocessing offers parallelism, it still cannot overcome the synchronous nature of I/O-bound processes, as the data

quantifies with a 719% increase in frame capture durations between the standard single-core and standard multiprocessing systems. The PREEMPT-RT patch should've reduced system latency or at least resulted in more constant latency measurements. However, the data illustrates the patch increasing the frequency of preemption points in the kernel, resulting in more context switches, and when paired with the IPCs, slowing down the system rate and increasing latency. Nevertheless, my single-core RPi SBC system achieves a total processing latency of just 2.6 ms, a great improvement from the system in De Charette et al., which takes 4.1 ms to process frames on a much more powerful desktop computer, and achieving the 33.33 ms (30FPS) target.

## 6 Conclusion

This project set out to design, implement, and evaluate a real-time backscatter cancellation system for underwater imaging, leveraging an RPi SBC for portability and accessibility. The project began by developing the toolsets for the final system, including a backscatter simulation to generate a synthetic ground truth to test and validate the final system, and a lossless recording script to capture underwater footage to test the final system without requiring underwater deployment. These toolsets provided crucial assistance in the final system's development.

The project achieves the objective of precise backscatter particle segmentation by employing an image processing pipeline centred around the Canny edge detection algorithm and a simple minimum enclosing circle segmentation method. The project uncovers mixed results when reducing system latency with a real-time kernel and multiprocessing for increasing system throughput to achieve the latency targets, including the adverse effects of the real-time kernel patch for Linux and Python multiprocessing. However, the single-core system achieves a commendable 2.6 ms average frame processing latency, a clear improvement over previous research. Underwater testing of the system, with the lossless recording program, uncovered the drastic parallax and distortion effects due to the submersible housing construction, which resulted in the project's shift from focusing on the development of a final working system, to real-time software optimisation, to balance the short project time duration. Therefore, driving the DLP projector, including functionality to control and establish a fixed system frame rate, was no longer an actionable item. Appendix E illustrates the evolution of the project schedule using Gantt charts.

In conclusion, this project successfully delivers a functional and efficient backscatter segmentation system, meeting real-time targets. The insights gained from the performance evaluation highlight the intricacies of optimising such systems and suggest that, for specific applications, simpler single-core implementations may offer superior performance compared to more complex multiprocessing or RTOS-enhanced solutions. In addition to completing the objectives for DLP-driven projections and fine-grain framerate controls, the following aspects for future work can drastically improve the system: (a) FPGA implementation for accelerated image processing and DLP projector driving by harnessing the inherently multithreaded architecture, (b)

improved submersible housing, mitigating the component offsets with high-precision alignment and a beamsplitter to eliminate parallax by co-location, and finally, (c), a predictive system to track and estimate the future location of backscatter particles to mitigate backscatter movement against system latencies, with options to incorporate machine-learning technologies, using a more realistic backscatter simulation for training data.

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# Appendix A Bubble Backscatter Simulator

## A.1 Description of Class Fields & Methods

Name	Description
WINDOW_WIDTH	The maximum width of the simulation window.
WINDOW_HEIGHT	The maximum height of the simulation window.
SIMULATION_FPS	The frame rate to simulate.
MAX_VELOCITY_X	The maximum possible x-axis velocity for particles.
MIN_VELOCITY_X	The minimum possible x-axis velocity for particles.
MAX_VELOCITY_Y	The maximum possible y-axis velocity for particles.
MIN_VELOCITY_Y	The minimum possible y-axis velocity for particles.
VELOCITY_CHANGE_RATE	The rate at which the velocity changes.
MAX_RADIUS	The maximum possible spawn-time particle radius.
MIN_RADIUS	The minimum possible spawn-time particle radius.
HEIGHT_RADIUS_GROW_MULTIPLIER	The particle radius growth rate as the particle rises.
BG_COLOUR	The background colour of the simulation window.
PARTICLE_COLOUR	The particle colour the simulation backscatter.
MAX_PARTICLES	The maximum possible particles in each frame.
CONSTANT_PARTICLE_GENERATION	Option to constantly spawn particles.
PARTICLE_RANDOMISE_VELOCITY_PROB	The probability of particle movement randomisation.

Table 2: Simulation parameter constants and their descriptions from the Bubble Backscatter Generator program.

Name	Description
id	The unique ID of the particle, generated by <code>uuid.uuid4()</code> .
x	The x-axis coordinate position of the particle.
y	The y-axis coordinate position of the particle.
radius	The radius of the particle.
velocity_x	The current x-axis velocity of the particle.
velocity_y	The current y-axis velocity of the particle.
target_velocity_x	The target future x-axis velocity of the particle.
target_velocity_y	The target future y-axis velocity of the particle.

Table 3: Fields and their descriptions from the Bubble class of the Bubble Backscatter Generator program.

Name	Description
<code>__init__()</code>	Initialises a new backscatter Bubble object, generating a unique id with <code>uuid.uuid4()</code> , a random x starting position, y starting position at the bottom of the screen, random <code>target_velocity_x</code> and <code>target_velocity_y</code> velocities which are set equal to the initial velocities, <code>velocity_x</code> and <code>velocity_y</code> .
<code>randomiseVelocities()</code>	Generates a random value for <code>target_velocity_y</code> and <code>target_velocity_x</code> , with the value between <code>MIN_VELOCITY_Y</code> , <code>MAX_VELOCITY_Y</code> , and <code>MIN_VELOCITY_X</code> , <code>MAX_VELOCITY_X</code> .
<code>move()</code>	Updates the particle's x and y positions based on its <code>velocity_x</code> and <code>velocity_y</code> and the simulation time since the last frame. Also updates the particle's velocities, based on the difference between the current velocity and the target velocity, with the <code>VELOCITY_CHANGE_RATE</code> multiplier.
<code>draw()</code>	Draws the particle based on its x and y positions, and <code>radius</code> , with the colour from the <code>PARTICLE_COLOUR</code> constant, using the Pygame library's <code>pygame.draw.circle()</code> function.

Table 4: Methods and their descriptions from the Bubble class of the Bubble Backscatter Generator program.

## A.2 Python Code

```

1 import pygame
2 import random
3 import uuid
4 from datetime import datetime
5 import csv
6 import os
7
8 WINDOW_WIDTH = 800           # Width of simulation window
9 WINDOW_HEIGHT = 600          # Height of simulation window
10 SIMULATION_FPS = 60         # Simulation frame rate
11
12 MAX_VELOCITY_X = 50         # Maximum possible x-axis velocity for particles
13 MIN_VELOCITY_X = -50        # Minimum possible x-axis velocity for particles
14 MAX_VELOCITY_Y = 200        # Maximum possible y-axis velocity for particles
15 MIN_VELOCITY_Y = 50         # Minimum possible y-axis velocity for particles
16 VELOCITY_CHANGE_RATE = 0.1  # Rate at which velocity changes
17
18 MAX_RADIUS = 6              # Maximum possible spawn-time particle radius
19 MIN_RADIUS = 2              # Minimum possible spawn-time particle radius
20 HEIGHT_RADIUS_GROW_MULTIPLIER = 0.05    # Grow multiplier as particle rises
21
22 BG_COLOUR = (0, 0, 0)      # Background colour (default is black)
23 PARTICLE_COLOUR = (255, 255, 255)  # Particle colour (default is white)
24
25 MAX_PARTICLES = 300        # Maximum particles on screen
26 CONSTANT_PARTICLE_GENERATION = True    # Whether to constantly maintain MAX_PARTICLES
27 PARTICLE_RANDOMISE_VELOCITY_PROB = 0.01 # Probability of particle movement randomisation
28
29 class Bubble:
30     """ A bubble-based backscatter particle. """
31     def __init__(self):
32         self.id = uuid.uuid4()                  # Initialise ID
33         self.x = random.randint(0, WINDOW_WIDTH) # Randomly initialise x-axis spawn

```

```

position
34     self.y = WINDOW_HEIGHT                         # Initialise y-axis spawn position to
bottom
35     self.radius = random.randint(MIN_RADIUS, MAX_RADIUS)    # Randomly initialise radius
36     self.randomiseVelocities()                      # Randomly initialise velocities
37     self.velocity_x = self.target_velocity_x      # Randomly initialise velocities
38     self.velocity_y = self.target_velocity_y      # Randomly initialise velocities
39
40 def randomiseVelocities(self):
41     """ Randomly update x and y-axis particle velocities. """
42     self.target_velocity_y = random.uniform(MIN_VELOCITY_Y, MAX_VELOCITY_Y) # Update
vertical velocity randomly
43     self.target_velocity_x = random.uniform(MIN_VELOCITY_X, MAX_VELOCITY_X) # Update
horizontal velocity randomly
44
45 def move(self, delta_t):
46     """ Update position and radius based on velocity and position. """
47     self.y -= self.velocity_y * delta_t           # Update vertical position
48     self.x += self.velocity_x * delta_t           # Update horizontal position
49
50     # Gradually adjust velocities towards target velocities
51     self.velocity_y += (self.target_velocity_y - self.velocity_y) * VELOCITY_CHANGE_RATE
52     self.velocity_x += (self.target_velocity_x - self.velocity_x) * VELOCITY_CHANGE_RATE
53
54     # As a bubble travels upwards, it must get bigger
55     height_factor = (WINDOW_HEIGHT - self.y) / WINDOW_HEIGHT                 # Calculate height
factor
56     self.radius += HEIGHT_RADIUS_GROW_MULTIPLIER * height_factor            # Grow radius based on
height factor and multiplier
57
58 def draw(self, screen):
59     """ Draw the bubble-based backscatter particle on screen. """
60     pygame.draw.circle(screen, PARTICLE_COLOUR, (int(self.x), int(self.y)), self.radius)
61
62 if __name__ == "__main__":
63     # Initialise pygame module
64     pygame.init()
65
66     # Initialise pygame window and set window title
67     screen = pygame.display.set_mode((WINDOW_WIDTH, WINDOW_HEIGHT))
68     pygame.display.set_caption("Bubble Simulation")
69
70     # Create clock object to track time
71     clock = pygame.time.Clock()
72
73     # Initialise runtime variables
74     running = True                  # Stores whether the simulation is running
75     delta_t = 0                     # Stores the time in seconds since the last frame
76     bubbles = []                   # Array of bubbles which are on the screen
77     bubble_positions = {}          # Dictionary storing individual bubble positions in each frame
78
79     # Log timestamp when simulation starts
80     simulation_start_ts = datetime.now()
81
82     # Generate export filename
83     export_filename_generic = "export_" + simulation_start_ts.strftime("%m-%d-%Y-%H-%M-%S")
84
85     # Create folder for the frame image export
86     if not os.path.exists(export_filename_generic):
87         os.makedirs(export_filename_generic)
88
89     if not CONSTANT_PARTICLE_GENERATION:

```

```

90     while len(bubbles) < MAX_PARTICLES:
91         bubbles.append(Bubble())
92
93     # Initialise frame counter
94     frame_num = 0
95
96     while running:
97         # Fill window with the background colour
98         screen.fill(BG_COLOUR)
99
100        # Generate new bubbles randomly and constantly
101        if CONSTANT_PARTICLE_GENERATION:
102            while len(bubbles) < MAX_PARTICLES:
103                bubbles.append(Bubble())
104
105        # Log bubble positions and radius in this frame
106        for bubble in bubbles:
107            # If this bubble has not been previously tracked...
108            if bubble.id not in bubble_positions:
109                # ... Initialise an empty list to track in subsequent frames
110                bubble_positions[bubble.id] = {'positions': [], 'radius': []}
111
112            # Append the list with the bubble's position in this frame
113            bubble_positions[bubble.id]['positions'].append((bubble.x, bubble.y))
114            bubble_positions[bubble.id]['radius'].append(bubble.radius)
115
116        # Update and draw bubbles
117        for bubble in bubbles:
118            bubble.move(delta_t)
119            bubble.draw(screen)
120
121        # Randomly update bubble velocities
122        if random.random() < PARTICLE_RANDOMISE_VELOCITY_PROB:
123            for bubble in bubbles:
124                bubble.randomiseVelocities()
125
126        # Remove bubbles that are out of the screen
127        bubbles = [bubble for bubble in bubbles if bubble.y > -bubble.radius]
128
129        # Event handling
130        for event in pygame.event.get():
131            if event.type == pygame.QUIT:
132                running = False
133
134        # Update the contents of the full display
135        pygame.display.flip()
136
137        # Export frame as png
138        filename = os.path.join(export_filename_generic, f"{frame_num}.png")
139        pygame.image.save(screen, filename)
140
141        # Limit FPS and store time in seconds since last frame
142        delta_t = clock.tick(SIMULATION_FPS) / 1000
143
144        # Increment frame number counter
145        frame_num += 1
146
147        # Generate CSV dataset of simulated bubble positions
148        export_filename_csv = export_filename_generic + ".csv"
149
150        with open(export_filename_csv, mode='w', newline='') as file:
151            writer = csv.writer(file)
152            # Write header

```

```

152     writer.writerow(['Bubble ID', 'Frame #', 'X Position', 'Y Position', 'Radius'])
153     # Write bubble positions and radius
154     for bubble_id, data in bubble_positions.items():
155         for frame, (x, y) in enumerate(data['positions']):
156             radius = data['radius'][frame]
157             writer.writerow([bubble_id, frame, x, y, radius])
158
159     pygame.quit()

```

Listing 1: The Python code for the Bubble Backscatter Simulator, commit version: 34b9a82 from [27].

