Polarisation experiments with motion tracking for reliable reproducibility

Final Research Report submitted for EGH400-2 Semester 2 2023

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Submission Date: 01/11/2023

Executive Summary

This project delves into the domain of reproducible experimentation in polarised imaging by integrating a moving light source and a moving polarimetric camera with the support of a motion capture system. The goal is to enable consistent and precise polarimetric data acquisition in a controlled environment.

The research commences with a comprehensive review of the existing literature, identifying gaps and areas where advancements are needed in the context of polarized imaging and motion tracking. By understanding the limitations and challenges posed by current methodologies, the project set the stage for innovative solutions.

The project adopts a multi-faceted methodology, addressing the physical environment, software infrastructure, and the polarimetric camera technology. The physical environment is carefully designed to facilitate controlled experiments. Software development focuses on establishing a robust ROS2 network for data acquisition and real-time analysis. The polarisation camera's integration is a key component of the methodology. The design approach includes the establishment of a well-structured experimental environment, a comprehensive description of the ROS2 network architecture, and a detailed image processing pipeline. The synergy of these components ensures data integrity and consistency.

The results of this project demonstrate the successful implementation of the designed system. Key findings include the achievement of reproducible and reliable polarimetric data, underscoring the importance of the advanced approach.

In summary, this project explores the integration of a moving light source and polarisation camera using motion capture technology to enable reproducible polarised imaging experiments. It addresses the gaps in current literature, details the methodology for achieving this goal, and presents key results that emphasize the potential for further advancements in the field.

Table of Contents

1 Introduction

As NASA explains, “Humans are driven to explore the unknown, discover new worlds, push the boundaries of our scientific and technical limits, and then push further” [1]. It is now the time where a lunar base is feasible, and progress has been made in this area [1]. As a precursor to a lunar base, it has been decided by NASA and ASA that there needs to be lunar rovers on the moon [2]. Due to the nature of extra-terrestrial rovers, they require full autonomy, with that terrain traversability and navigation is a major focus from QUT. As part of terrain traversability, terrain classification is an important component. Traditional methods of terrain classification use LiDAR, Vision, Radar, RGB-D, IR, etc [3]. Polarised imaging is gaining traction to assist in this field [4].

Before polarisation for terrain traversability can be fully explored, there has been minimal studies on testing conditions for training polarisation images. One such study explores a testing environment that achieves reproducible polarisation images for the analysis of snow [5]. This study has standardised lighting, camera, and polarisation direction using measurement instruments and semi-automatic or automatic limited motion. The primary limitation with this study is that the light source is fixed, and the polarisation camera moves, this is not typical for a lunar rover to do terrain classification. Usually the light source (sun) moves, and the polarisation camera (mounted on the rover) moves. This poses a challenge with determining the azimuth and zenith angles and the resulting angle of polarisation (AoP) and degree of polarisation (DoP) [6]. As a result, this project will explore how to ensure reproducible experimentation of polarised imaging with a moving light source and polarisation camera with the help of a motion capture camera.

2 Literature Review

2.1 Traversabilty Estimation

TE, otherwise known as traversability estimation, is used to describe a method that maps sensor data or terrain maps to traversability criterion [7], it is the step between perception and navigation [8]. TE allows for optimal autonomous navigation of an unknown environment, with varying levels of complexity whilst ensuring safety and goal attainment [9]. There are two main types of TE: exteroceptive and pro-prioceptive [9]. Exteroceptive TE relies on using environmental sensory systems to determine whether terrain is traversable. Exteroceptive TE can be performed through three approaches: geometry-based analysis, appearance-based analysis, or a hybrid of both [9]. Geometry-based analysis uses geometric processing of the terrain to determine traversability, this is commonly achieved with LiDAR or stereovision. While appearance-based analysis uses image processing to determine traversability, this is commonly achieved with vision sensors. Pro-prioceptive TE relies on platform based sensory systems which analyse vibrations, wheel slips, etc to determine terrain traversability [9]. Use of polarisation would be a form of exteroceptive traversability estimation of the appearance-based analysis type. Polarisation on its own has been used to some degree for traversability estimation [4] but it has yet to be explored in a hybrid solution. Polarisation has features that can improve other solutions, such as how LiDAR has limited information regarding the surface features, polarisation specifically excels at [10]. This could be combined resulting in improved results.

2.2 Terrain Classification

TE is the step between perception and navigation [8]. One of the components within that step is the ability to classify the terrain. TC is not a new concept and has been extensively researched [8]. TC has been achieved with different sensing techniques such as LiDAR, stereovision, radar, sound, inertial measurement, and sensor fusion (a combination of sensors) [11]. These have also been implemented using various software methodologies from visual, 3D points clouds, machine learning techniques and control filtering. Deep learning is quickly becoming the popular method for TC. One paper [11] has experimented using deep learning for TC and reported promising results. While in another paper, sensor fusion combined with deep learning was able to achieve substantial results of up to 90% accuracy [12]. Both papers use SVM methods for TC. A recent paper has been proposed that combines SVM with polarisation [10], showing promising results. While there has been no study on polarisation sensor fusion for TC, there has been experimentation on it for obstacle recognition [13]. Due to the well-known nature of polarisation for terrain Classification [4][14][15], combined with other sensors it could improve the downsides of such other sensors.

2.3 Polarisation

An electromagnetic wave has three primary properties: wavelength, frequency, and polarisation. Polarisation is the direction in which the electric wave is propagating as an electromagnetic wave [16]. Most light sources are non-polarised, such as the sun and lamps, meanwhile lasers are an example of polarised light. There are three types of polarisations:

linear, circular, and elliptical. Linear polarisation is when the direction vector is fixed (one direction) with the electric wave, while circular polarisation is when the electric wave rotates (either clockwise or anticlockwise) around the direction vector and elliptical polarisation is the combination of both. Through polarisation, certain information can be extracted about the light source and where the light has passed through [16]. The idea of light polarisation has been used as far back as the early 1800's to understand light transmission [17]. In the context of robotics, it has been experimented with navigation systems such as SLAM [18], Biomimetic Navigation [19], and Obstacle Detection [13]. It has also been used to identify different surfaces and their makeup for both general computer vision and robotics [4][14][15]. Although polarisation has been thoroughly researched and used in robotic navigation and in surface identification, it has not been extensively researched in TC and TE. Polarisation can greatly enhance these areas due to its improved capability in distinguishing surface texture.

2.4 Capturing Polarisation Imagery

Capturing polarisation images, in theory, relies on three main components: the source, the observer and the subject. The source is typically a form of light, the observer is usually a camera with a polarisation filter (either attached or built in) and the subject is what needs to be captured by the observer. This provides multiple angles of references to determine the polarisation characteristics, these angles include the azimuth and zenith angles. They also provide the information required to calculate the angle of polarisation and degree of polarisation [6]. Due to the number of angles and moving parts (each component), this ends up as laborious trigonometry calculation. As a result, this introduces human error as measurements and calculations can become incorrect. [5], is a study that includes the capturing of reproducible polarised imaging. In their setup they use servo motors and goniometers to ensure a consistent and reliable measurement system, there is still manual calculation but much less measurement problems. Ensuring reproducible and consistent polarisation imagery capturing is paramount for future work within TE, TC and polarisation sensor fusion.

2.5 Motion Capture Systems

Motion capture cameras record the movement of objects or people, including their position and orientation [20]. It is used in sport, video gaming, entertainment, and animation [21]. There are two categories of motion capture, marker based and markerless capture, within those two categories there are many different types of motion capture such as mechanical, optical, and magnetic [21]. Each of these have different ways of working and have their own advantages and disadvantages. One of the more common motion capture options is the optical, passive option [21]. This option uses a retro-reflective marker that is tracked by IR to capture the marker position and orientation using advanced software [22]. Due to the difficulties with calculations for polarisation, motion capture systems could be used to track the position of the components and facilitate automatic calculations through scripting.

3 Methodology

3.1 Stakeholders

The objective of this project is to enhance the accessibility of polarisation research within the realm of robotic engineering, specifically focusing on extra-terrestrial rovers. The key individuals invested in this project include researchers and enthusiasts within this field, including project supervisors. These stakeholders are keen to ascertain whether the research can enhance the acquisition of polarisation data. However, it's important to note that there are no industry stakeholders or others with a specific interest in the project. Consequently, the primary stakeholder is the project supervisor, along with one of their team members, Steve Jones. The supervisor regularly meets on a bi-weekly basis to assess project progress and provide valuable insights, drawing upon their extensive expertise in research.
The key stakeholders of the project are:

1. Associate Professor Thierry Peynot, Supervisor, Queensland University of Technology.
2. Steve Jones, HDR Student, Queensland University of Technology.

3.2 Reproducible Environment

3.2.1 Opti-Track

The central and indispensable aspect of this project hinges on the incorporation of a motion capture system, which serves as the cornerstone for ensuring reproducibility. More specifically, the project harnesses the capabilities of a sophisticated 16-camera array Opti-Track Prime X22 [23] system, meticulously configured within a designated area spanning 10 meters by 15 meters.