## Appendix B Lossless Video Recorder

### B.1 Description of Class Fields & Methods

Name	Description
REC_FPS	The recording frame rate.
REC_WIDTH	The horizontal resolution of recording.
REC_HEIGHT	The vertical resolution of recording.
FB_WIDTH	The horizontal resolution of the Framebuffer.
FB_HEIGHT	The vertical resolution of the Framebuffer.
FB_DEPTH	The bit depth of the Framebuffer.

Table 5: Software configuration constants and their descriptions from the Lossless Raspberry Pi Camera Recorder program.

#### B.1.1 The ‘ProjectorManager’ Module

Name	Description
width	The horizontal resolution of the Framebuffer device, same as FB_WIDTH.
height	The vertical resolution of the Framebuffer device, same as FB_HEIGHT.
height	The Framebuffer bit depth, same as FB_DEPTH.
status	Stores <code>True</code> if the projector light is ‘on’, <code>False</code> if ‘off’.

Table 6: Fields and their descriptions from the Projector class of the ‘ProjectorManager’ module from the Lossless Raspberry Pi Camera Recorder program.

Name	Description
<code>__init__()</code>	Initialises a new <code>Projector</code> object, populating the <code>Framebuffer</code> fields for <code>FB_WIDTH</code> , <code>FB_HEIGHT</code> , and <code>FB_DEPTH</code> . Initialising the bitmaps for light ‘on’ and ‘off’, and setting the light status to ‘off’.
<code>getStatus()</code>	A simple ‘getter’ function for the <code>status</code> class field.
<code>on()</code>	Writes the ‘on’ bitmap to the <code>Framebuffer</code> memory location, thus turning on the projector light source.
<code>off()</code>	Writes the ‘off’ bitmap to the <code>Framebuffer</code> memory location, thus turning off the projector light source.
<code>toggle()</code>	Writes the ‘on’ bitmap to the <code>Framebuffer</code> memory location if the <code>status</code> stores ‘off’, and vice-versa, thus toggling on the projector light source.

Table 7: Methods and their descriptions from the `Projector` class of the ‘ProjectorManager’ module from the Lossless Raspberry Pi Camera Recorder program.

### B.1.2 The ‘CameraManager’ Module

Name	Description
<code>picam2</code>	Stores the initialised <code>Picamera2</code> instance.
<code>recording</code>	Stores <code>True</code> if the recording is in progress, otherwise stores <code>False</code> .
<code>recording_filename</code>	Stores the filename which the recorded file will be saved as.
<code>recording_start_ts</code>	Stores the timestamp of when the recording was started.
<code>recording_end_ts</code>	Stores the timestamp of when the recording was stopped.

Table 8: Fields and their descriptions from the `Camera` class of the ‘CameraManager’ module from the Lossless Raspberry Pi Camera Recorder program.

Name	Description
<code>__init__()</code>	Initialises and configures the <code>Picamera2</code> instance by setting the recording resolution from <code>REC_WIDTH</code> and <code>REC_HEIGHT</code> , the frame rate from <code>REC_RATE</code> , capture stream as the ‘main’ output stream, and an ISP output format as ‘BGR888’, and finally starts the RPi Camera module.
<code>getStatus()</code>	A simple ‘getter’ function for the <code>recording</code> class field.
<code>captureFrame()</code>	Retrieves and returns the camera’s sensor output array.
<code>startRecording()</code>	Sets the <code>recording</code> class field to <code>True</code> , then initialises a memory buffer, logging the timestamp for <code>recording_start_ts</code> before finally initialising the ‘Null’ encoder and starting the recording.
<code>stopRecording()</code>	Sets the <code>recording</code> class field to <code>False</code> , then stops the ‘Picamera2’ recording, before applying the lossless FFV1 encoding to the footage bitstream, then finally writing to a file and closing the memory buffer.
<code>toggleRecording()</code>	Starts a recording if not already recording, and vice-versa, thus toggling the Pi Camera recording.
<code>shutdown()</code>	Stops recording if there is one in progress before finally sending a graceful shutdown signal to the ‘Picamera2’ module to stop and disconnect the Pi Camera.

Table 9: Methods and their descriptions from the `Camera` class of the ‘CameraManager’ module from the Lossless Raspberry Pi Camera Recorder program.

### B.1.3 The ‘PreviewManager’ Module

Name	Description
<code>__init__()</code>	Initialises a new OpenCV-based GUI window.
<code>getKeypress()</code>	Retrieves a keypress using the OpenCV GUI functions.
<code>shutdown()</code>	Destroys the OpenCV GUI window.
<code>showFrame()</code>	Renders the image frame on the GUI window and overlays the status variable text using OpenCV.

Table 10: Methods and their descriptions from the Preview class of the ‘PreviewManager’ module from the Lossless Raspberry Pi Camera Recorder program.

## B.2 Python Code

### B.2.1 Entry Point: ‘app.py’

```

1 """ Records video from a Raspberry Pi Camera. """
2
3 from ProjectorManager import Projector
4 from CameraManager import Camera
5 from PreviewManager import Preview
6
7 # Recording parameters
8 REC_FPS = 30          # Max available framerate is 60 FPS
9 REC_WIDTH = 728        # Set to half of full sensor width
10 REC_HEIGHT = 544       # Set to half of full sensor height
11
12 # Framebuffer parameters
13 FB_WIDTH = 1920
14 FB_HEIGHT = 1080
15 FB_DEPTH = 16
16
17 if __name__ == "__main__":
18     # Create preview window instance
19     preview = Preview()
20
21     # Initialise framebuffer - reset fb with light source off
22     light = Projector(FB_WIDTH, FB_HEIGHT, FB_DEPTH, False)
23
24     # Initialise Pi camera
25     camera = Camera(REC_WIDTH, REC_HEIGHT, REC_FPS)
26
27     # This is the main runtime loop
28     while True:
29         # Retrieve a frame from the Pi camera for the preview window
30         preview.showFrame(
31             camera.captureFrame(),
32             camera.getStatus(),
33             light.getStatus()
34         )
35
36         # Read key press
37         keypress = preview.getKeypress()
38
39         # Toggle light when 'l' key is pressed
40         if keypress == ord('l'):
41             light.toggle()
42

```

```

43
44     # Toggle recording when 'r' key is pressed
45     if keypress == ord('r'):
46         camera.toggleRecording()
47
48
49     # Exit program when 'e' key is pressed
50     if keypress == ord('e'):
51         # Send shutdown request to camera instance
52         camera.shutdown()
53
54         # When exiting, reset framebuffer with zero array
55         light.off()
56
57         # Send shutdown request to preview instance
58         preview.shutdown()
59
60         # Exit
61         break
62
63     # Exit from the script
64     exit()

```

Listing 2: The Python code for the ‘app.py’ entry point to the Lossless Raspberry Pi Camera Recorder, commit version: 30efb5a from [28].

### B.2.2 ProjectorManger: ‘ProjectorManager.py’

```

1 import numpy as np
2
3 class Projector:
4     """
5     A simple object which controls the framebuffer to drive a HDMI-interfaced light source.
6     """
7
8     def __init__(self, width, height, depth, status):
9         self.width = width
10        self.height = height
11        self.depth = depth
12        self.status = status
13
14        # Initialise framebuffer outputs
15        self.light_off_output = np.full(
16            (self.height, self.width), # fill into array of this size
17            0,                      # fill array with this value (black/off = 0)
18            dtype=np.uint16
19        ).reshape(-1)           # flatten to 1d array for writing to framebuffer
20
21        self.light_on_output = np.full(
22            (self.height, self.width), # fill into array of this size
23            (2 ** self.depth - 1),   # Maximum value for given colour depth (white)
24            dtype=np.uint16
25        ).reshape(-1)           # flatten to 1d array for writing to framebuffer
26
27        # Initialise the light to the given status
28        if self.status:
29            self.on()
30        else:
31            self.off()
32
33    def getStatus(self):

```

```

34     """ Return whether or not light is on. """
35     return self.status
36
37     def on(self):
38         """ Turn on the light. """
39         try:
40             with open('/dev/fb0', 'wb') as buf:
41                 buf.write(self.light_on_output.tobytes())
42                 self.status = True
43         except Exception as e:
44             print("Error: couldn't turn on FB light:", e)
45
46     def off(self):
47         """ Turn off the light. """
48         try:
49             with open('/dev/fb0', 'wb') as buf:
50                 buf.write(self.light_off_output.tobytes())
51                 self.status = False
52         except Exception as e:
53             print("Error: couldn't turn off FB light:", e)
54
55     def toggle(self):
56         """ Toggle the light. """
57         # Turn off if already on
58         if self.status:
59             self.off()
60         # Turn on light if already off
61         else:
62             self.on()

```

Listing 3: The Python code for ‘ProjectorManager.py’ in the Lossless Raspberry Pi Camera Recorder, commit version: 30efb5a from [28].

### B.2.3 CameraManager: ‘CameraManager.py’

```

1 import io
2 import os
3 import subprocess
4 from picamera2 import Picamera2
5 from picamera2.encoders import Encoder
6 from picamera2.outputs import FileOutput
7 from datetime import datetime
8
9 class Camera:
10     """
11     A wrapper to interface with the Pi camera with implementations to capture a frame for
12     preview, start and stop a recording.
13     This interface will record and capture the 'main' stream which is set up as the processed
14     'raw' feed.
15     """
16
17     def __init__(self, width, height, rate):
18
19         # Initialise Pi camera instance
20         self.picam2 = Picamera2()
21
22         # Pi camera configuration:
23         self.picam2.video_configuration.size = (width, height)      # Capture video at defined
24         resolution/size
25         self.picam2.video_configuration.controls.FrameRate = rate    # Capture video at defined
26         framerate

```

```

23         self.picam2.video_configuration.encode = 'main'           # Use 'main' stream for
encoder
24         self.picam2.video_configuration.format = 'BGR888'        # Use this format for
OpenCV compatibility
25         self.picam2.video_configuration.align()                  # Align stream size (THIS
CHANGES THE RES SLIGHTLY!)
26
27         # Apply the configuration to the Pi camera
28         self.picam2.configure("video")
29
30         # Print camera configurations to confirm correct set up
31         print(self.picam2.camera_configuration()['sensor'])
32         print(self.picam2.camera_configuration()['main'])
33         print(self.picam2.camera_configuration()['controls'])
34
35         # Start the Pi camera
36         self.picam2.start()
37
38         # Variable to store whether recording is in progress
39         self.recording = False
40
41         # Initialise variable to store recording filename and timestamps
42         self.recording_filename = ""
43         self.recording_start_ts = None
44         self.recording_stop_ts = None
45
46     def getStatus(self):
47         """ Return whether or not recording is in progress. """
48         return self.recording
49
50     def captureFrame(self):
51         """ Capture a frame from the camera for constructing a frame-by-frame preview feed.
"""
52         return self.picam2.capture_array("main")
53
54     def startRecording(self):
55         """ Start recording from the Pi camera to the memory buffer. """
56         # Only start is not already recording
57         if not self.recording:
58             # Set recording status
59             self.recording = True
60
61             # Initialise a memory buffer to store video recording
62             self.recording_membuff = io.BytesIO()
63             self.recording_output = FileOutputStream(self.recording_membuff)
64
65             # Generate starting timestamp
66             self.recording_start_ts = datetime.now()
67             self.recording_start_ts_str = self.recording_start_ts.strftime("%m-%d-%Y-%H-%M-%S"
)
68
69             # Generate filename
70             self.recording_filename = "recording_" + self.recording_start_ts_str
71
72             # Reset recording end timestamp
73             self.recording_stop_ts = None
74
75             # Initialise a 'null' encoder to record without any encoding
76             self.recording_encoder = Encoder()
77
78             # Start the recording
79             self.picam2.start_recording(

```

```

80             encoder=self.recording_encoder, # Null encoder for 'raw' footage
81             output=self.recording_output     # Record directly to memory
82         )
83
84         # Log to console
85         print("Started recording:", self.recording_filename)
86     else:
87         # Log to console if user requests recording start when already in progress
88         print("Cannot start recording, existing recording is in progress!")
89
90     def stopRecording(self):
91         """ Stop recording, unload from memory buffer to disk and convert to MKV with the
92             lossless FFV1 codec. """
93         # Only stop recording if already in progress
94         if self.recording:
95             # Stop the recording
96             self.picam2.stop_recording()
97
98             # stop_recording() entirely stops the Pi camera with stop()
99             self.picam2.start()
100
101            # Generate stopped timestamp
102            self.recording_stop_ts = datetime.now()
103            self.recording_stop_ts_str = self.recording_stop_ts.strftime("%m-%d-%Y-%H-%M-%S")
104
105            # Log to console
106            print("Stopped recording:")
107            + self.recording_filename
108            + " (Stopped at: "
109            + self.recording_stop_ts_str
110            + ")"
111        )
112        print("Please wait, unloading recording from memory buffer...")
113
114        # Save to file
115        with open(self.recording_filename, "xb") as file:
116            file.write(self.recording_membuff.getbuffer())
117
118        # Reset recording start timestamp
119        self.recording_start_ts = None
120
121        # Close recording memory buffer to discard data and clear RAM space
122        self.recording_membuff.close()
123
124        # Generate encoded recording filename
125        self.recording_filename_mkv = self.recording_filename + ".mkv"
126
127        # Log to console
128        print("Please wait, encoding raw recording to lossless mkv...: " + self.
129        recording_filename_mkv)
130
131        # Get the aligned resolution of the recording
132        (aligned_width, aligned_height) = self.picam2.camera_configuration()['main']['size']
133    ]
134
135    # FFmpeg command to convert video from BGR888 to MKV (lossless FFV1 codec)
136    ffmpeg_command = [
137        'ffmpeg',                                     # call FFmpeg
138        '-f', 'rawvideo',                            # force raw data type
139        '-s', f'{aligned_width}x{aligned_height}',   # width and height
140        '-pix_fmt', 'bgr24',                          # set BGR888 format
141        '-i', self.recording_filename,                # filename of raw file

```

```

139         '-c:v', 'ffv1',
140         '-y',
141         '-loglevel', 'error',
142         '-stats',
143         self.recording_filename_mkv
144     ]
145
146     # Run FFmpeg command as a subprocess
147     subprocess.run(ffmpeg_command)
148
149     # Delete raw file
150     os.remove(self.recording_filename)
151
152     # Log to console
153     print("Write complete, it is safe to exit or record again: " + self.
154 recording_filename_mkv)
155
156     # Set the recording status to false to allow program exiting
157     self.recording = False
158 else:
159     # If not already recording, log error to console
160     print("Cannot stop recording, program is currently not recording anything!")
161
162 def toggleRecording(self):
163     """ Toggle the Pi camera recording. """
164     # Turn off if already on
165     if self.recording:
166         self.stopRecording()
167     # Turn on light if already off
168     else:
169         self.startRecording()
170
171 def shutdown(self):
172     """ Gracefully stop the Pi camera instance. """
173     # If recording in progress, stop it
174     if self.recording:
175         print("Exit request received while recording - recording will be stopped.")
176         self.stopRecording()
177
178     # Stop the Pi camera instance.
179     self.picam2.stop()
180
181     # Log to console
182     print("Camera instance has been gracefully stopped.")

```

Listing 4: The Python code for ‘CameraManager.py’ in the Lossless Raspberry Pi Camera Recorder, commit version: 30efb5a from [28].

#### B.2.4 PreviewManager: ‘PreviewManager.py’

```

1 import cv2 as cv
2
3 class Preview:
4     """ Preview window which renders frame-by-frame to an OpenCV window. """
5
6     def __init__(self):
7         cv.namedWindow("Pi Camera Feed")
8
9     def getKeypress(self):
10        """ Waits 1ms for a keypress and returns it. """
11        return cv.waitKey(1)

```

```

12
13     def shutdown(self):
14         """ Destroys all OpenCV windows for a clean exit. """
15         cv.destroyAllWindows()
16
17     def showFrame(self, frame, recording, light):
18         """ Updates the window with the new frame, adds status text overlays. """
19
20         # Generate a text-based status for the light source
21         match light:
22             case True:
23                 light_status = "LON"
24             case False:
25                 light_status = "LOFF"
26
27         # Generate a text-based status for recording
28         match recording:
29             case True:
30                 recording_status = "REC"
31             case False:
32                 recording_status = ""
33
34         # Add the two status text together
35         overlay_text = light_status + "    " + recording_status
36
37         # Overlay the text to the frame
38         frame_overlay = cv.putText(
39             img=frame,
40             text=overlay_text,
41             org=(10, 25),
42             fontFace=cv.FONT_HERSHEY_SIMPLEX,
43             fontScale=0.75,
44             color=(255, 0, 0),
45             thickness=1,
46             lineType=cv.LINE_AA
47         )
48
49         # Render the frame
50         cv.imshow("Pi Camera Feed", frame)

```

Listing 5: The Python code for ‘PreviewManager.py’ in the Lossless Raspberry Pi Camera Recorder, commit version: 30efb5a from [28].

# Appendix C Standard Backscatter Cancellation System

## C.1 Description of Class Fields & Methods

Name	Description
VIDEO_CAPTURE_SOURCE	Set with directory path to input a list of individual frames, file path to input a video file, or integer '0' to use the RPi Camera input.
VIDEO_CAPTURE_WIDTH	The horizontal resolution of recording.
VIDEO_CAPTURE_HEIGHT	The vertical resolution of recording.
VIDEO_CAPTURE_CROP_HEIGHT	The vertical resolution to crop for the region of interest.
VIDEO_CAPTURE_CROP_WIDTH	The horizontal resolution to crop for the region of interest.
BS_MANAGER_DEBUG_WINDOWS	Whether to render debug windows showing the post-processed frame after intermediate processing stages.

Table 11: Software configuration constants and their descriptions from the Backscatter Cancellation program.

## C.2 Python Code

### C.2.1 Entry Point: ‘app.py’

```
1 from datetime import datetime
2 import numpy as np
3 import pandas as pd
4 import psutil
5 import cv2
6 import os
7
8 from CaptureManager import FrameStream, VideoStream, PicameraStream
9 from WindowManager import Window
10 from BSManager import Detector
11 from TimeManager import Timer
12
13 OS_NICE_PRIORITY_LEVEL = 0
14 X11_XAUTHORITY_PATH = '/home/sid/.Xauthority'
15
16 ### VIDEO CAPTURE SOURCE
17 # Input a directory path to feed in a series of frame images,
18 # named as an integer denoting the frame number and must be
19 # in PNG format.
20 #
21 # Input a file path to feed in a video file.
22 #
23 # Input integer '0' to use Picamera2 capture_array() to capture
24 # feed frame-by-frame.
25 # VIDEO_CAPTURE_SOURCE = 0
26 # VIDEO_CAPTURE_SOURCE = "./import_04-08-2024-14-35-53/"
27 # VIDEO_CAPTURE_SOURCE = "../Tank Recordings/recording_04-22-2024-14-36-49.mkv"
28 VIDEO_CAPTURE_SOURCE = "../Tank Recordings/recording_04-22-2024-14-16-08.mkv"
29
30 ### VIDEO CAPTURE PARAMETERS
31 # WIDTH & HEIGHT:
32 # These are the recording parameters which dictate capture
33 # resolution.
34 #
```

```

35 #      When wanting to use the frame-by-frame output from the
36 #      bubble-backscatter-simulation program, set these values
37 #      to the same as the ones input to that program (800x600).
38 #
39 #      When wanting to use a pre-recorded video source, these
40 #      values will be updated to match the correct resolution
41 #      of the video. Ensure they are similar to avoid confusion.
42 #
43 #      Want wanting to use the Pi Camera feed, these values will
44 #      be used when configuring the camera resolution parameters,
45 #      however, the camera will align the stream size to force
46 #      optimal alignment, so the resolution may be slightly
47 #      different.
48 #
49 #      CROP WIDTH & HEIGHT:
50 #          Apply a crop to isolate the region of interest, mitigating
51 #          the submersible housing offsets
52 VIDEO_CAPTURE_WIDTH = 800
53 VIDEO_CAPTURE_HEIGHT = 600
54 VIDEO_CAPTURE_CROP_HEIGHT = (0, 320)
55 VIDEO_CAPTURE_CROP_WIDTH = (430, 700)
56
57 ### PREVIEW WINDOW NAMES
58 #      These constants store the names for each GUI window
59 INPUT_PREVIEW_WINDOW_NAME = "Input Feed"
60 SEGMENTATION_PREVIEW_WINDOW_NAME = "Backscatter Segmentation"
61 PROJECTOR_PREVIEW_WINDOW_NAME = "Projected Light Pattern"
62
63 ### BSMANAGER PARAMETERS
64 #      CANNY_THRESHOLD_SIGMA: Threshold for the zero-parameter
65 #      Canny implementation - (https://pyimagesearch.com/2015/04/06/zero-parameter-automatic-canny-edge-detection-with-python-and-opencv/)
66 #
67 #      BS_MANAGER_DEBUG_WINDOWS: Whether or not to display the intermediate
68 #          step visualisation.
69 CANNY_THRESHOLD_SIGMA = 0
70 BS_MANAGER_HISTOGRAM_EQUALISATION = True
71 BS_MANAGER_DEBUG_WINDOWS = True
72 BINARY_THRESHOLD_THRESH = (200, 255)
73
74
75 if __name__ == "__main__":
76     # Required to run X11 forwarding as sudo
77     os.environ['XAUTHORITY'] = X11_XAUTHORITY_PATH
78
79     # Set the OS priority level
80     p = psutil.Process(os.getpid())
81     print("Current OS priority: ", p.nice())
82     p.nice(OS_NICE_PRIORITY_LEVEL)
83     print("New OS priority: ", p.nice())
84
85     # Generate CSV export filename
86     export_filename_csv = "export_" + datetime.now().strftime("%m-%d-%Y-%H-%M-%S") + ".csv"
87
88     # Initialise capture stream
89     match VIDEO_CAPTURE_SOURCE:
90         # If int 0 then set up Pi camera stream
91         case 0:
92             # Initialise FrameStream
93             stream = PicameraStream(VIDEO_CAPTURE_WIDTH, VIDEO_CAPTURE_HEIGHT)
94         # If not int 0 then check if it is a valid path
95         case _:

```

```

96     # If the path is a directory, then FrameStream
97     if os.path.isdir(VIDEO_CAPTURE_SOURCE):
98         # Initialise FrameStream
99         stream = FrameStream(VIDEO_CAPTURE_SOURCE)
100    # If the path is a file, then VideoStream
101    elif os.path.isfile(VIDEO_CAPTURE_SOURCE):
102        # Initialise VideoStream
103        stream = VideoStream(
104            source=VIDEO_CAPTURE_SOURCE,
105            crop_w=VIDEO_CAPTURE_CROP_WIDTH,
106            crop_h=VIDEO_CAPTURE_CROP_HEIGHT,
107            loop=True
108        )
109
110    # Initialise window to display the input
111    input_feed_window = Window(INPUT_PREVIEW_WINDOW_NAME)
112
113    # Initialise window to display the particle segmentation
114    segmentation_window = Window(SEGMENTATION_PREVIEW_WINDOW_NAME)
115
116    # Initialise window to display the projector output
117    projector_window = Window(PROJECTOR_PREVIEW_WINDOW_NAME)
118
119    # Initialise the backscatter detector
120    detector = Detector(
121        canny_threshold=CANNY_THRESHOLD_SIGMA,
122        thresh_threshold=BINARY_THRESHOLD_THRESH,
123        debug_windows=BS_MANAGER_DEBUG_WINDOWS
124    )
125
126    # Initialise variable to track frame processing duratione (sec)
127    total_frame_processing_time = 0
128
129    # Initialise a Pandas DataFrame to log real-time metrics
130    rt_metrics_df = pd.DataFrame(
131        columns=[
132            'Capture Duration (s)',
133            'Greyscale Conversion Duration (s)',
134            'Gaussian Blur Duration (s)',
135            'Histogram Equalisation Duration (s)',
136            'Binary Thresholdind Duration (s)',
137            'Canny Algorithm Duration (s)',
138            'CV2 findContours() Duration (s)',
139            'CV2 minEnclosingCircle() Duration (s)',
140            'Number of MECs on screen',
141            'Total frame processing time (s)'
142        ]
143    )
144
145    while True:
146        # Start timer to calculate capture duration
147        timer = Timer()
148
149        # Read a frame
150        frame = stream.read()
151
152        # Stop timer
153        capture_duration = timer.stop()
154
155        # Detect keypress
156        keypress = cv2.waitKey(1)
157

```

```

158     # Exit if the 'e' key is pressed
159     if keypress == ord('e'):
160         break
161
162     # While there are frames...
163     if frame is not None:
164         # Update the input visualisation window
165         input_feed_window.update(frame)
166
167         # Start timer for the total frame processing duration
168         timer = Timer()
169
170         # Detect the particles and retrieve real-time metrics
171         particles, metrics = detector.detect(frame)
172
173         # Stop the total frame processing duration timer
174         frame_processing_time = timer.stop()
175
176         # Create a black mask for the segmentation preview
177         particle_mask = np.copy(frame)
178
179         # Draw white circles on the black mask for each MEC
180         for particle in particles:
181             cv2.circle(
182                 particle_mask,
183                 particle[0],
184                 particle[1],
185                 (0, 0, 255),
186                 1
187             )
188
189         # Display the black mask with white circles
190         segmentation_window.update(particle_mask)
191
192         # Create a white mask for the projector preview
193         projector_mask = np.ones_like(frame) * 255
194
195         # Draw black circles on the white mask for each MEC
196         for particle in particles:
197             cv2.circle(
198                 projector_mask,
199                 particle[0],
200                 particle[1],
201                 (0, 0, 0),
202                 -1
203             )
204
205         # Display the white mask with black circles
206         projector_window.update(projector_mask)
207
208         # Prepend the capture time to the metrics
209         metrics = [capture_duration] + metrics
210
211         # Append metrics list to end of dataframe
212         rt_metrics_df.loc[len(rt_metrics_df)] = metrics
213     else:
214         # break out of the while loop when there are no more frames
215         break
216
217     # Export dataframe as CSV
218     rt_metrics_df.to_csv(
219         path_or_buf=export_filename_csv,

```

```

220     encoding='utf-8'
221 )
222
223 cv2.destroyAllWindows()

```

Listing 6: The Python code for the ‘app.py’ entry point to the Backscatter Cancellation System program, commit version: 46b962a from [29].