Figure 1: The environment with the Opti-Track cameras hanging from the roof (Blue LEDs)

The sophisticated configuration of this cutting-edge system assumes a central role in the precise capture and replication of movements essential for calculating various aspects of polarisation, including zenith and azimuth angles. The environment is staged as such in Figure 1. This innovation alleviates the need for manual measurements of distances between key elements such as the light source, camera, and sample. Additionally, it opens new possibilities for enhancing automation in the computation of parameters like Stokes parameters, Angle of Linear Polarisation (AoLP), and Degree of Linear Polarisation (DoLP). This setup not only enhances accuracy but also streamlines the research process.

3.2.2 Robot Operating System (ROS2) and other software

The Robot Operating System (ROS2) [24] stands as a pivotal platform for the development and control of robotic systems, providing a modular and standardized framework for programming, which is essential for ensuring reproducible experiments. Simultaneously, the integration of powerful libraries like NumPy [25] and OpenCV [26], alongside Polanalyser [27] specialised in polarised light analysis, significantly enhances the capabilities of this research environment. NumPy facilitates efficient numerical computations, aiding in the processing of polarisation data, while OpenCV empowers advanced computer vision techniques for analysing polarised light imagery. Combining ROS2, NumPy, OpenCV, and Polanalyser creates a potent synergy, enabling precise control over robotic systems, seamless hardware integration, automation of experiments, and standardised data processing, all of which are vital for ensuring replicability. This integrated approach not only enhances the credibility and reproducibility of polarisation research but also enables precise experimentation, robust data analysis, and open sharing of results across a wide array of applications, spanning from robotics to remote sensing and beyond.

3.2.3 Polarisation Camera

A Triton TRI050S-PC Mono Polarisation Camera [28] is a specialised imaging device tailored to capture and analyse light's polarisation properties within an environment. Differing from typical cameras that collect colour and intensity data, polarisation cameras register information concerning the orientation and polarisation state of incident light. These cameras typically employ polarising filters and sensors capable of detecting various polarisation states.

Utilizing a Triton TRI050S-PC Polarisation Camera with the ROS2 framework, especially when integrated with the lucid_vision_driver ROS2 package [29], provides a streamlined approach to interface with this camera and extract valuable data for robotic and computer vision applications. In this experiment, a Triton TRI050S-PC Polarisation Camera, fitted with a lens, serves as the polarimetric imaging device.

3.3 Design Approach

3.3.1 Environment

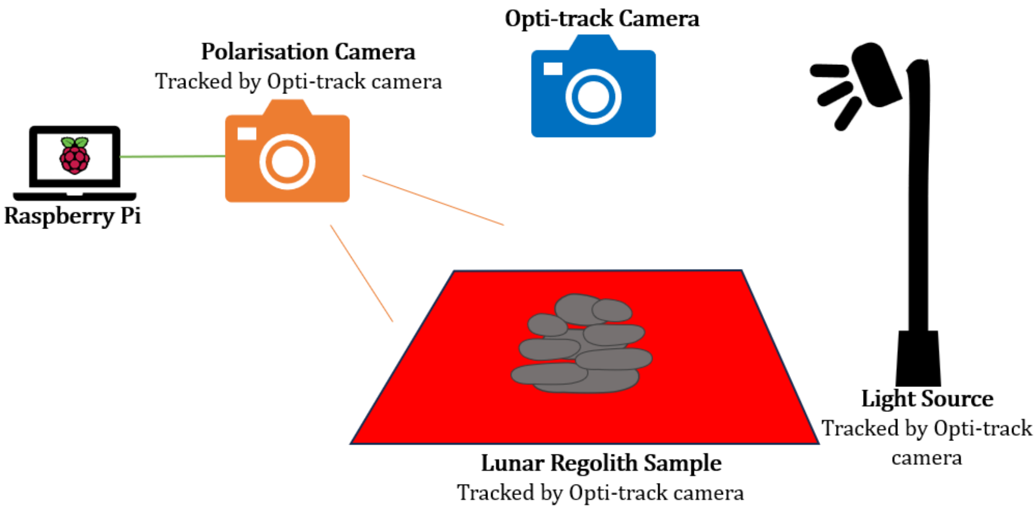

Figure 2: The environment setup

The setup comprises several integral components that work in concert to facilitate precise data collection and analysis. Figure 2 is a detailed simple diagram for the setup. At the heart of this environment are lunar regolith samples securely positioned within specialised sample trays. These trays serve as the foundation for conducting detailed analysis on the samples. To aid in boundary detection and enhance precision, a distinct, red-coloured boundary box is under the lunar regolith samples. This boundary provides a clear reference point for capturing the samples during analysis. A polarisation camera is positioned to focus exclusively on the lunar regolith samples within the sample trays.

Figure 3: The environment setup at night

A torch emits polarised light onto the lunar regolith samples, enabling controlled interactions and data generation. This is visibly highlighted within Figure 3. The polarised light torch, the polarisation camera and sample are equipped with Opti-Track retroreflectors.

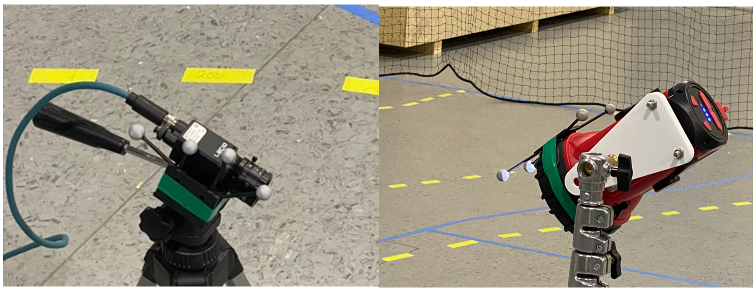

Figure 4: The environment's retro reflectors

Figure 4 has some of the environment's retroreflectors zoomed in. These retroreflectors play a pivotal role in real-time tracking and motion analysis. They ensure precise tracking of the torch and camera as they are moved around the samples. The setup incorporates a real-time tracking system that continuously monitors the positions and movements of the polarised light torch and the polarisation camera. As researchers manipulate these devices, the tracking system records their exact positions, guaranteeing accurate data collection. In parallel, the polarisation camera captures high-resolution polarised images of the lunar regolith samples illuminated by the torch. Real-time data analysis is performed to extract critical polarisation data.

3.3.2 ROS 2 Network

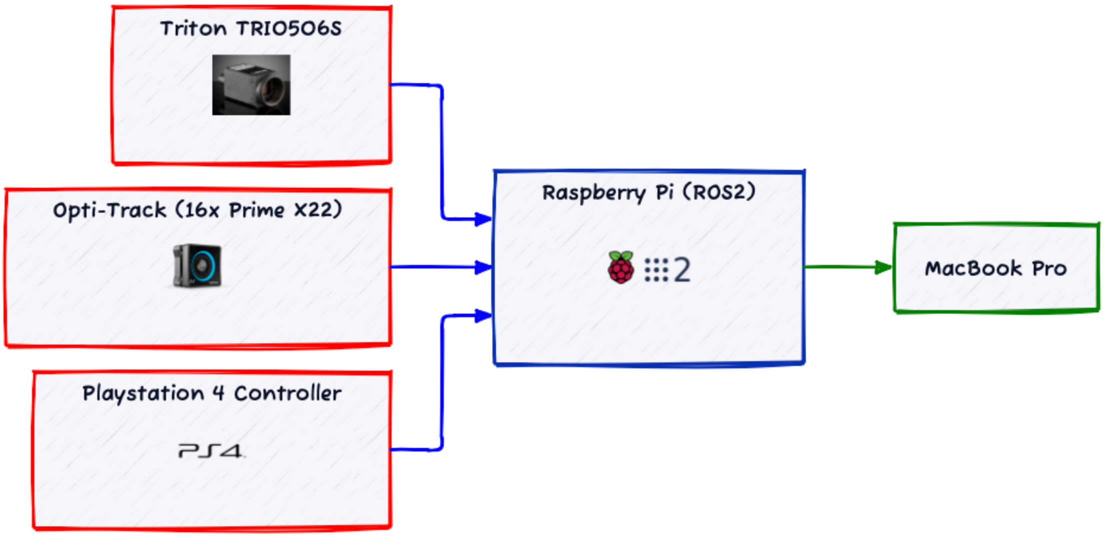

Figure 5: The flow of data in the ROS2 network

The ROS2 network configuration integrates a Raspberry Pi 4 2G and a MacBook Pro. The network interaction involves a seamless flow of data between the Raspberry Pi and the MacBook. This flow of data is diagrammatically visualised in Figure 5.

The Raspberry Pi's purpose is to act as the transmission and aggregation machine within the ROS2 network. It is equipped with a PoE injector to the Triton TRI050S-PC Polarisation camera and itself, responsible for capturing and publishing the polarised images to the ROS2 network. Additionally, the Raspberry Pi functions as a VRPN (Virtual-Reality Peripheral Network) remapper, collecting data from Opti-Track and remapping this information for publishing within the ROS2 network. It also has Bluetooth support, which will be used in connecting the PlayStation 4 (PS4) controller to control the capturing and processing after being published to the ROS2 network.

On the MacBook, the ROS2 network is managed using RoboStack [30], a package manager for ROS2. This allows for the installation of ROS2 and relevant packages essential for robotics and computer vision applications. The MacBook receives the polarisation images, VRPN and PS4 Controller data. During the receival of these streams of data, it constantly saves the latest polarisation image and the latest poses from the VRPN remapper while waiting for a button to be pressed on the PlayStation controller. Once this button press has been activated, the MacBooks runs polarised image processing which uses OpenCV and NumPy, resulting in the extraction of polarisation details, including sampled AoLP and sampled DoLP. The latest pose information of the sample, polarisation camera and Light source are used to calculate zenith and azimuth angles. The calculated zenith and azimuth angles, along with any other pertinent data, can be structured and stored in a CSV file. This CSV output provides a comprehensive and organised record of the polarisation analysis and tracking information. The latest polarisation image and its processed counterparts are also saved.