### C.2.2 CaptureManager: ‘CaptureManager.py’

```

1 import os
2 import cv2
3 import logging
4 from queue import Queue
5 from threading import Thread
6 from natsort import natsorted
7
8
9 class PicameraStream:
10     """ Streams from a Picamera frame-by-frame. """
11
12     def __init__(self, width, height):
13         # Try to import and use Picamera2 library - this will fail on non-RPi platforms
14         try:
15             # Pylint - Ignore the missing import error on non RPi platforms
16             from picamera2 import Picamera2      # type: ignore
17
18             # Initialise Pi camera instance
19             self.picam2 = Picamera2()
20
21             # Pi camera configuration:
22             self.picam2.still_configuration.size = (width, height)      # Capture stills at
23             defined resolution/size
24             self.picam2.still_configuration.format = 'BGR888'          # Use this format for
25             OpenCV compatibility
26             self.picam2.still_configuration.align()                      # Align stream size (
27             THIS CHANGES THE RES SLIGHTLY!)
28
29             # Apply the configuration to the Pi camera
30             self.picam2.configure("video")
31
32             # Print camera configurations to confirm correct set up
33             logging.debug(self.picam2.camera_configuration()['sensor'])
34             logging.debug(self.picam2.camera_configuration()['main'])
35             logging.debug(self.picam2.camera_configuration()['controls'])
36
37             # Start the Pi camera
38             self.picam2.start()
39
40             # Return the aligned stream resolution
41             (aligned_width, aligned_height) = self.picam2.camera_configuration()['main']['size']
42         ]
43
44             return (aligned_width, aligned_height)
45
46     # If the Picamera2 module is not found, then the program is probably not running on a
47     # RPi
48     except ImportError:
49         logging.error("Picamera2 module not found. Make sure you are running this on a
50         Raspberry Pi.")
51         # No other exceptions should be encountered, if they are then log it
52         except Exception as e:

```

```

46         logging.error("Unforeseen error encountered: ", e)
47
48     def read(self):
49         """ Capture camera sensor array for constructing a frame-by-frame feed. """
50
51         success, frame = True, self.picam2.capture_array("main")
52         return success, frame
53
54     def exit(self):
55         """ Gracefully stop the Pi camera instance. """
56
57         # Stop the Pi camera instance.
58         self.picam2.stop()
59
60         # Log to console
61         logging.info("Camera instance has been gracefully stopped.")
62
63 class FrameStream:
64     """ Streams a video represented by a set of PNG images for each frame. """
65
66     def __init__(self, path):
67         # Initialise path to folder
68         self.path = path
69
70         # Initialise queue to store frames in memory
71         self.q = Queue()
72
73         # Populate queue with image frames
74         self._load_frames()
75
76     def _load_frames(self):
77         """ Internal method that populates the image frame queue. """
78
79         logging.debug("Beginning to populate frame queue...")
80
81         # Sort all of the frame files inside the folder
82         frames = natsorted(os.listdir(self.path))
83
84         # For each file in the sorted list of frame files...
85         for file in frames:
86             # Ensure that the file is a PNG
87             if file.endswith('.png'):
88                 # Extract the frame number from the filename
89                 frame_num = int(os.path.splitext(file)[0])
90                 # Generate the filepath
91                 frame_path = os.path.join(self.path, file)
92                 # Read in the file
93                 frame = cv2.imread(frame_path)
94                 # Store the file in the queue along with the frame number
95                 self.q.put(frame)
96
97             # Log status
98             logging.debug("Frame queue has been populated.")
99
100    def read(self):
101        """ Dequeues the next frame in the sequence. """
102
103        if not self.empty():
104            return self.q.get()
105        else:
106            return None
107

```

```

108     def empty(self):
109         """ Returns true if there are no more frames to stream. """
110
111         return self.q.empty()
112
113 class VideoStream:
114     """ Streams an input video file. """
115
116     def __init__(self, source, crop_w=None, crop_h=None, loop=False):
117         # initialise the OpenCV stream
118         self.capture = cv2.VideoCapture(source)
119         self.crop_w = crop_w
120         self.crop_h = crop_h
121         self.loop = loop
122
123         # check if capture is accessible
124         if not self.capture.isOpened():
125             logging.error("Cannot open video stream!")
126             raise Exception("Cannot open video stream!")
127
128         # calculate FPS and FPT of the capture
129         self.target_fps = self.capture.get(cv2.CAP_PROP_FPS)
130         self.target_fpt = (1 / self.target_fps) * 1000
131
132     def read(self):
133         _, frame = self.capture.read()
134         if frame is not None:
135             if (self.crop_w is not None) and (self.crop_h is not None):
136                 frame = frame[self.crop_h[0]:self.crop_h[1], self.crop_w[0]:self.crop_w[1]]
137             elif self.loop is True:
138                 self.capture.set(cv2.CAP_PROP_POS_FRAMES, 0)
139                 _, frame = self.capture.read()
140
141         return frame
142
143     def exit(self):
144         self.capture.release()
145
146 class t_VideoStream:
147     """ Streams an input video file using threading. """
148
149     def __init__(self, source, queueSize=4096):
150         # initialise the OpenCV stream
151         self.capture = cv2.VideoCapture(source)
152         # initialise parameter that stops video stream
153         self.stopped = False
154         # initialise the queue for pushing frames
155         self.queue = Queue(maxsize=queueSize)
156
157     def start(self):
158         # start a thread to read frames from stream
159         t = Thread(
160             target=self._update,
161             args=()
162         )
163         # allow thread to be killed when main app exits
164         t.daemon = True
165         # start the thread
166         t.start()
167         return self
168
169     def _update(self):
170         while True:

```

```

170         # stop reading if stream is stopped
171         if self.stopped:
172             return
173
174         # otherwise, keep reading and queuing until queue is full
175         if not self.queue.full():
176             # read the next frame from the file
177             success, frame = self.capture.read()
178
179             # check if we have reached the end of video stream
180             if not success:
181                 self.stop()
182             return
183
184         # push the frame to the queue
185         self.queue.put(frame)
186
187     def read(self):
188         # return a frame from the queue
189         return self.queue.get()
190
191     def stop(self):
192         # indicate that thread should be stopped
193         self.stopped = True
194         self.capture.release()
195
196     def empty(self):
197         # returns True if queue is empty
198         if self.queue.qsize():
199             return True
200         return False

```

Listing 7: The Python code for ‘CaptureManager.py’ in the Backscatter Cancellation System program, commit version: 1bf8131 from [29].

### C.2.3 BSManager: ‘BSManager.py’

```

1 import cv2
2 import numpy as np
3
4 from WindowManager import Window
5 from TimeManager import Timer
6
7 ### DEBUG WINDOW NAMES
8 # These constants store the names for each GUI window
9 GREYSCALE_DEBUG_WINDOW_NAME = "BSDetector Debug: Greyscale"
10 GAUSBLUR_DEBUG_WINDOW_NAME = "BSDetector Debug: Gaussian Blur"
11 CANNY_DEBUG_WINDOW_NAME = "BSDetector Debug: Canny Algorithm"
12 HISTEQU_DEBUG_WINDOW_NAME = "BSDetector Debug: Histogram Equalisation"
13 TRESHOLD_DEBUG_WINDOW_NAME = "BSDetector Debug: Binary Thresholding"
14
15 class Detector:
16     """ Backscatter detection logic (V1): (a) edges are detected using the Canny algorithm, (b)
17     ) the detected edges are segmented using a simple method - minimum enclosing circle (MEC),
18     (c) the centre coordinates and radius of the detected particles (MECs) are returned. """
19
20     def __init__(self, canny_threshold, thresh_threshold, debug_windows=True):
21         # Zero-parameter threshold for canny (https://pyimagesearch.com/2015/04/06/zero-parameter-automatic-canny-edge-detection-with-python-and-opencv/)
22         self.canny_threshold = canny_threshold

```

```

22     self.thresh_threshold = thresh_threshold
23
24     # Whether or not to print the intermediate step visualisation
25     self.debug_windows = debug_windows
26
27     # Initialise the debug windows if enabled
28     if self.debug_windows:
29         self.greyscale_window = Window(GREYSCALE_DEBUG_WINDOW_NAME)
30         self.gausblur_window = Window(GAUSBLUR_DEBUG_WINDOW_NAME)
31         self.canny_window = Window(CANNY_DEBUG_WINDOW_NAME)
32         # self.histequ_window = Window(HISTEQU_DEBUG_WINDOW_NAME)
33         self.threshold_window = Window(TRESHOLD_DEBUG_WINDOW_NAME)
34
35     def _greyscale(self, frame):
36         """ (Internal) Applies a greyscale filter to the frame. """
37
38         # Log start timestamp
39         timer = Timer()
40
41         # apply the single-channel conversion with greyscale filter
42         greyscale = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
43
44         # Calculate process duration
45         duration = timer.stop()
46
47         # output to the debug window if enabled
48         if self.debug_windows:
49             self.greyscale_window.update(greyscale)
50
51         # return the greyscaled frame
52         return greyscale, duration
53
54     def _threshold(self, frame):
55         """ (Internal) Applies a binary threshold to the frame. """
56
57         # Log start timestamp
58         timer = Timer()
59
60         # apply binary threshold
61         _, thresh = cv2.threshold(
62             frame,
63             self.thresh_threshold[0],
64             self.thresh_threshold[1],
65             cv2.THRESH_BINARY
66         )
67
68         # Calculate process duration
69         duration = timer.stop()
70
71         # output to the debug window if enabled
72         if self.debug_windows:
73             self.threshold_window.update(thresh)
74
75         # return the thresholded
76         return thresh, duration
77
78     def _histequ(self, frame):
79         """ (Internal) Applies a histogram equalisation to the frame. """
80
81         # Log start timestamp
82         timer = Timer()
83

```

```

84     # apply histogram equalisation
85     histequ = cv2.equalizeHist(frame)
86
87     # Calculate process duration
88     duration = timer.stop()
89
90     # output to the debug window if enabled
91     if self.debug_windows:
92         self.histequ_window.update(histequ)
93
94     # return the histogram equalised frame
95     return histequ, duration
96
97 def _gausblur(self, frame):
98     """ (Internal) Applies a Gaussian blur to the frame. """
99
100    # Log start timestamp
101    timer = Timer()
102
103    # apply the Gaussian blur
104    gausblur = cv2.GaussianBlur(frame, (5,5), 0)
105
106    # Calculate process duration
107    duration = timer.stop()
108
109    # output to the debug window if enabled
110    if self.debug_windows:
111        self.gausblur_window.update(gausblur)
112
113    # return the Gaussian blurred frame
114    return gausblur, duration
115
116 def _canny(self, frame):
117     """ (Internal) Applies the Canny algorithm to the frame. """
118
119     # Log start timestamp of Canny process
120     timer = Timer()
121
122     # compute the median single-channel pixel intensities
123     gaus_median = np.median(frame)
124
125     # compute threshold values for canny using single parameter Canny
126     lower_threshold = int(max(0, (1.0 - self.canny_threshold) * gaus_median))
127     upper_threshold = int(min(255, (1.0 + self.canny_threshold) * gaus_median))
128
129     # perform Canny edge detection
130     edges = cv2.Canny(
131         frame,
132         lower_threshold,
133         upper_threshold
134     )
135
136     # Calculate the Canny process duration
137     duration = timer.stop()
138
139     # output to the debug window if enabled
140     if self.debug_windows:
141         self.canny_window.update(edges)
142
143     return edges, duration
144
145 def _segmentation(self, edges):
146     """ (Internal) Finds contours using cv2.findContours() then calculates the minumum
147     enclosing circles using cv2.minEnclosingCircle(). """