The described ROS2 network effectively integrates hardware and software components to process polarised images, extract valuable polarisation data, and calculate zenith and azimuth angles. This structured CSV output facilitates further analysis and applications in diverse fields, including robotics, remote sensing, and scientific research, thereby enhancing data accuracy and research reproducibility.

3.3.3 Image Processing

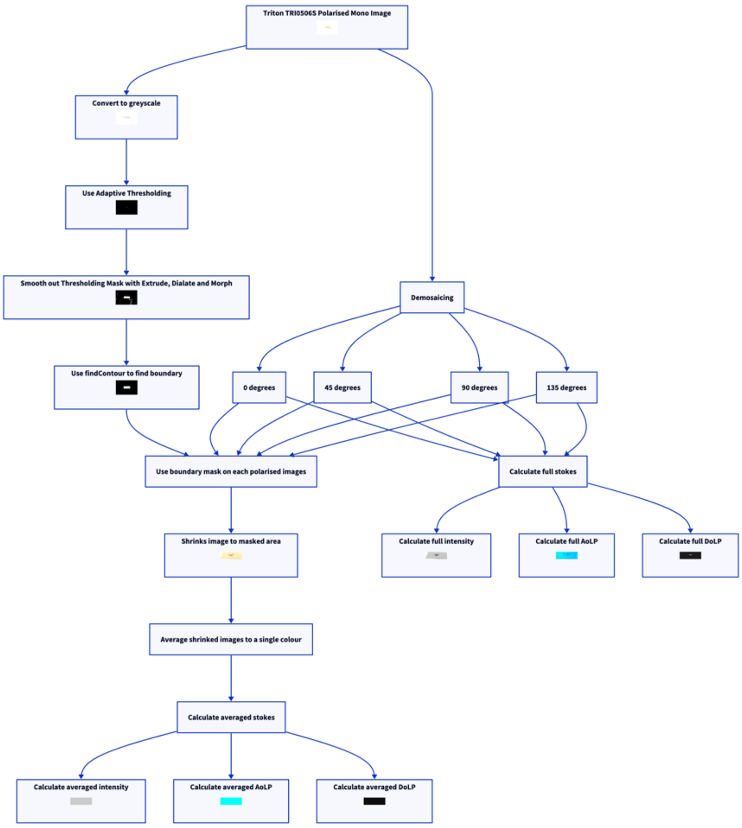

Figure 6: Workflow of Polarisation Processing (APPENDIX 7.1.3)

The objective is to calculate the polarisation information of the captured images quickly and precisely. The summarised flow of the processing is described in Figure 6 and Appendix 7.1.3. The process can be summarised by creating a mask that captures the red-coloured boundary of the subject and then apply this mask to the original image and averaging the pixels, enabling the Polanalyser to calculate key polarisation properties such as the Angle of Linear Polarisation (AoLP), Intensity, and Degree of Linear Polarisation (DoLP) images without attempting to calculate the Angle of Linear Polarisation (AoLP) and Degree of Linear Polarisation (DoLP) of an entire image but rather a single averaged Angle of Linear Polarisation (AoLP)/Degree of Linear Polarisation (DoLP) of the subject.

The initial step involves taking the captured image containing the lunar regolith and reconstructing the image from the polarised light intensity data acquired using a sensor with various polarisation filters, this is referred to as demosaicing.

To facilitate the isolation of the regolith, the images are converted from the BGR colour space to the greyscale. This conversion separates colour information from intensity, making it easier to identify the red-coloured boundary. A red mask is generated using adaptive thresholding. This technique calculates optimal threshold values for each pixel neighbourhood, effectively identifying the red regions in the image. The adaptive thresholding ensures robust boundary detection, particularly useful when lighting conditions vary. The adaptive thresholding-derived mask is applied to the original image, enabling the isolation of the lunar regolith subject. The application of the subject mask effectively removes the background, resulting in an image where only the subject is visible.

Before proceeding with polarisation analysis, average pixel values are calculated for the subject. This pre-analysis step provides quantitative insight into the subject's colour characteristics, paving the way for a simple but comprehensive understanding of polarisation properties. With the isolated subject image averaged, polarisation analysis is performed using Polanalyser. This analysis encompasses the calculation of crucial polarisation properties, including the Angle of Linear Polarisation (AoLP), Intensity, and Degree of Linear Polarisation (DoLP) images. The process of isolating the lunar regolith subject from the original image, utilizing adaptive thresholding for subject mask creation and by calculating average pixel values for the subject prior to polarisation analysis with examples of the images for each step in Appendix 7.2.2 onwards. A comprehensive examination of the lunar regolith's polarisation properties is achieved, offering deeper insights into its characteristics for further analysis.

3.4 Assumptions

Assumptions play a pivotal role in shaping the methodology and interpretation of experimental results. They guide the experimental design and data analysis. Accurate and well-considered assumptions are crucial for drawing meaningful conclusions and ensuring the experiment's reliability and relevance to real-world scenarios.

It is assumed that the polarisation analysis conducted by Polanalyser is accurate, and the zenith/azimuth calculations made within this experiment are reliable. This assumption is crucial for obtaining precise information about the polarisation state of light in the experimental setup.

The accuracy and reliability of the Opti-Track system for tracking and positioning are presumed to be high. The data obtained from this system is crucial for calculating the angles and other elements within the experiment. Accurate tracking is essential for collecting meaningful data.

In the context of applying this work to a lunar rover, it is assumed that the sole source of light for the lunar rover is from the sun. This simplifying assumption is made to model the natural lighting conditions on the Moon, as direct sunlight is typically the primary source of illumination in lunar environments.

Another assumption for applying this work to a lunar rover, is that the localization of the rover or samples is achievable, and the system can accurately infer the relative distance of these samples concerning both the lunar rover and the sun. This capability is essential for understanding the spatial relationships between objects and extrapolate data for use in matters such as terrain classification and traversability.

This experiment strategically incorporates assumptions to optimize its methodology. These assumptions are considered during result interpretation and provide a foundation for shaping the trajectory of future research endeavours. They contribute to the experiment's effectiveness and its potential for advancing scientific understanding.

3.5 Risks

In this project, several potential risks must be identified and addressed to ensure the safety and well-being of individuals and the smooth operation of the environment. Four prominent risks include fine dust exposure, hazards associated with working in a dark room, the challenges of prolonged desk coding, and tripping hazards posed by cables.

Fine dust exposure is a concern, primarily due to the health risks associated with inhaling fine particles. To mitigate this risk, proper ventilation and air filtration systems should be in place, and individuals must wear personal protective equipment, such as dust masks and goggles, when working with materials that generate fine dust. Regular workspace cleaning also helps minimize dust accumulation.

Working in a dark room can be risky due to low visibility, potentially leading to accidents or equipment damage. Mitigation strategies include installing adequate lighting and emergency systems, clear signage, and safety protocols. Training on safe navigation within the dark room is crucial.

Prolonged desk usage is common but can result in musculoskeletal issues and reduced productivity. Mitigation efforts include providing ergonomic desk setups, encouraging regular breaks, and stretching exercises, and promoting a culture of good posture and physical activity.

Tripping hazards from unmanaged cables and wires pose another risk. Effective cable management, such as using cable trays or clips, is essential to keep workspaces organized and prevent tripping accidents. Employee education and regular safety inspections further contribute to mitigating this hazard.

Overall, proactively addressing these risks is vital for creating a safe and productive project. Each of these risks were also managed with accordance to Queensland University of Technologies Risk Assessment program. Implementing appropriate safety measures, promoting a culture of health and safety, and providing proper training and equipment can significantly reduce the potential negative impacts associated with these risks, ensuring a conducive and secure environment for work and research activities.

3.6 Ethics

In accordance with the Code of Ethics (828145) set forth by Engineers Australia (EA) [31], this project abides by the four fundamental values and principles that guide decision-making in engineering practice. These criteria encompass demonstrating integrity, practicing competence, exercising leadership, and promoting sustainability.

3.6.1 Demonstrating Integrity

Integrity is upheld in this project through the principled approach of making decisions based on a well-informed conscience. When faced with knowledge gaps or insufficient understanding of a particular topic crucial to decision-making, diligent research or consultation with relevant parties is prioritized to ensure sound decision-making. Objectivity is maintained, with decisions being justified and reasoned, while embracing constructive criticism. There is a steadfast commitment to avoid engaging in fraudulent, corrupt, or criminal behaviour, and strict adherence to all applicable laws, regulations, and confidentiality agreements. Treating everyone with equal courtesy and respect, regardless of race, religion, gender, age, sexual orientation, marital or family status, national origin, or mental or physical abilities, is paramount. While specific examples may not be prominent in the regular course of this project, these considerations of integrity and equality are upheld and valued throughout its entirety.

3.6.2 Practicing Competence

Engineering is executed with a high level of competence, and a significant aspect of this practice aligns with the principles of demonstrating integrity. Adhering to their field of expertise, engineers engage in continuous research throughout the project to enhance their knowledge and skills. They actively seek peer reviews to ensure the quality of their work. Actions are carried out diligently and cautiously to foster the growth of others and maintain their own professional development.

These competencies were demonstrated in the academic context of university honour groups, where students engaged in similar projects contributed immensely valuable feedback. Adhering to the principles of honesty and trustworthiness inherent in demonstrating integrity, no information or understanding has been misrepresented or falsified. Every aspect of the project has been presented transparently and truthfully, even in cases where tasks were incomplete or unfavourable.

Supervisors are consulted when the subject matter extends beyond their areas of expertise, ensuring proper guidance. Furthermore, all legal and statutory requirements, including the appropriate use of software licenses, are strictly followed throughout the project.

3.6.3 Exercising Leadership

Leadership is consistently demonstrated throughout the project, maintaining the reputation and trustworthiness of the engineering practice. All discussions pertaining to the topic are conducted ethically, avoiding unfamiliar subjects, and promoting ethical conduct throughout the project. While the project involves only one student and a supervisor, limiting the scope for supporting and fostering diversity, the university discussions with peers, as mentioned earlier, embrace diversity, and do not tolerate any form of discrimination towards fellow students.

Although the project entails minimal costs and risks, regular communication is maintained with the supervisor through meetings and email correspondence. The supervisor is kept well-informed about the progress of deliverables, ensuring they are aware of the status at every stage of the project.

3.6.4 Promoting Sustainability

In line with the growing importance of sustainable practices, this project strives to incorporate sustainability principles throughout its implementation. The utilization of a 3D tracking camera system to track a light source, camera array with polarisation filters, and soil samples presents an opportunity to integrate sustainability considerations in several ways. Energy efficiency is a key focus, achieved through the careful selection of components and power management strategies. Sustainable material/product choices are made, favouring options with low environmental footprints, and promoting waste reduction through efficient data management and proper disposal practices. Through these initiatives, the project strives to maximize energy efficiency and reduce waste generation. Ultimately, this approach supports the overall goal of achieving a more environmentally conscious and responsible project implementation, aligning with the principles of sustainability, and ensuring a positive impact on both the project and the surrounding ecosystem.

4 Discussion, Results and Analysis

4.1 Stakeholder Feedback

As outlined in Section 3.1, the project's stakeholders encompass anyone with an interest in polarisation research within the field of robotic engineering, with a specific focus on extra-terrestrial rovers. The primary stakeholders in this venture are Thierry Peynot and Steve Jones. Regular biweekly meetings were conducted with Thierry, and experiments with Steve took place whenever possible, although some exceptions arose due to scheduling constraints and occasional project setbacks. Nevertheless, these meetings constituted the primary means of obtaining feedback from the stakeholders, which greatly informed the project's direction, helping in decision-making regarding methodologies and the optimal presentation of research findings. Additionally, valuable input was solicited from colleagues engaged in related research areas, and insights garnered from their work on analogous topics were occasionally repurposed for this project.

4.2 Experimental Results

In accordance with the methodology detailed in Section 3, the experimental process was meticulously carried out, producing a wealth of valuable data. During this experiment, precise positional information and the corresponding polarisation angles were methodically gathered and stored in a CSV file through the ROS2 program on the Mac, in conjunction with images that were precisely timestamped to ensure data synchronization.

time/photo	x - light	y - light	z - light	x - cam	y - cam	z - cam	x - sample	y - sample	z - sample	phase	zenith	aolp	dolp
2023-10-23T22:01:48.127632	-0.4482	-1.3954	1.2241	-0.5061	1.5382	0.5795	-0.4785	0.1182	0.0074	111.6200	-27.2000	2.0882	135.0000
2023-10-23T22:01:58.965218	0.2812	-1.2226	1.2276	-0.5060	1.5382	0.5795	-0.4786	0.1181	0.0072	115.7500	-3.9300	1.9997	135.0000
2023-10-23T22:02:12.333605	0.9114	-0.4255	1.2300	-0.5060	1.5382	0.5795	-0.4787	0.1181	0.0073	98.4800	26.0400	2.1214	135.0000
2023-10-23T22:05:23.655324	-0.6182	2.1046	1.2476	-0.5061	1.5382	0.5796	-0.4785	0.1180	0.0075	10.0700	8.6500	1.8700	135.0000
2023-10-23T22:05:30.246259	-0.6190	2.1041	1.2484	-0.5061	1.5382	0.5797	-0.4784	0.1183	0.0073	10.0900	8.5300	1.8978	135.0000
2023-10-23T22:05:40.248303	0.8506	1.6106	1.2523	-0.5061	1.5382	0.5796	-0.4785	0.1182	0.0071	43.1700	54.7300	1.8972	135.0000
2023-10-23T22:05:49.054034	1.4882	0.1778	1.2527	-0.5061	1.5382	0.5796	-0.4785	0.1181	0.0073	85.7900	45.2400	2.0555	135.0000
2023-10-23T22:05:58.026248	0.9780	-1.2256	1.2459	-0.5061	1.5382	0.5796	-0.4784	0.1182	0.0073	118.7700	17.0300	2.0456	135.0000
2023-10-23T22:06:06.097597	-0.3951	-1.9028	1.2439	-0.5061	1.5382	0.5796	-0.4784	0.1181	0.0075	120.3600	-27.3000	2.0148	135.0000
2023-10-23T22:06:14.299206	-1.7436	-1.4151	1.2296	-0.5061	1.5382	0.5797	-0.4785	0.1181	0.0073	97.5900	-51.1300	1.9176	135.0000
2023-10-23T22:06:21.418926	-2.5264	-0.1063	1.2285	-0.5060	1.5382	0.5796	-0.4784	0.1181	0.0075	67.8000	-61.6500	1.9000	135.0000

Figure 7: Generated CSV

The results, as presented in the output table above, are indicative of the project's considerable success in showcasing the efficiency and reliability of utilising the Opti-Track system for the automatic calculation of polarisation angles. As evident by the numbers, the light source was moved around before each image was captured, while both the camera and sample stayed stationary. It was able to calculate the phase and zenith reliably with each movement of the light source.

Unfortunately, there was an issue with the calculation of the Angle of Linear Polarisation (AoLP) and Degree of Linear Polarisation (DoLP) values for the averaged images. This is visible in the results of Figure 7, this was caused by the lucid_vision_driver ROS2 package and the limited time to test learn the polarisation camera as it arrived late. When the lucid_vision_driver converts the captured image into a ROS2 Image Message, it converts the image encoding multiple times. From an 8-bit single channel encoded image to a Bayer encoded BGR8 image. This mistake is visible in the code snippet within Appendix 7.2.1. As a result, this causes the image to appear coloured when it isn’t, and it also forces a pseudo-mosaic effect which cannot be demosaiced through Polanalyser.

Despite the problems with the results, this experiment was still relatively successful. The seamless integration of the Opti-Track system into the experiment facilitated the collection of polarisation data. Furthermore, the successful demonstration of the Opti-Track system's ability to automatically calculate polarisation angles underscores its potential for various applications beyond this specific project. It showcases how advanced tracking systems can significantly streamline data acquisition processes, enhancing the efficiency and accuracy of experiments in fields where polarisation research is critical.

4.3 Limitations

The limitations stemming from the absence of robust processing power, late polarisation camera arrival, difficulty scheduling a time to do the experiment and image processing constraints are significant in the context of this project.

When dealing with intricate polarisation data, the computational demands can be substantial. In cases where processing power is limited, the ability to carry out real-time or complex data analysis, including tasks like calculating the Stokes vector or extracting detailed polarisation information, becomes constrained. This can result in slower data processing, extended experiment durations, or even incomplete data analysis which occurred during this project.

One significant limitation of this experiment is the constrained timeframe for the polarisation camera's arrival. The equipment arrived less than three weekdays before the assignment deadline, allowing only a brief window for familiarisation, setup, and data collection. This time limitation poses challenges in optimising the camera's usage, exploring its full potential, and conducting comprehensive experiments. Moreover, it restricts the opportunity for troubleshooting, fine-tuning, and addressing unexpected issues that may arise during data acquisition. Inadequate time for pre-experiment preparation may compromise the thoroughness and depth of the research, affecting the quality of results and the ability to explore the camera's capabilities fully.

A notable limitation of this experiment arises from the high demand for the laboratory housing the Opti-Track system, resulting in limited experimental opportunities. The lab's frequent use and scheduling constraints created challenges in securing dedicated time for extensive experimentation. This limitation hindered the ability to conduct additional trials, perform in-depth calibration, and explore various scenarios systematically. Consequently, the experiment may have been subject to a restricted scope, reducing the capacity to investigate the full range of polarisation interactions or conduct exhaustive data collection. Addressing this limitation necessitates careful scheduling and resource management to optimize experimental conditions and opportunities in the future.

Another limitation in the polarization analysis process arises from the potential skewing of results due to the presence of a red bounding box. When conducting polarisation calculations, the average pixel value of the region of interest is a critical factor. However, if a red bounding box is introduced into the scene, it can impact this average value, consequently affecting the polarisation results. This discrepancy can distort the overall average, leading to inaccurate polarisation measurements. The impact could be particularly pronounced if the red bounding box is close to the regions of interest for polarisation analysis, causing unintended bias.