```

```

145
146     # Log start timestamp of findContours()
147     timer_findContours = Timer()
148
149     # RETR_EXTERNAL only retrieves the extreme outer contours
150     # CHAIN_APPROX_SIMPLE compresses horizontal, vertical, and
151     # diagonal segments and leaves only their end points
152     contours, _ = cv2.findContours(
153         edges,
154         cv2.RETR_EXTERNAL,           # RetrievalModes
155         cv2.CHAIN_APPROX_SIMPLE    # ContourApproximationModes
156     )
157
158     # Calculate findContours process duration
159     findContours_duration = timer_findContours.stop()
160
161     # Log start timestamp of minEnclosingCircle()
162     timer_segmentContours = Timer()
163
164     # List to store the particle information (centre coords + radius)
165     particles = []
166
167     for contour in contours:
168         # Find the minimum enclosing circle for each contour
169         ((x, y), radius) = cv2.minEnclosingCircle(contour)
170         # Find the centre
171         centre = (int(x), int(y))
172         # Find the radius
173         radius = int(radius)
174         # Store the information
175         particles.append((centre, radius))
176
177     # Calculate findContours process duration
178     segmentContours_duration = timer_segmentContours.stop()
179
180     # return the segmented particle information
181     return particles, findContours_duration, segmentContours_duration
182
183 def detect(self, input):
184     """ Detects the backscatter particles. Returns the particle coordinates and radius,
185     and the real-time metrics. """
186
187     # single channel conversion using greyscaling
188     frame, greyscale_duration = self._greyscale(input)
189
190     # apply Gaussian blur noise reduction and smoothening, prep for Canny
191     frame, gausblur_duration = self._gausblur(frame)
192
193     # apply histogram equalisation to improve contrasts for better Canny
194     # frame, histequ_duration = self._histequ(frame)
195
196     # apply a binary threshold to isolate bright backscatter
197     frame, thresh_duration = self._threshold(frame)
198
199     # apply the Canny algorithm to the frame
200     edges, canny_duration = self._canny(frame)
201
202     # segment the particles
203     particles, findContours_duration, segmentContours_duration = self._segmentation(edges)
204
205     # compile metrics into a list
206     metrics = [

```

```

206     greyscale_duration,
207     gausblur_duration,
208     # histequ_duration,
209     0,
210     thresh_duration,
211     canny_duration,
212     findContours_duration,
213     segmentContours_duration
214 ]
215
216     # Get the total frame processing time, add it to metrics with total particles
217     metrics = metrics + [len(particles)] + [sum(metrics)]
218
219     # return detected particles
220     return particles, metrics

```

Listing 8: The Python code for ‘BSManager.py’ in the Backscatter Cancellation System program, commit version: 46b962a from [29].

#### C.2.4 TimeManager: ‘TimeManager.py’

```

1 import time
2
3 class Timer:
4     """ Time durations accurately using the performance counter. """
5
6     def __init__(self):
7         """ Start the timer on initialisation. """
8         self.start()
9
10    def start(self):
11        """ Starts the timer. """
12
13        self.start_timestamp = time.perf_counter()
14        self.end_timestamp = 0
15        self.duration = 0
16
17    def stop(self):
18        """ Stops the timer. """
19
20        self.end_timestamp = time.perf_counter()
21        self.duration = self.end_timestamp - self.start_timestamp
22
23    # return (self.start_timestamp, self.end_timestamp, self.duration)
24    return self.duration

```

Listing 9: The Python code for ‘TimeManager.py’ in the Backscatter Cancellation System program, commit version: 2367e84 from [29].

#### C.2.5 WindowManager: ‘WindowManager.py’

```

1 import cv2
2 import numpy as np
3
4 class Window:
5     """ A GUI window manager utilising OpenCV. """
6
7     def __init__(self, name, frame=None):
8         self.name = name
9
10        # created OpenCV named window

```

```

11     cv2.namedWindow(self.name)
12
13     # initialise window with input frame or test img
14     if frame:
15         cv2.imshow(self.name, frame)
16     else:
17         # create black image 800x600
18         test = np.zeros((600, 800, 3), dtype=np.uint8)
19
20         # Generate a rainbow gradient along the height (600)
21         for i in range(600):
22             hue = int(180 * i / 600) # Vary the hue from 0 to 180
23             colour = list(
24                 map(
25                     int,
26                     cv2.cvtColor(
27                         np.array(
28                             [[[hue, 255, 255]]],
29                             dtype=np.uint8
30                         ),
31                         cv2.COLOR_HSV2BGR
32                     )[0, 0]
33                 )
34             )
35             test[i, :, :] = colour
36
37         # display rainbow test image
38         cv2.imshow(self.name, test)
39
40     def update(self, frame):
41         """ Updates the window with the given frame. """
42         cv2.imshow(self.name, frame)
43
44     def destroy(self):
45         """ Gracefully terminates the window instance. """
46         cv2.destroyWindow(self.name)

```

Listing 10: The Python code for ‘ WindowManager.py ’ in the Backscatter Cancellation System program, commit version: 407ac01 from [29].

## Appendix D Multiprocessing Backscatter Cancellation System

### D.1 Python Code

#### D.1.1 Entry Point: ‘app2.py’

```

1 from multiprocessing import Process, Queue
2 from datetime import datetime
3 import pandas as pd
4 import numpy as np
5 import logging
6 import psutil
7 import cv2
8 import os
9
10 from CaptureManager import FrameStream, VideoStream, PicameraStream
11 from WindowManager import Window

```

```

12 from TimeManager import Timer
13
14 OS_NICE_PRIORITY_LEVEL = -20
15 X11_XAUTHORITY_PATH = '/home/sid/.Xauthority'
16
17 ### VIDEO CAPTURE SOURCE
18 # Input a directory path to feed in a series of frame images,
19 # named as an integer denoting the frame number and must be
20 # in PNG format.
21 #
22 # Input a file path to feed in a video file.
23 #
24 # Input integer '0' to use Picamera2 capture_array() to capture
25 # feed frame-by-frame.
26 VIDEO_CAPTURE_SOURCE = "./import_04-08-2024-14-35-53/"
27
28 ### VIDEO CAPTURE RESOLUTION
29 # These are the recording parameters which dictate capture
30 # resolution.
31 #
32 # When wanting to use the frame-by-frame output from the
33 # bubble-backscatter-simulation program, set these values
34 # to the same as the ones input to that program (800x600).
35 #
36 # When wanting to use a pre-recorded video source, these
37 # values will be updated to match the correct resolution
38 # of the video. Ensure they are similar to avoid confusion.
39 #
40 # Want wanting to use the Pi Camera feed, these values will
41 # be used when configuring the camera resolution parameters,
42 # however, the camera will align the stream size to force
43 # optimal alignment, so the resolution may be slightly
44 # different.
45 VIDEO_CAPTURE_WIDTH = 800
46 VIDEO_CAPTURE_HEIGHT = 600
47
48 ### PREVIEW/DEBUG WINDOW NAMES
49 # These constants store the names for each GUI window
50 INPUT_PREVIEW_WINDOW_NAME = "Input Feed"
51 PROJECTOR_PREVIEW_WINDOW_NAME = "Projected Light Pattern"
52 GREYSCALE_DEBUG_WINDOW_NAME = "BSDetector Debug: Greyscale"
53 GAUSBLUR_DEBUG_WINDOW_NAME = "BSDetector Debug: Gaussian Blur"
54 CANNY_DEBUG_WINDOW_NAME = "BSDetector Debug: Canny Algorithm"
55 CONTOUR_DEBUG_WINDOW_NAME = "BSDetector Debug: Detected Contours"
56 HISTEQU_DEBUG_WINDOW_NAME = "BSDetector Debug: Histogram Equalisation"
57
58 ### BSMANAGER PARAMETERS
59 # CANNY_THRESHOLD_SIGMA: Threshold for the zero-parameter
60 # Canny implementation - (https://pyimagesearch.com/2015/04/06/zero-parameter-automatic-canny-edge-detection-with-python-and-opencv/)
61 #
62 # BS_MANAGER_HISTOGRAM_EQUALISATION: Whether or not to carry
63 # out the histogram equalisation step.
64 #
65 # BS_MANAGER_DEBUG_WINDOWS: Whether or not to display the intermediate
66 # step visualisation.
67 CANNY_THRESHOLD_SIGMA = 0.33
68 BS_DEBUG_WINDOWS = False
69
70 LOGGING_FILEPATH = ""
71 LOGGING_FILEPATH_S1 = "export_log-s1.csv"
72 LOGGING_FILEPATH_S2 = "export_log-s2.csv"

```

```

73 LOGGING_FILEPATH_S3 = "export_log-s3.csv"
74 LOGGING_FILEPATH_S4 = "export_log-s4.csv"
75 LOGGING_FILEPATH_S5 = "export_log-s5.csv"
76 LOGGING_FILEPATH_S6 = "export_log-s6.csv"
77 LOGGING_FILEPATH_S7 = "export_log-s7.csv"
78 LOGGING_FILEPATH_S8 = "export_log-s8.csv"
79
80 PROCESS_QUEUE_QUIT_SIGNAL = "QUIT"
81 PROCESS_QUEUE_FQUIT_SIGNAL = "FQUIT"
82
83 class S1_Capture(Process):
84     """ Acquires and enqueues frames from the capture source. """
85
86     def __init__(self, output_q):
87         """
88             output_q: Queue to store captured frames and metrics.\n        """
89
90         super().__init__()
91         self.output_q = output_q
92         self.capture_duration = 0
93
94     def run(self,):
95         # Turn on logging
96         logging.basicConfig(
97             level=logging.DEBUG,
98             format='%(created).6f,%(levelname)s,S1_Capture,%(message)s',
99             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S1,
100            filemode='w'
101        )
102
103         # Log the start
104         logging.info("Process started with PID=%d", self.pid)
105
106         # Initialise capture stream
107         match VIDEO_CAPTURE_SOURCE:
108             # If int 0 then set up Pi camera stream
109             case 0:
110                 # Log
111                 logging.debug("Initialising PicameraStream")
112                 # Initialise FrameStream
113                 stream = PicameraStream(VIDEO_CAPTURE_WIDTH, VIDEO_CAPTURE_HEIGHT)
114                 # Log
115                 logging.debug("PicameraStream initialised")
116             # If not int 0 then check if it is a valid path
117             case _:
118                 # If the path is a directory, then FrameStream
119                 if os.path.isdir(VIDEO_CAPTURE_SOURCE):
120                     # Log
121                     logging.debug("Initialising FrameStream")
122                     # Initialise FrameStream
123                     stream = FrameStream(VIDEO_CAPTURE_SOURCE)
124                     # Log
125                     logging.debug("FrameStream initialised")
126             # If the path is a file, then VideoStream
127             elif os.path.isfile(VIDEO_CAPTURE_SOURCE):
128                 # Log
129                 logging.debug("Initialising VideoStream")
130                 # Initialise VideoStream
131                 stream = VideoStream(VIDEO_CAPTURE_SOURCE)
132                 # Log
133                 logging.debug("VideoStream initialised")
134

```

```

135     # Initialise window to display the input
136     input_feed_window = Window(INPUT_PREVIEW_WINDOW_NAME)
137
138     # Counter to track frames that have been read
139     frame_count = 0
140
141     # Exit status
142     exit = False
143
144     while not stream.empty():
145         # Log frame retrieval
146         logging.debug("Retrieving frame %d", frame_count)
147
148         # Track capture duration
149         timer = Timer()
150
151         # Capture the frame
152         frame, _ = stream.read()
153
154         # Stop the timer
155         duration = timer.stop()
156
157         # Log the retrieval
158         logging.debug("Retrieved frame %d", frame_count)
159
160         # Enqueue frame and metrics
161         self.output_q.put_nowait((frame, [duration]))
162
163         # Log the frame enqueue
164         logging.debug("Enqueued frame %d", frame_count)
165
166         # Update the preview window
167         keypress = input_feed_window.update(frame)
168
169         # Increment frame count
170         frame_count += 1
171
172         # Forcefully exit when the 'e' key is pressed
173         if keypress == ord('e'):
174             exit = True
175             break
176
177     # Handle event where capture has finished!
178     stream.exit()
179
180     if exit:
181         logging.info("User pressed exit key - sending quit signal")
182         self.output_q.put((PROCESS_QUEUE_FQUIT_SIGNAL, None), block=True, timeout=None)
183     else:
184         logging.info("No frames left to capture - sending quit signal")
185         self.output_q.put((PROCESS_QUEUE_QUIT_SIGNAL, None), block=True, timeout=None)
186
187 class S2_Greyscale(Process):
188     """ Process that applies a greyscale filter to an input. """
189
190     def __init__(self, input_q, output_q):
191         """
192             input_q: Queue that stores frames that require greyscaling prev. stage metrics.\n
193             output_q: Queue that stores greyscaled frames and metrics.
194         """
195
196         super().__init__()
197         self.input_q = input_q
198         self.output_q = output_q

```

```

197     def run(self,):
198         # Turn on logging
199         logging.basicConfig(
200             level=logging.DEBUG,
201             format='%(created).6f,%(levelname)s,S2_Greyscale,%(message)s',
202             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S2,
203             filemode='w'
204         )
205
206         # Log the start
207         logging.info("Process started with PID=%d", self.pid)
208
209         # Initialise frame counter to 0
210         frame_count = 0
211
212         # Initialise window to display debug preview
213         if BS_DEBUG_WINDOWS:
214             greyscale_window = Window(GREYSCALE_DEBUG_WINDOW_NAME)
215
216         while True:
217             # Log input backlog
218             # logging.debug("Input backlog of %d", self.input_q.qsize())
219
220             # Log frame retrieval
221             logging.debug("Retrieving frame %d", frame_count)
222             # Retrieve frame
223             frame, metrics = self.input_q.get(block=True)
224             # Log the retrieval
225             logging.debug("Retrieved frame %d", frame_count)
226
227             # Check if the frame is a quit signal (check whether it's a string first!)
228             if type(frame) == str:
229                 if frame == PROCESS_QUEUE_QUIT_SIGNAL or PROCESS_QUEUE_FQUIT_SIGNAL:
230                     # If it is then send quit signal to next stage and break
231                     logging.info("Quit signal received - I am now quitting")
232                     self.output_q.put((frame, None))
233                     break
234
235             # Track capture duration
236             timer = Timer()
237             # Apply the single-channel conversion with greyscale filter
238             greyscale = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
239             # Stop the timer
240             duration = timer.stop()
241
242             # Compile metrics
243             metrics.append(duration)
244
245             # Enqueue frame and metrics
246             self.output_q.put_nowait((greyscale, metrics))
247
248             # Log the frame enqueue
249             logging.debug("Processed and enqueued frame %d", frame_count)
250
251             # Update the preview window
252             if BS_DEBUG_WINDOWS:
253                 greyscale_window.update(greyscale)
254
255             # Increment frame count
256             frame_count += 1
257
258 class S3_HistogramEqualisation(Process):

```

```

259     """ Process that applies a histogram equalisation to an input. """
260
261     def __init__(self, input_q, output_q):
262         """
263             input_q: Queue that stores frames that require hist. equ. and prev. frame metrics\n
264             output_q: Queue that stores hist. equalised frames and metrics.\n
265         """
266         super().__init__()
267         self.input_q = input_q
268         self.output_q = output_q
269
270
271     def run(self,):
272         # Turn on logging
273         logging.basicConfig(
274             level=logging.DEBUG,
275             format='%(created).6f,%(levelname)s,S3_HistogramEqualisation,%(message)s',
276             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S3,
277             filemode='w'
278         )
279
280         # Log the start
281         logging.info("Process started with PID=%d", self.pid)
282
283         # Initialise frame counter to 0
284         frame_count = 0
285
286         # Initialise window to display debug preview
287         if BS_DEBUG_WINDOWS:
288             histequ_window = Window(HISTEQU_DEBUG_WINDOW_NAME)
289
290         while True:
291             # Log input backlog
292             # logging.debug("Input backlog of %d", self.input_q.qsize())
293
294             # Log frame retrieval
295             logging.debug("Retrieving frame %d", frame_count)
296             # Retrieve frame
297             frame, metrics = self.input_q.get(block=True)
298             # Log the retrieval
299             logging.debug("Retrieved frame %d", frame_count)
300
301             # Check if the frame is a quit signal (check whether it's a string first!)
302             if type(frame) == str:
303                 if frame == PROCESS_QUEUE_QUIT_SIGNAL or PROCESS_QUEUE_FQUIT_SIGNAL:
304                     # If it is then send quit signal to next stage and break
305                     logging.info("Quit signal received - I am now quitting")
306                     self.output_q.put((frame, None))
307                     break
308
309             # Track capture duration
310             timer = Timer()
311             # Apply the histogram equalisation
312             histequ = cv2.equalizeHist(frame)
313             # Stop the timer
314             duration = timer.stop()
315
316             # Compile metrics
317             metrics.append(duration)
318
319             # Enqueue frame and metrics
320             self.output_q.put_nowait((histequ, metrics))

```

```

321
322     # Log the frame enqueue
323     logging.debug("Processed and enqueueued frame %d", frame_count)
324
325     # Update the preview window
326     if BS_DEBUG_WINDOWS:
327         histequ_window.update(histequ)
328
329     # Increment frame count
330     frame_count += 1
331
332 class S4_GaussianBlur(Process):
333     """ Process that applies a Gaussian blur to an input. """
334
335     def __init__(self, input_q, output_q):
336         """
337             input_q: Queue that stores frames that require Gaus. blurring and prev. frame metrics\
338         n
339             output_q: Queue that stores Gaussian blurred frames and metrics.
340         """
341
342         super().__init__()
343         self.input_q = input_q
344         self.output_q = output_q
345
346     def run(self,):
347         # Turn on logging
348         logging.basicConfig(
349             level=logging.DEBUG,
350             format='%(created).6f,%(levelname)s,S4_GaussianBlur,%(message)s',
351             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S4,
352             filemode='w'
353         )
354
355         # Log the start
356         logging.info("Process started with PID=%d", self.pid)
357
358         # Initialise frame counter to 0
359         frame_count = 0
360
361         # Initialise window to display debug preview
362         if BS_DEBUG_WINDOWS:
363             gausblur_window = Window(GAUSBLUR_DEBUG_WINDOW_NAME)
364
365         while True:
366             # Log input backlog
367             # logging.debug("Input backlog of %d", self.input_q.qsize())
368
369             # Log frame retrieval
370             logging.debug("Retrieving frame %d", frame_count)
371             # Retrieve frame
372             frame, metrics = self.input_q.get(block=True)
373             # Log the retrieval
374             logging.debug("Retrieved frame %d", frame_count)
375
376             # Check if the frame is a quit signal (check whether it's a string first!)
377             if type(frame) == str:
378                 if frame == PROCESS_QUEUE_QUIT_SIGNAL or PROCESS_QUEUE_FQUIT_SIGNAL:
379                     # If it is then send quit signal to next stage and break
380                     logging.info("Quit signal received - I am now quitting")
381                     self.output_q.put((frame, None))
382                     break

```

```

382
383     # Track capture duration
384     timer = Timer()
385     # Apply the gaussian blur
386     gausblur = cv2.GaussianBlur(frame, (5,5), 0)
387     # Stop the timer
388     duration = timer.stop()
389
390     # Compile metrics
391     metrics.append(duration)
392
393     # Enqueue frame and metrics
394     self.output_q.put_nowait((gausblur, metrics))
395
396     # Log the frame enqueue
397     logging.debug("Processed and enqueued frame %d", frame_count)
398
399     # Update the preview window
400     if BS_DEBUG_WINDOWS:
401         gausblur_window.update(gausblur)
402
403     # Increment frame count
404     frame_count += 1
405
406 class S5_Canny(Process):
407     """ Process that applies the Canny algorithm to an input. """
408
409     def __init__(self, input_q, output_q):
410         """
411             input_q: Queue that stores frames to apply Canny with and prev. frame metrics\n
412             output_q: Queue that stores the frame, Canny output edges, and metrics.\n
413         """
414
415         super().__init__()
416         self.input_q = input_q
417         self.output_q = output_q
418
419     def run(self,):
420         # Turn on logging
421         logging.basicConfig(
422             level=logging.DEBUG,
423             format='%(created).6f,%(levelname)s,S5_Canny,%(message)s',
424             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S5,
425             filemode='w',
426         )
427
428         # Log the start
429         logging.info("Process started with PID=%d", self.pid)
430
431         # Initialise frame counter to 0
432         frame_count = 0
433
434         # Initialise window to display debug preview
435         if BS_DEBUG_WINDOWS:
436             canny_window = Window(CANNY_DEBUG_WINDOW_NAME)
437
438         while True:
439             # Log input backlog
440             # logging.debug("Input backlog of %d", self.input_q.qsize())
441
442             # Log frame retrieval
443             logging.debug("Retrieving frame %d", frame_count)

```

```

444     # Retrieve frame
445     frame, metrics = self.input_q.get(block=True)
446     # Log the retrieval
447     logging.debug("Retrieved frame %d", frame_count)
448
449     # Check if the frame is a quit signal (check whether it's a string first!)
450     if type(frame) == str:
451         if frame == PROCESS_QUEUE_QUIT_SIGNAL or PROCESS_QUEUE_FQUIT_SIGNAL:
452             # If it is then send quit signal to next stage and break
453             logging.info("Quit signal received - I am now quitting")
454             self.output_q.put((frame, None, None))
455             break
456
457     # Track capture duration
458     timer = Timer()
459     # compute the median single-channel pixel intensities
460     gaus_median = np.median(frame)
461     # compute threshold values for canny using single parameter Canny
462     lower_threshold = int(max(0, (1.0 - CANNY_THRESHOLD_SIGMA) * gaus_median))
463     upper_threshold = int(min(255, (1.0 + CANNY_THRESHOLD_SIGMA) * gaus_median))
464     # perform Canny edge detection
465     edges = cv2.Canny(
466         frame,
467         lower_threshold,
468         upper_threshold
469     )
470     # Stop the timer
471     duration = timer.stop()
472
473     # Compile metrics
474     metrics.append(duration)
475
476     # Enqueue frame and metrics
477     self.output_q.put_nowait((frame, edges, metrics))
478
479     # Log the frame enqueue
480     logging.debug("Processed and enqueued frame %d", frame_count)
481
482     # Update the preview window
483     if BS_DEBUG_WINDOWS:
484         canny_window.update(edges)
485
486     # Increment frame count
487     frame_count += 1
488
489 class S6_Segmentation(Process):
490     """ Process that segments edges using minimum enclosing circles (MECs). """
491
492     def __init__(self, input_q, output_q):
493         """
494             input_q: Queue that stores Canny detected edges and prev. frame metrics\n
495             output_q: Queue that stores Canny output edges and metrics.\n
496         """
497         super().__init__()
498         self.input_q = input_q
499         self.output_q = output_q
500
501
502     def run(self,):
503         # Turn on logging
504         logging.basicConfig(
505             level=logging.DEBUG,

```

```

506     format='%(created).6f,%(levelname)s,S6_Segmentation,%(message)s',
507     filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S6,
508     filemode='w'
509 )
510
511 # Log the start
512 logging.info("Process started with PID=%d", self.pid)
513
514 # Initialise frame counter to 0
515 frame_count = 0
516
517 # Initialise window to display debug preview
518 if BS_DEBUG_WINDOWS:
519     contour_window = Window(CONTOUR_DEBUG_WINDOW_NAME)
520
521 while True:
522     # Log input backlog
523     # logging.debug("Input backlog of %d", self.input_q.qsize())
524
525     # Log frame retrieval
526     logging.debug("Retrieving frame %d", frame_count)
527     # Retrieve frame
528     frame, edges, metrics = self.input_q.get(block=True)
529     # Log the retrieval
530     logging.debug("Retrieved frame %d", frame_count)
531
532     # Check if the frame is a quit signal (check whether it's a string first!)
533     if type(frame) == str:
534         if frame == PROCESS_QUEUE_QUIT_SIGNAL or PROCESS_QUEUE_FQUIT_SIGNAL:
535             # If it is then send quit signal to next stage and break
536             logging.info("Quit signal received - I am now quitting")
537             self.output_q.put((frame, None, None))
538             break
539
540     # Track find contours process
541     timer = Timer()
542     # 01 - Find the contours
543     # RETR_EXTERNAL only retrieves the extreme outer contours
544     # CHAIN_APPROX_SIMPLE compresses horizontal, vertical, and
545     # diagonal segments and leaves only their end points
546     contours, _ = cv2.findContours(
547         edges,
548         cv2.RETR_EXTERNAL,          # RetrievalModes
549         cv2.CHAIN_APPROX_SIMPLE   # ContourApproximationModes
550     )
551     # Stop the timer
552     duration = timer.stop()
553
554     # Compile metrics
555     metrics.append(duration)
556
557     # Track find contours process
558     timer = Timer()
559     # List to store the particle information (centre coords + radius)
560     particles = []
561     # 02 - Find minimum enclosing circles
562     for contour in contours:
563         # Find the minimum enclosing circle for each contour
564         ((x, y), radius) = cv2.minEnclosingCircle(contour)
565         # Find the centre
566         centre = (int(x), int(y))
567         # Find the radius