As a result, the project encountered substantial limitations due to insufficient processing power, delayed polarising camera arrival, scheduling challenges, and image processing constraints. These constraints have had a notable impact on the project's efficiency and have highlighted the importance of addressing such limitations in future endeavours.

4.4 Consideration of Risk, Ethics and Sustainability

As delineated in Sections 3.5 and 3.6, this project meticulously addressed various aspects such as risks, ethical considerations, and sustainability. The project's results, as expounded in Section 4.2, encompass multiple ROS2 projects. While these results are not included in this report, they are available upon request and open for third-party use. As noted in Section 3.4, certain limitations were acknowledged, which were conscientiously managed in an ethically responsible manner. It is essential to emphasize that, aside from these considerations, there were no substantial alterations made to the project or its outcomes directly in response to the factors of risk, ethics, and sustainability.

5 Conclusion

5.1 Key Findings

The conclusion of this project yields several key findings that have significant implications for future research in the field of polarisation experiments.

First and foremost, the transition from manual to automated processes marks a substantial improvement. By employing automation and motion tracking, we have achieved a level of reliability and reproducibility that significantly reduces the potential for human error and tedium in data acquisition. This shift not only streamlines the experiment but also enhances data consistency and precision.

However, it is crucial to acknowledge the limitations encountered during the project. The absence of robust processing power constrained the efficiency of data processing, at times leading to delays and the need for more advanced computational resources. Additionally, the late arrival of the polarisation camera and scheduling difficulties introduced challenges in experiment execution.

We also made key assumptions regarding the accuracy of the Polanalyser's polarisation analysis and the high precision of the Opti-Track system for tracking and positioning. These assumptions were necessary for the experiment but warrant ongoing verification.

Despite these limitations and assumptions, this project can be considered a success. It has paved the way for more extensive and ambitious research projects, including terrain classification training and other applications in the realm of polarimetry. The foundation laid by this work can serve as a springboard for exploring complex polarisation phenomena and their practical applications.

In conclusion, the project represents a step forward in polarimetric experimentation, offering a more reliable and automated approach. While room for improvement exists, the project's overall success underscores the potential for future advancements and applications in the field.

5.2 Recommendations for Future Work

As has been shown in this report, there is sufficient benefit to be found through future work with using motion capture to automatically calculate polarisation angles.

One promising avenue for future research involves the integration of real-time polarisation processing into data collection and analysis. This advancement would enable researchers to extract polarisation information as it's acquired, facilitating immediate insights. This real-time integration can be achieved through advanced software and hardware solutions, allowing for on-the-fly calculations of parameters like Degree of Linear Polarisation (DoLP) and Angle of Linear Polarisation (AoLP) as data is being captured. This would open doors for applications in robotics, computer vision, and various scientific fields where immediate polarisation insights are valuable.

In future iterations of this experiment, a pivotal improvement is suggested: replacing the lucid_vision_driver with the arena_camera_ros2 library [32]. This change is motivated by a known image conversion bug in the lucid_vision_driver, which has been affecting data quality. By adopting the arena_camera_ros2 library, which is maintained by the creators of the camera, the experiment is poised to enhance its functionality and ensure more reliable and accurate data collection. This switch not only resolves a specific issue but also contributes to the overall robustness and success of the experiment, underscoring the importance of choosing the right tools and software libraries for precise and dependable research outcomes.

Incorporating both the angle and spatial position of objects in future iterations of the experiment is pivotal. Future research endeavours should prioritise the development of methods that effectively account for the orientation of polarised light in relation to object positions. Notably, the integration of quaternion-based calculations for orientation, available within the received data from the Opti-track/VRPN, offers an exciting opportunity for this holistic approach. This should unveil a richer understanding of how polarisation properties dynamically evolve across varying angles and spatial settings. By considering both orientation and position, the experiment aims to achieve more comprehensive and nuanced polarisation insights, advancing the field's scientific understanding.

These developments have the potential to impact diverse domains, including remote sensing, material analysis, and autonomous robotics, by providing richer and more immediate data insights.

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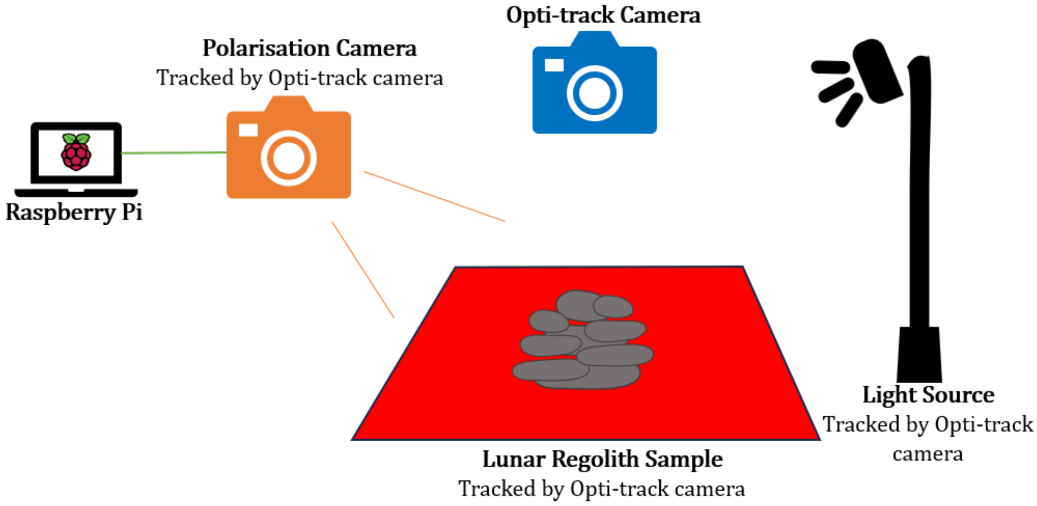
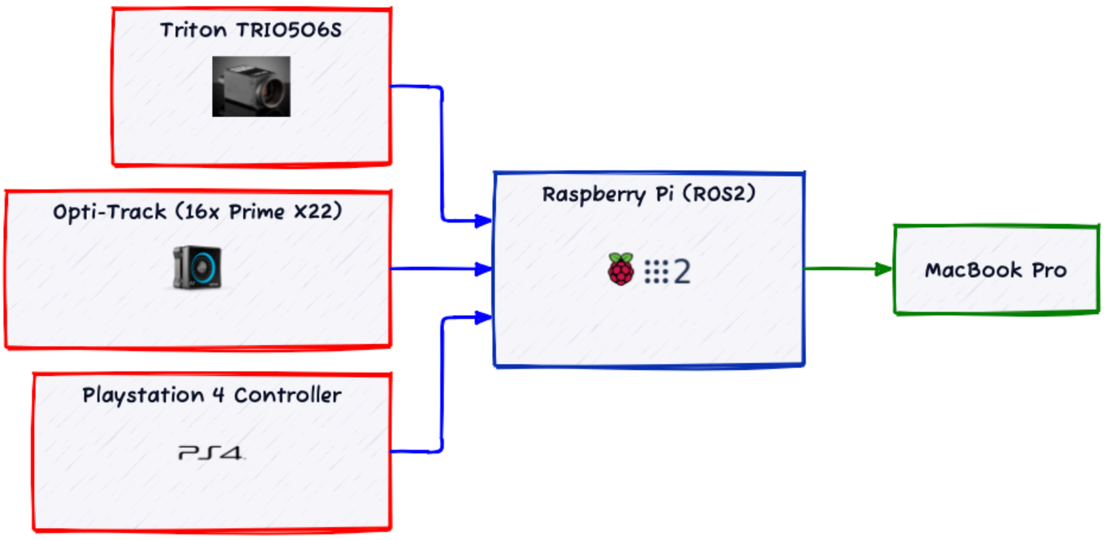
7 Appendix

7.1 Appendix A

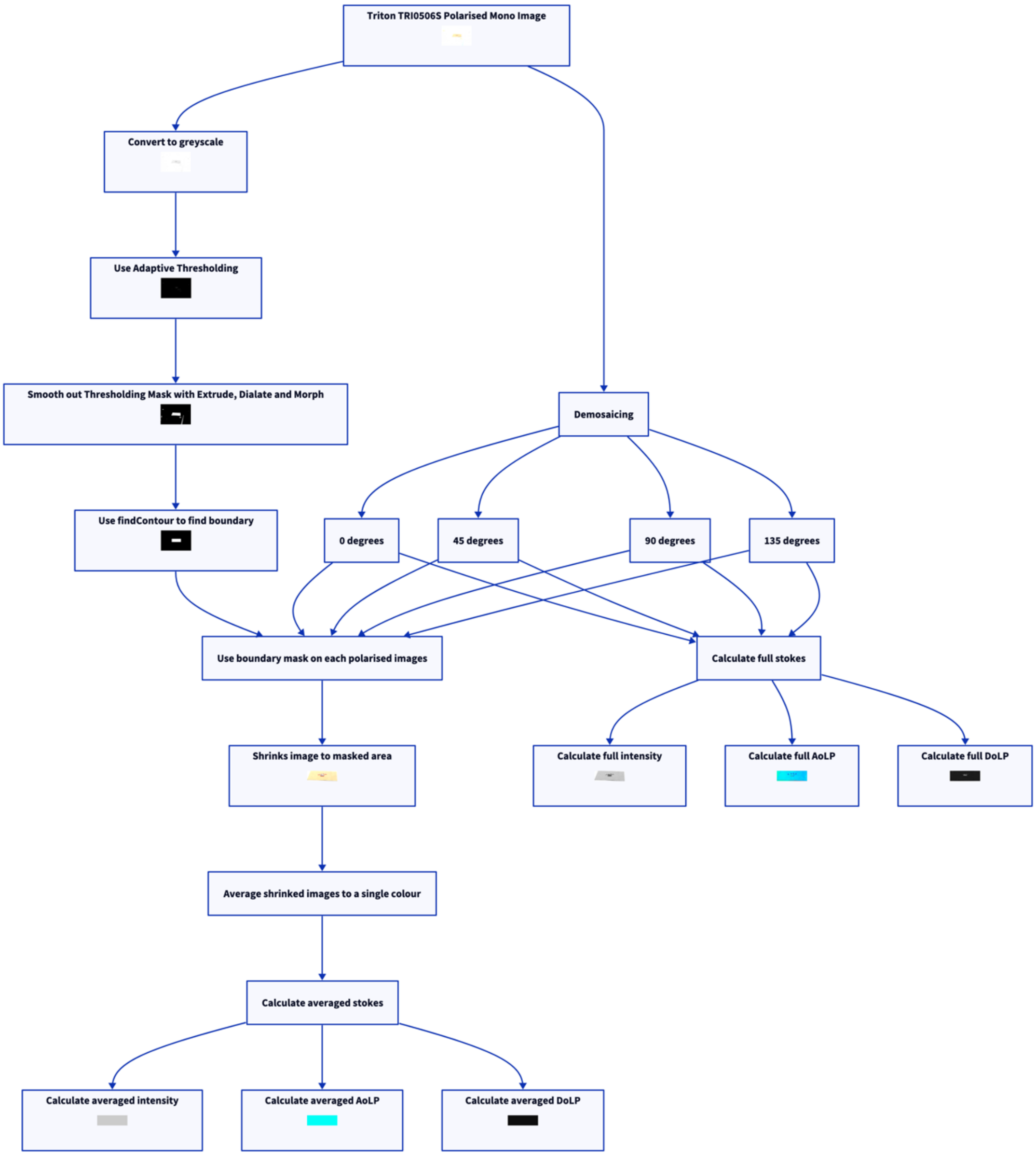
7.1.1 Environment Setup



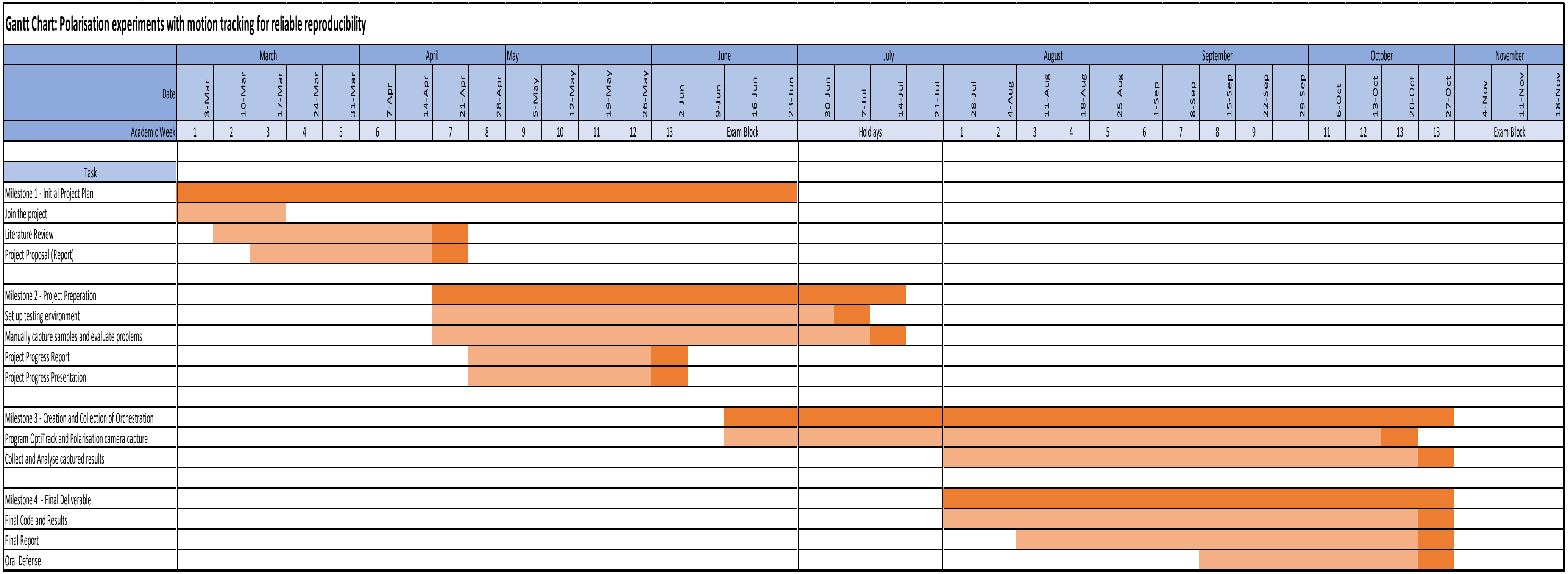
7.1.2 ROS2 Network Flow



7.1.3 Image Processing Diagram



7.1.1 Final Project Timeline



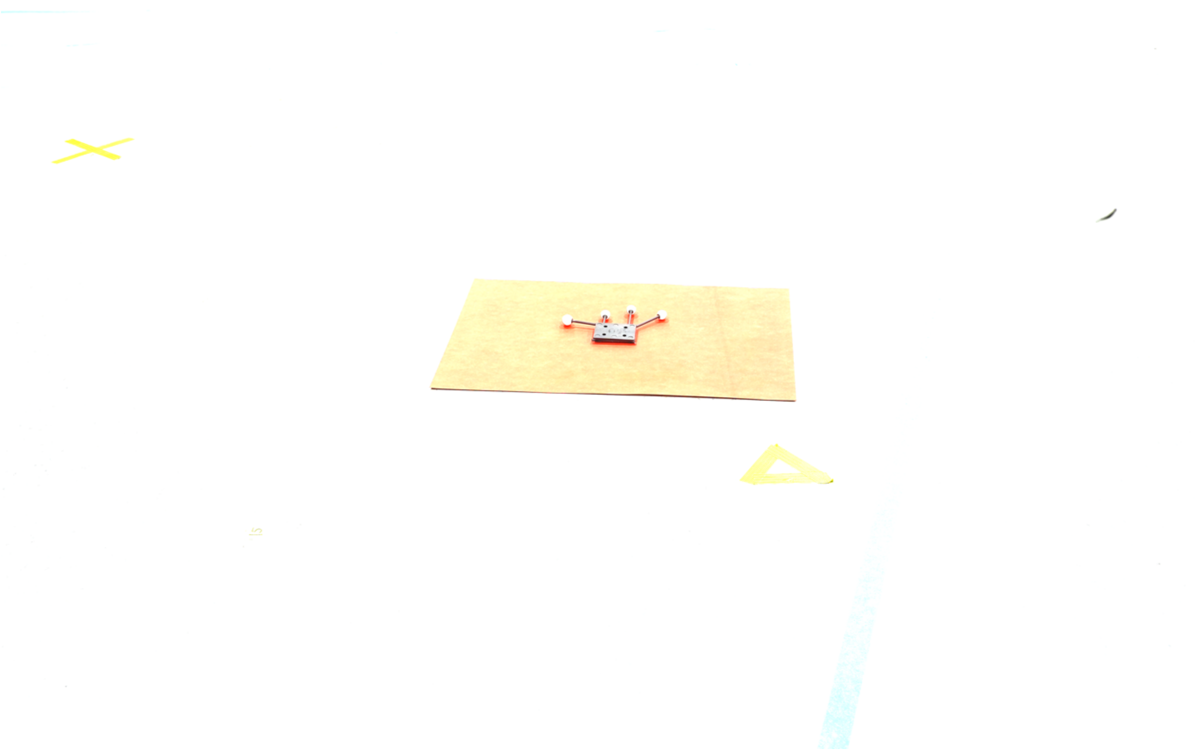
7.2 Appendix B

7.2.1 Bug in lucid_vision_driver

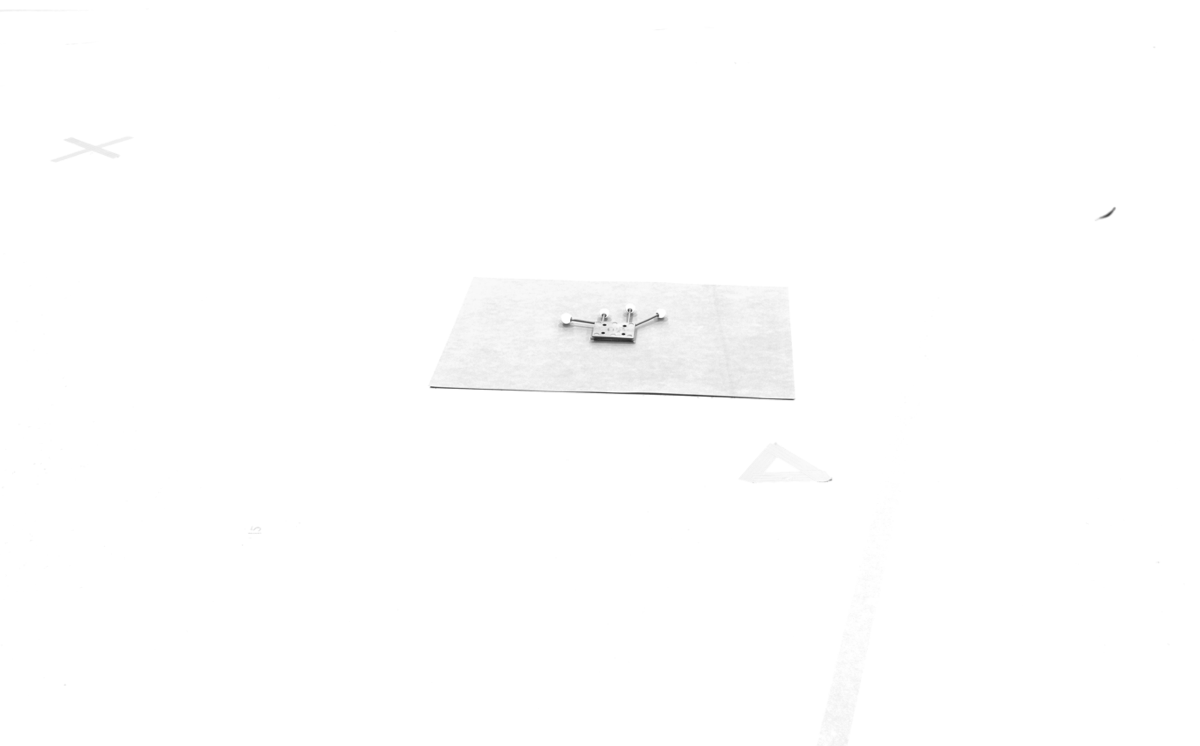
Bug in lucid_vision_driver

```
cv::Mat image_cv = cv::Mat(pImage->GetHeight(), pImage->GetWidth(), CV_8UC1, (uint8_t
*)pImage->GetData()); cv::Mat image_bgr(image_cv.rows, image_cv.cols, CV_8UC3);
cvtColor(image_cv, image_bgr, cv::COLOR_BayerBG2BGR);
```