```

```

568         radius = int(radius)
569         # Store the information
570         particles.append((centre, radius))
571         # Stop the timer
572         duration = timer.stop()
573
574         # Compile metrics
575         metrics.append(duration)
576
577         # Enqueue frame and metrics
578         self.output_q.put_nowait((frame, particles, metrics))
579
580         # Log the frame enqueue
581         logging.debug("Processed and enqueued frame %d", frame_count)
582
583         # Update the preview window
584         if BS_DEBUG_WINDOWS:
585             # create a black mask
586             mask = np.zeros_like(edges)
587             # draw contours white white fill
588             cv2.drawContours(mask, contours, -1, (255), cv2.FILLED)
589             # display window
590             self.contour_window.update(mask)
591
592             # Increment frame count
593             frame_count += 1
594
595 class S7_Project(Process):
596     """ Project the backscatter-cancelling light patterns. """
597
598     def __init__(self, input_q, output_q):
599         """
600             input_q: Queue that stores computed backscatter particles and prev. frame metrics\n
601             output_q: Queue that stores metrics.\n
602         """
603
604         super().__init__()
605         self.input_q = input_q
606         self.output_q = output_q
607
608     def run(self,):
609         # Turn on logging
610         logging.basicConfig(
611             level=logging.DEBUG,
612             format='%(asctime).6f,%(levelname)s,S7_Project,%(message)s',
613             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S7,
614             filemode='w'
615         )
616
617         # Log the start
618         logging.info("Process started with PID=%d", self.pid)
619
620         # Initialise frame counter to 0
621         frame_count = 0
622
623         # Initialise window to display debug preview
624         projector_window = Window(PROJECTOR_PREVIEW_WINDOW_NAME)
625
626         while True:
627             # Log input backlog
628             # logging.debug("Input backlog of %d", self.input_q.qsize())

```

```

630     # Log frame retrieval
631     logging.debug("Retrieving frame %d", frame_count)
632     # Retrieve frame
633     frame, particles, metrics = self.input_q.get(block=True)
634     # Log the retrieval
635     logging.debug("Retrieved frame %d", frame_count)
636
637     # Check if the frame is a quit signal (check whether it's a string first!)
638     if type(frame) == str:
639         if frame == PROCESS_QUEUE_QUIT_SIGNAL or PROCESS_QUEUE_FQUIT_SIGNAL:
640             # If it is then send quit signal to next stage and break
641             logging.info("Quit signal received - I am now quitting")
642             self.output_q.put((frame))
643             break
644
645     # Track capture duration
646     # timer = Timer()
647     # Create a white mask for the projector preview
648     projector_mask = np.ones_like(frame) * 255
649     # Process the particles:
650     for particle in particles:
651         cv2.circle(
652             projector_mask,
653             particle[0],
654             particle[1],
655             (0, 0, 0),
656             -1
657         )
658     # Display the white mask with black circles
659     projector_window.update(projector_mask)
660     # Stop the timer
661     # duration = timer.stop()
662
663     # Compile metrics
664     metrics.append(len(particles))
665
666     # Enqueue frame and metrics
667     self.output_q.put_nowait(metrics)
668
669     # Log the frame enqueue
670     logging.debug("Projected frame %d", frame_count)
671
672     # Increment frame count
673     frame_count += 1
674
675 class S8Logging(Process):
676     """ Project the backscatter-cancelling light patterns. """
677
678     def __init__(self, input_q):
679         """
680             input_q: Queue that stores each frame's metrics.\n        """
681
682         super().__init__()
683         self.input_q = input_q
684
685
686     def run(self):
687         # Turn on logging
688         logging.basicConfig(
689             level=logging.DEBUG,
690             format='%(created).6f,%(levelname)s,S8Logging,%(message)s',
691             filename=LOGGING_FILEPATH + LOGGING_FILEPATH_S8,

```

```

692         filemode='w',
693     )
694
695     # Log the start
696     logging.info("Process started with PID=%d", self.pid)
697
698     # Initialise frame counter to 0
699     frame_count = 0
700
701     # Generate CSV export filename
702     export_filename_csv = "export_" + datetime.now().strftime("%m-%d-%Y-%H-%M-%S") + ".csv"
703
704     # Initialise a Pandas DataFrame to log real-time metrics
705     rt_metrics_df = pd.DataFrame(
706         columns=[
707             'Capture Duration (s)',
708             'Greyscale Conversion Duration (s)',
709             'Histogram Equalisation Duration (s)',
710             'Gaussian Blur Duration (s)',
711             'Canny Algorithm Duration (s)',
712             'CV2 findContours() Duration (s)',
713             'CV2 minEnclosingCircle() Duration (s)',
714             'Number of MECs on screen',
715         ]
716     )
717
718     while True:
719         # Log input backlog
720         # logging.debug("Input backlog of %d", self.input_q.qsize())
721
722         # Log frame retrieval
723         logging.debug("Retrieving metrics for frame %d", frame_count)
724         # Retrieve frame
725         metrics = self.input_q.get(block=True)
726         # Log the retrieval
727         logging.debug("Retrieved metrics for frame %d", frame_count)
728
729         # Check if the input is a quit signal (check whether it's a string first!)
730         if type(metrics) == str:
731             if metrics == PROCESS_QUEUE_QUIT_SIGNAL:
732                 # If it is then export to CSV and break
733                 logging.info("Quit signal received - starting to export")
734                 # Export dataframe as CSV
735                 rt_metrics_df.to_csv(
736                     path_or_buf=export_filename_csv,
737                     encoding='utf-8'
738                 )
739                 logging.info("Successfully exported - now exiting")
740                 break
741             elif metrics == PROCESS_QUEUE_FQUIT_SIGNAL:
742                 logging.info("Force quit signal received - I am now quitting")
743                 break
744
745             # Log the particles retrieval
746             logging.debug("Logging data for frame %d", frame_count)
747             # Add this frame's metrics to the end of the dataframe
748             rt_metrics_df.loc[len(rt_metrics_df)] = metrics
749             # Log the particle retrieval and processing
750             logging.debug("Logged data for frame %d", frame_count)
751             # Increment frame count
752             frame_count += 1

```

```

753
754 if __name__ == "__main__":
755     # Required to run X11 forwarding as sudo
756     os.environ['XAUTHORITY'] = X11_XAUTHORITY_PATH
757
758     # Set the OS priority level
759     p = psutil.Process(os.getpid())
760     print("Current OS priority: ", p.nice())
761     p.nice(OS_NICE_PRIORITY_LEVEL)
762     print("New OS priority: ", p.nice())
763
764     q1_2 = Queue() # Queue between stages 1 and 2
765     q2_3 = Queue() # Queue between stages 2 and 3
766     q3_4 = Queue() # Queue between stages 3 and 4
767     q4_5 = Queue() # Queue between stages 4 and 5
768     q5_6 = Queue() # Queue between stages 5 and 6
769     q6_7 = Queue() # Queue between stages 6 and 7
770     q7_8 = Queue() # Queue between stages 7 and 8
771
772     stages = [
773         S1_Capture(output_q=q1_2),
774         S2_Greyscale(input_q=q1_2, output_q=q2_3),
775         S3_HistogramEqualisation(input_q=q2_3, output_q=q3_4),
776         S4_GaussianBlur(input_q=q3_4, output_q=q4_5),
777         S5_Canny(input_q=q4_5, output_q=q5_6),
778         S6_Segmentation(input_q=q5_6, output_q=q6_7),
779         S7_Project(input_q=q6_7, output_q=q7_8),
780         S8_Logging(input_q=q7_8)
781     ]
782
783     # Start the stages
784     for stage in stages:
785         stage.start()
786
787     # Wait for stages to finish
788     for stage in stages:
789         stage.join()
790
791 cv2.destroyAllWindows()

```

Listing 11: The Python code for the ‘app2.py’ entry point to the Multiprocessing Backscatter Cancellation System program, commit version: 326e3b5 from [30].

### D.1.2 CaptureManager: ‘CaptureManager.py’

```

1 import os
2 import cv2
3 import logging
4 from queue import Queue
5 from threading import Thread
6 from natsort import natsorted
7
8
9 class PicameraStream:
10     """ Streams from a Picamera frame-by-frame. """
11
12     def __init__(self, width, height):
13         # Try to import and use Picamera2 library - this will fail on non-RPi platforms
14         try:
15             # Pylint - Ignore the missing import error on non RPi platforms
16             from picamera2 import Picamera2      # type: ignore

```

```

17
18     # Initialise Pi camera instance
19     self.picam2 = Picamera2()
20
21     # Pi camera configuration:
22     self.picam2.still_configuration.size = (width, height)      # Capture stills at
23     defined resolution/size
24     self.picam2.still_configuration.format = 'BGR888'          # Use this format for
25     OpenCV compatibility
26     self.picam2.still_configuration.align()                      # Align stream size (
27     THIS CHANGES THE RES SLIGHTLY!)
28
29     # Apply the configuration to the Pi camera
30     self.picam2.configure("video")
31
32     # Print camera configurations to confirm correct set up
33     logging.debug(self.picam2.camera_configuration()['sensor'])
34     logging.debug(self.picam2.camera_configuration()['main'])
35     logging.debug(self.picam2.camera_configuration()['controls'])
36
37     # Start the Pi camera
38     self.picam2.start()
39
40     # Return the aligned stream resolution
41     (aligned_width, aligned_height) = self.picam2.camera_configuration()['main']['size']
42     ]
43
44     return (aligned_width, aligned_height)
45
46     # If the Picamera2 module is not found, then the program is probably not running on a
47     RPi
48     except ImportError:
49         logging.error("Picamera2 module not found. Make sure you are running this on a
50         Raspberry Pi.")
51     # No other exceptions should be encountered, if they are then log it
52     except Exception as e:
53         logging.error("Unforeseen error encountered: ", e)
54
55     def read(self):
56         """ Capture camera sensor array for constructing a frame-by-frame feed. """
57
58         success, frame = True, self.picam2.capture_array("main")
59         return success, frame
60
61     def exit(self):
62         """ Gracefully stop the Pi camera instance. """
63
64         # Stop the Pi camera instance.
65         self.picam2.stop()
66
67         # Log to console
68         logging.info("Camera instance has been gracefully stopped.")
69
70     class FrameStream:
71         """ Streams a video represented by a set of PNG images for each frame. """
72
73         def __init__(self, path):
74             # Initialise path to folder
75             self.path = path
76
77             # Initialise queue to store frames in memory
78             self.q = Queue()

```

```

73     # Populate queue with image frames
74     self._load_frames()
75
76     def _load_frames(self):
77         """ Internal method that populates the image frame queue. """
78
79         logging.debug("Beginning to populate frame queue...")
80
81         # Sort all of the frame files inside the folder
82         frames = natsorted(os.listdir(self.path))
83
84         # For each file in the sorted list of frame files...
85         for file in frames:
86             # Ensure that the file is a PNG
87             if file.endswith('.png'):
88                 # Extract the frame number from the filename
89                 frame_num = int(os.path.splitext(file)[0])
90
91                 # Generate the filepath
92                 frame_path = os.path.join(self.path, file)
93
94                 # Read in the file
95                 frame = cv2.imread(frame_path)
96
97                 # Store the file in the queue along with the frame number
98                 self.q.put(frame)
99
100
101             # Log status
102             logging.debug("Frame queue has been populated.")
103
104     def read(self):
105         """ Dequeues the next frame in the sequence. """
106
107         if not self.empty():
108             return self.q.get()
109         else:
110             return None
111
112     def empty(self):
113         """ Returns true if there are no more frames to stream. """
114
115
116     class VideoStream:
117         """ Streams an input video file. """
118
119         def __init__(self, source, crop_w=None, crop_h=None, loop=False):
120             # initialise the OpenCV stream
121             self.capture = cv2.VideoCapture(source)
122             self.crop_w = crop_w
123             self.crop_h = crop_h
124             self.loop = loop
125
126             # check if capture is accessible
127             if not self.capture.isOpened():
128                 logging.error("Cannot open video stream!")
129                 raise Exception("Cannot open video stream!")
130
131         # calculate FPS and FPT of the capture
132         self.target_fps = self.capture.get(cv2.CAP_PROP_FPS)
133         self.target_fpt = (1 / self.target_fps) * 1000
134
135         def read(self):
136             _, frame = self.capture.read()
137             if frame is not None:

```

```

135         if (self.crop_w is not None) and (self.crop_h is not None):
136             frame = frame[self.crop_h[0]:self.crop_h[1], self.crop_w[0]:self.crop_w[1]]
137     elif self.loop is True:
138         self.capture.set(cv2.CAP_PROP_POS_FRAMES, 0)
139         _, frame = self.capture.read()
140     return frame
141
142     def exit(self):
143         self.capture.release()
144
145 class t_VideoStream:
146     """ Streams an input video file using threading. """
147
148     def __init__(self, source, queueSize=4096):
149         # initialise the OpenCV stream
150         self.capture = cv2.VideoCapture(source)
151         # initialise parameter that stops video stream
152         self.stopped = False
153         # initialise the queue for pushing frames
154         self.queue = Queue(maxsize=queueSize)
155
156     def start(self):
157         # start a thread to read frames from stream
158         t = Thread(
159             target=self._update,
160             args=()
161         )
162         # allow thread to be killed when main app exits
163         t.daemon = True
164         # start the thread
165         t.start()
166         return self
167
168     def _update(self):
169         while True:
170             # stop reading if stream is stopped
171             if self.stopped:
172                 return
173
174             # otherwise, keep reading and queuing until queue is full
175             if not self.queue.full():
176                 # read the next frame from the file
177                 success, frame = self.capture.read()
178
179                 # check if we have reached the end of video stream
180                 if not success:
181                     self.stop()
182                     return
183
184                 # push the frame to the queue
185                 self.queue.put(frame)
186
187     def read(self):
188         # return a frame from the queue
189         return self.queue.get()
190
191     def stop(self):
192         # indicate that thread should be stopped
193         self.stopped = True
194         self.capture.release()
195
196     def empty(self):

```

```

197     # returns True if queue is empty
198     if self.queue.qsize():
199         return True
200     return False

```

Listing 12: The Python code for ‘CaptureManager.py’ in the Multiprocessing Backscatter Cancellation System program, commit version: 1e69d8b from [30].