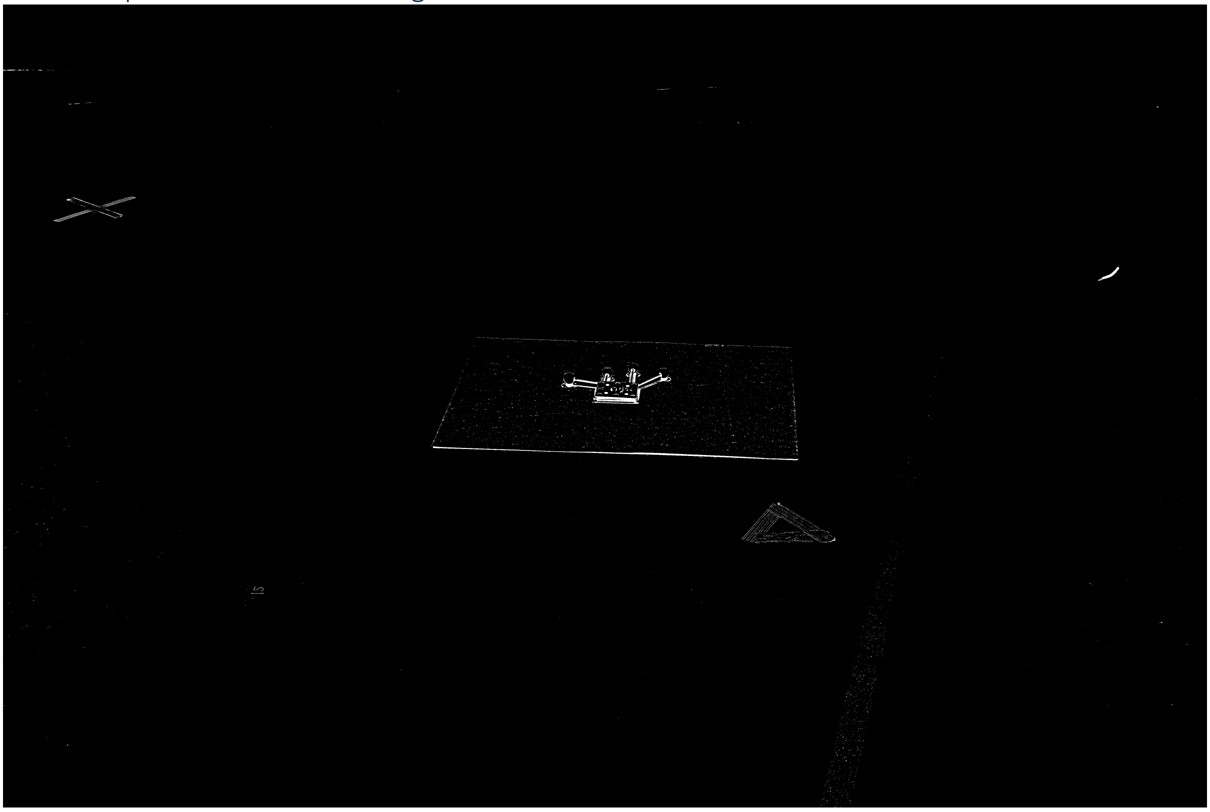
7.2.2 Polarisation Image



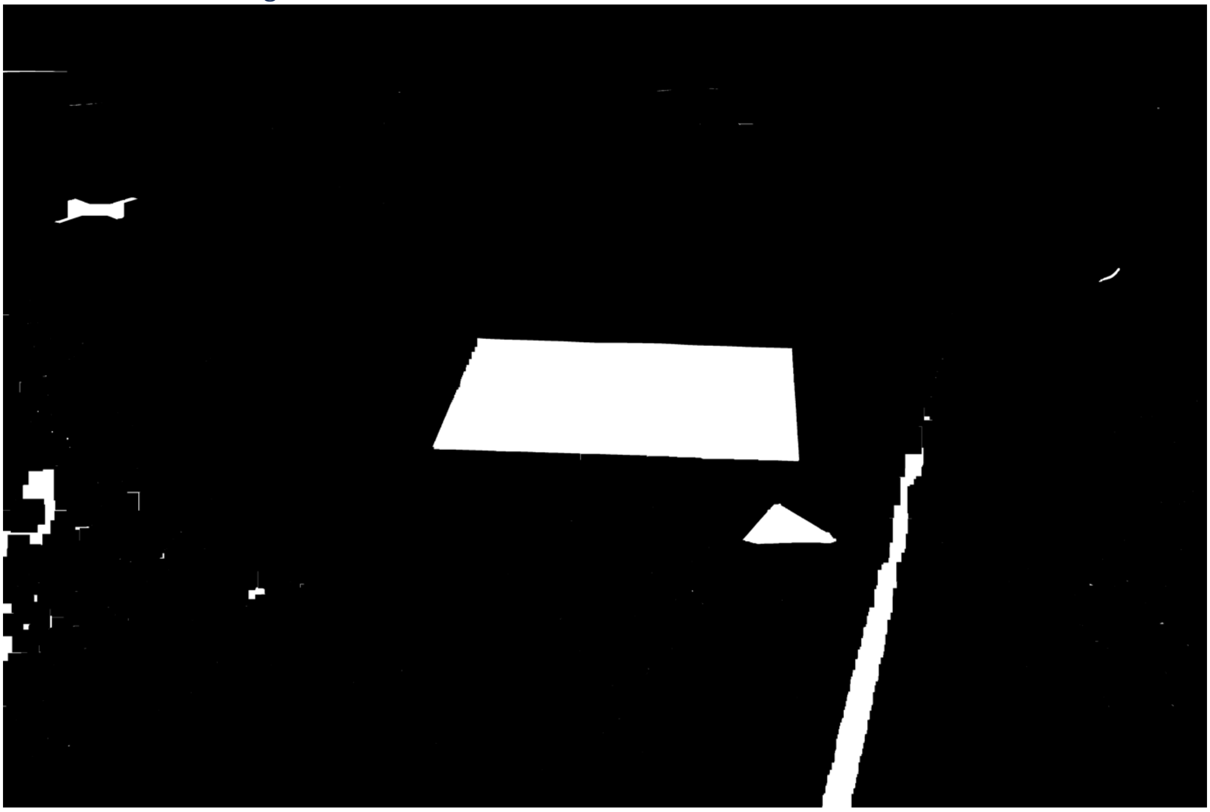
7.2.3 Greyscale Image



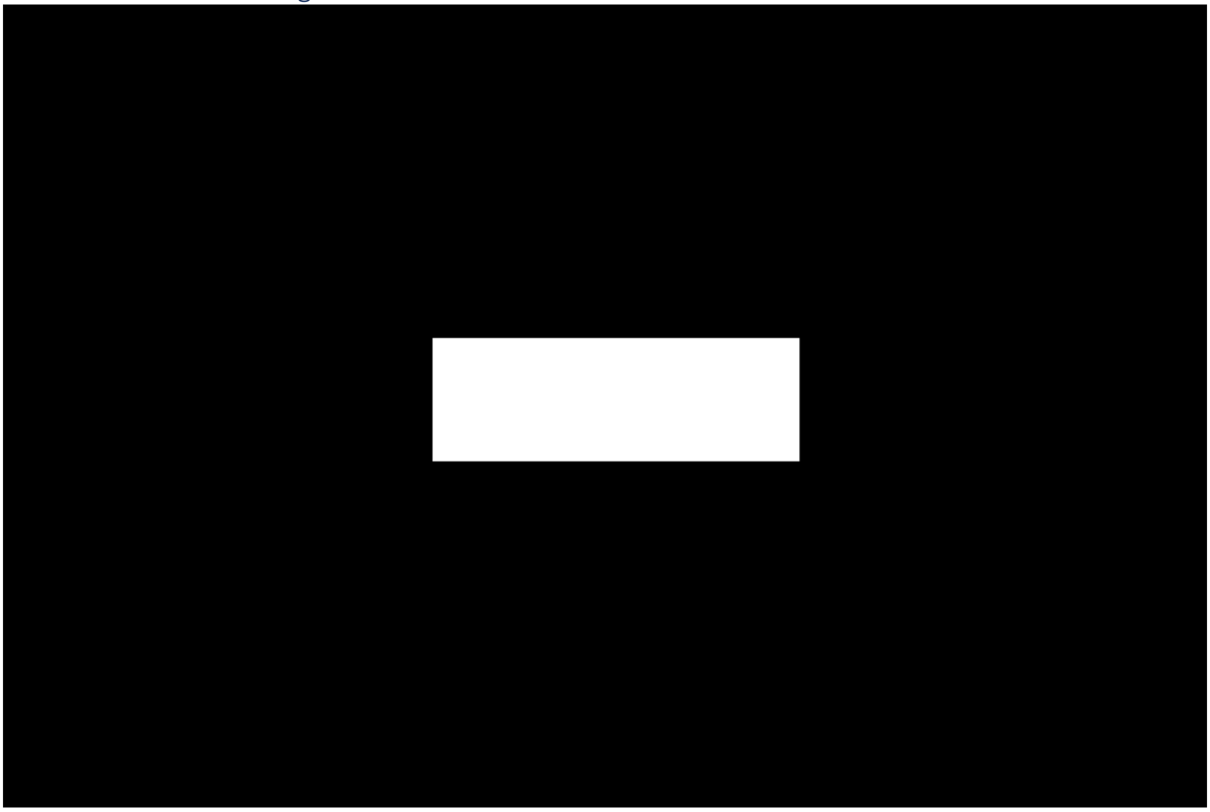
7.2.4 Adaptive Thresholded Image



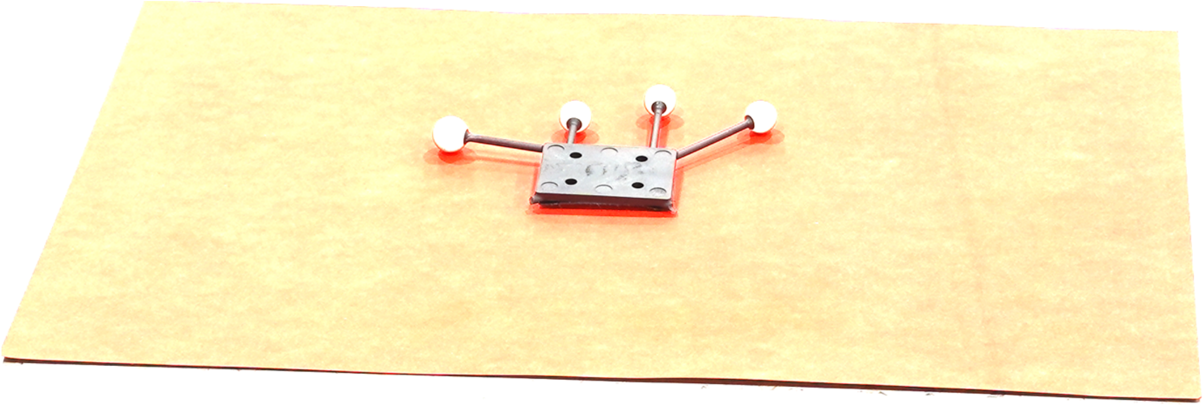
7.2.5 Smoothed Image