### D.1.3 TimeManager: ‘TimeManager.py’

Use the same `TimeManager.py` from the Standard Backscatter Cancellation System.

### D.1.4 WindowManager: ‘WindowManager.py’

Use the same `WindowManager.py` from the Standard Backscatter Cancellation System.

## Appendix E Project Progress Gantt Charts

### E.1 08-03-2024

#### Machine Vision-Based Anti-Backscatter Lighting System for Unmanned Underwater Vehicles

6 Mar 2024

##### Gantt Chart

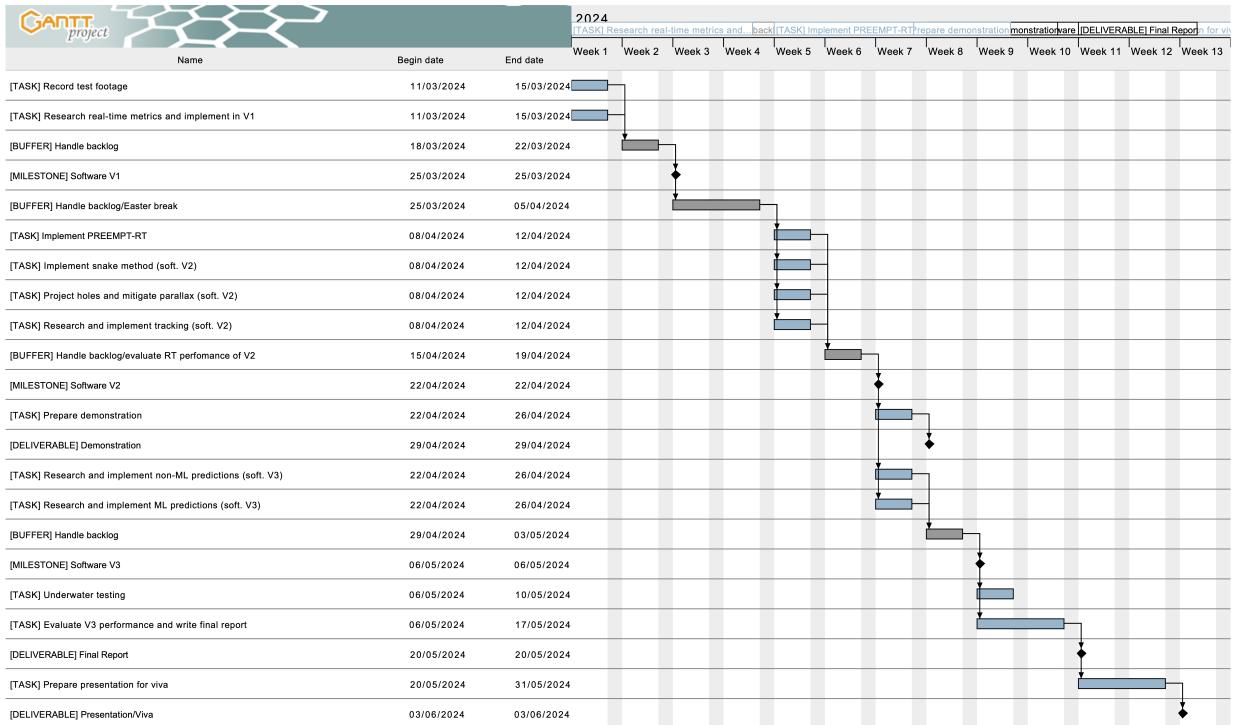


Figure 24: Gantt chart schedule as of the 8<sup>th</sup> of March, 2024.

## E.2 15-03-2024

### Machine Vision-Based Anti-Backscatter Lighting System for Unmanned Underwater Vehicles

15 Mar 2024

#### Gantt Chart

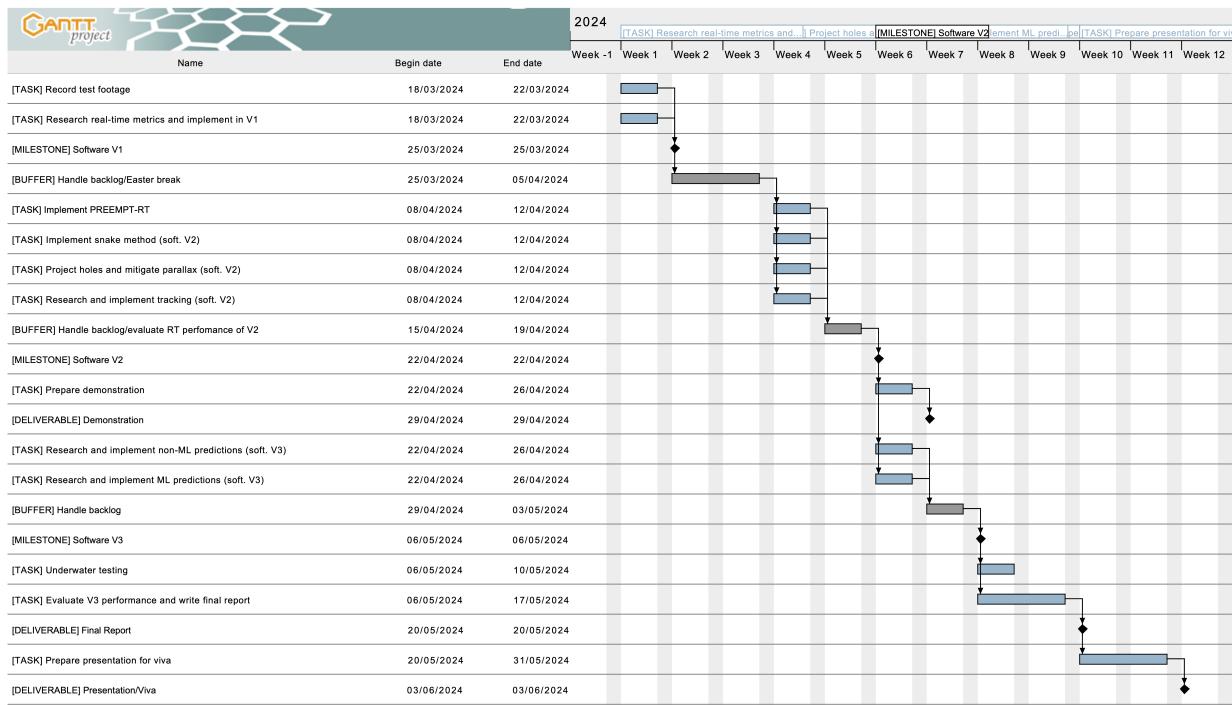


Figure 25: Gantt chart schedule as of the 15<sup>th</sup> of March, 2024.

## E.3 12-04-2024

### Machine Vision-Based Anti-Backscatter Lighting System for Unmanned Underwater Vehicles

12 Apr 2024

#### Gantt Chart

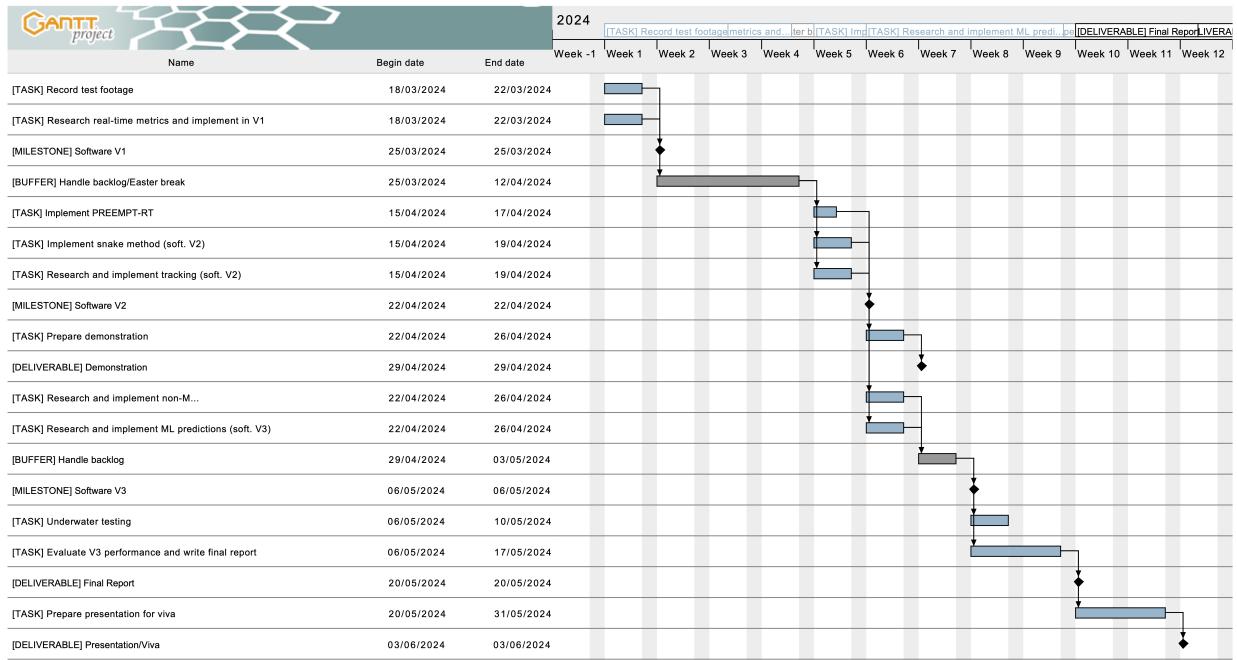


Figure 26: Gantt chart schedule as of the 12<sup>th</sup> of April, 2024.

## E.4 03-05-2024

### Machine Vision-Based Anti-Backscatter Lighting System for Unmanned Underwater Vehicles

3 May 2024

#### Gantt Chart

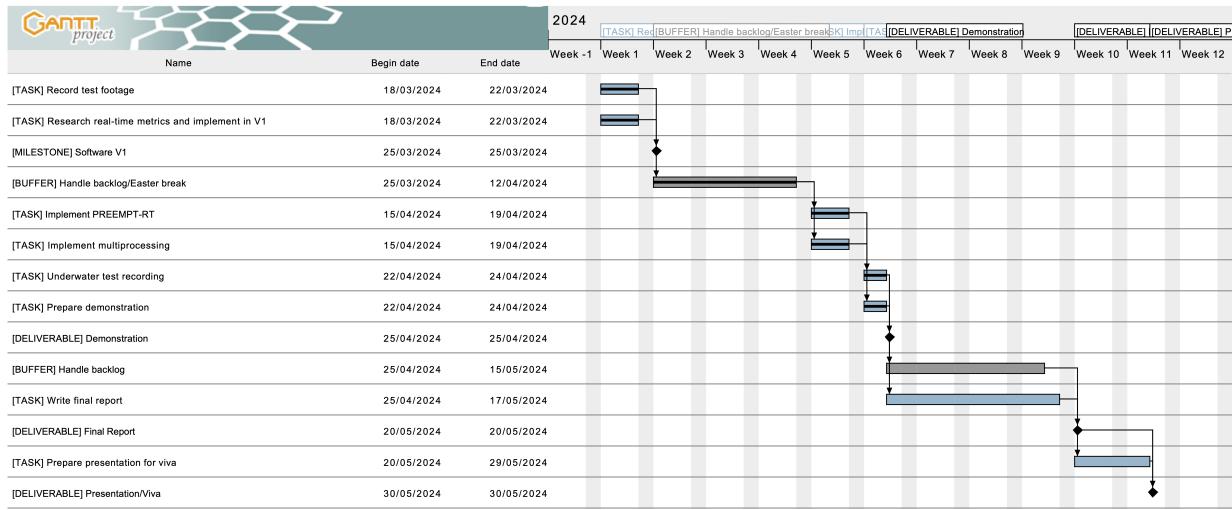


Figure 27: Gantt chart schedule as of the 3<sup>rd</sup> of May, 2024.