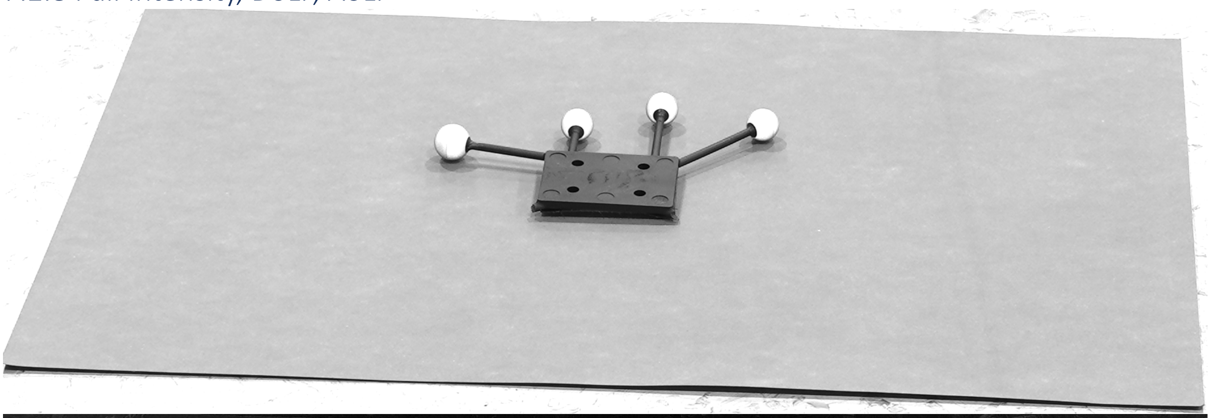
7.2.6 Find Contour Image

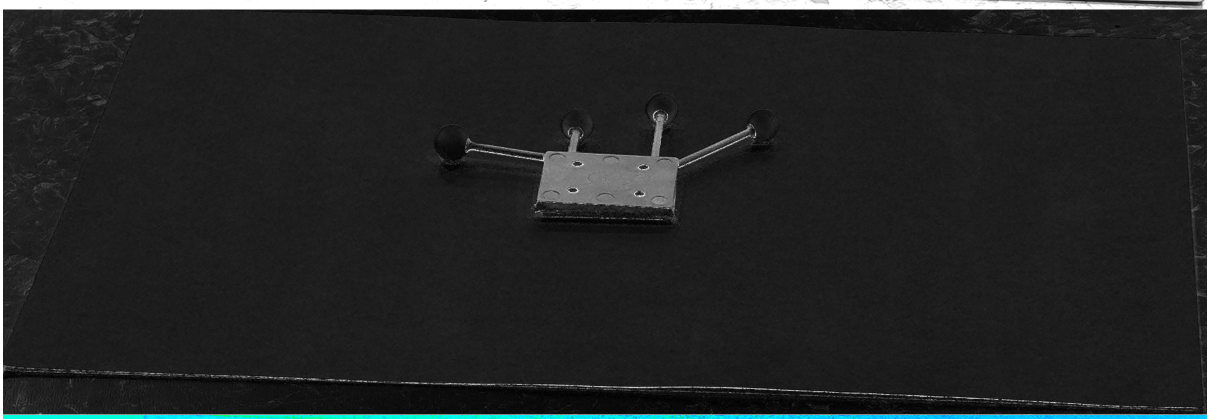


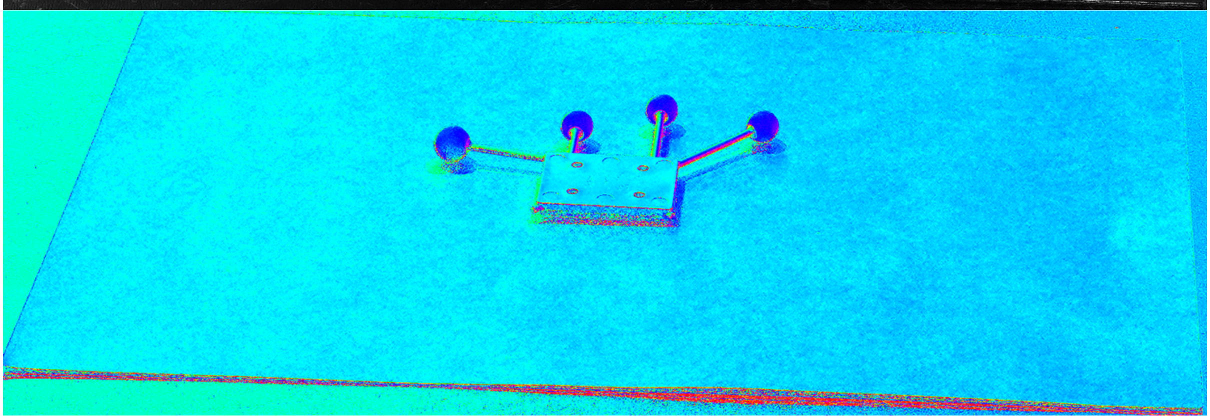
7.2.7 Shrinked Image



7.2.8 Full Intensity, DoLP, AoLP







7.2.9 Average (Mean) Intensity, DoLP, AoLP