

# Low Cost, Modular Light Source for Fluorescence Microscopy

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*A Project Report Submitted in  
Partial Fulfilment of the*

*Biomedical Engineering Degree*

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April, 2024

# **Acknowledgments**

We extend our sincerest gratitude to the individuals whose guidance and support were instrumental in the success of this project.

Firstly, we express our deepest appreciation to Dr Amanda Foust and Dr Akhil Kallepalli for their invaluable contributions as project supervisors. Their expertise, mentorship, and unwavering support throughout the project were indispensable in shaping its direction and ensuring its successful completion.

We also extend our heartfelt thanks to Pascal Egan for his role as Electronics Advisor. His technical insights, guidance, and dedication significantly enhanced the quality and functionality of our project.

We express our gratitude to Hamid Samivand for his invaluable technical support and supervision throughout the 3D printing process. Additionally, we extend our thanks to John Waldock for his ongoing guidance and advice during the prototyping phase.

# Low Cost, Modular Light Source for Fluorescence Microscopy

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## Abstract

Fluorescence microscopy is a ubiquitous tool in biomedical research, enabling the study of cellular and tissue structures in addition to electrical and chemical signalling pathways. While commercial fluorescence microscopes exist, accessibility is hindered by the high expense of conventional light sources, such as mercury and halogen-arc lamps, and their inflexible designs whereby individual wavelengths of light must be replaced or separated from the original source using expensive filters. While some low-cost solutions such as smartphone and light-emitting diode (LED) based devices have been created, many cannot be used for versatile biomedical imaging experiments due to limited functionality and restricted wavelengths offered. We have designed a modular, cost-effective LED light source utilising simple, off-the-shelf components. Our device allows electronic switching between up to four interchangeable LED modules, including a broad-spectrum red, green and blue (RGB) LED to image a wider variety of fluorophores.

**Keywords:** Low-Cost Fluorescence Microscopy, LED Light Sources, 3D-Printed Devices

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## 1. Introduction

Fluorescence microscopy is a versatile imaging technique, using fluorescent molecules to study biological structures at cellular and molecular levels. Its ability to detect specific molecules and proteins with fluorescence labelling facilitates effective use in the diagnosis of a range of widespread diseases including cancer, tuberculosis and autoimmune conditions, to name a few [1]. Unfortunately, commercially available fluorescence microscopes can incur high costs, with some over £100,000 (varying with design and manufacturer), hindering their use in low-income settings. The light source aspect is a key contributor to this and traditionally has utilised costly and environmentally damaging light sources including mercury arc lamps, halogen lamps and lasers [2]. Sophisticated optics for light filtering such as the use of filter cubes are often used in conjunction to achieve the specific wavelengths of light required to excite different fluorophores, adding to this

expense [2].

Comparatively, light-emitting diode (LED) technology use has risen in microscopy as a replacement, demonstrating superior light stability and longevity while remaining inexpensive compared to conventional sources, enabling more affordable and flexible light solutions without the need for complex filtering [3][4][5]. Their efficient switching mechanism between the on and off state with no warm-up time necessary enables rapid switching of wavelengths, saving unit working hours and maintenance requirements [3]. Users therefore have more precise control over light exposure, and coupled with its greater stability, reduces variability in intensity between experiments and hence the negative impact of photobleaching[3]. While some low-cost LED sources have been developed, multi-wavelength designs lack automated switching despite being a key advantage that could be utilised. Manual switching incurs inefficiency for the user and longer experiment times, impacting workflow ease.

Smartphone-based solutions have also become favourable as low-cost alternatives for an entire microscopy setup but at the expense of reduced performance and restricted functionality [6]. Designs have proved successful in specific applications such as malaria detection, blood screening and basic diagnostics, but further application is limited [5][6][7]. Many are designed with only one specific wavelength of light and offer limited resolutions far greater than high-end microscopes, which can reach resolutions down to 200 nm. This makes them unideal for biomedical imaging experiments where various wavelengths of light needs to be achieved, and higher-quality images produced [6]. For users who already have a working microscopy set-up, these smartphone solutions cannot be integrated into existing setups, or be used as a complete low-cost replacement due to their reduced functionality. They miss out on consumers who seek low-cost light sources that can be integrated into higher-quality systems, which would allow them to achieve the same high-quality images with low-cost light sources.

## 1.1. Project aims

To overcome this lack of adaptability and automated switching in low-cost devices, this project aims to create a light source device for fluorescence microscopy with the following objectives:

1. To allow easily swappable configurations of red, blue, green and white excitation wavelengths.
2. To allow switching between source wavelengths without manual interference.
3. To develop a low-cost design from off-the-shelf components.
4. To design a light source that is suitable for any microscope, while delivering the above intended advantages.
5. Able to image fluorophores including the widely used green fluorescence protein, and radiometric excitation of voltage-sensitive dyes.

## 2. Methods

The light source device is split into 4 sections:

- **Control unit** – where the user controls LED selection and intensity.
- **LED modules** – one design for single wavelength LEDs and another for a red, green and blue (RGB) LED.
- **Motor unit** – housing LED modules on a rotating platform with a servomotor to facilitate LED switching

- **Light beam delivery** – a path delivering light from LEDs to the microscope

Each section comprises a combination of 3D-printed parts and cheap, off-the-shelf components to produce a low-cost device. All 3D printed components were designed on SolidWorks computed-aided design (CAD) software, and 3D printed with polylactic acid (PLA), selected for its low cost and ease of 3D printing [8]. To improve access to research worldwide, we have made our design available as open source. All necessary CAD and printed circuit board (PCB) files, code, and list of components necessary along with assembly instructions have been uploaded to our GitHub repository: <https://github.com/igorroszczyk/Imperial-Y3-Project>

### 2.1. LED Modules

To fulfil the device's modularity aim, we designed interchangeable LED modules that are easily inserted into our device, accommodating four modules at a time. We selected four LEDs of varying wavelengths, (405 nm, 470 nm, 530 nm, and broad-spectrum RGB LED (380-690 nm)) to allow multi-wavelength imaging in various common applications. For example, the green 470 nm wavelength excites the common green fluorescence protein - key in imaging a versatile array of structures in biomedical imaging [9][10]. The RGB LED was selected for increased versatility in wavelength selection, with its spectrum shown in Figure 1, illustrating the broader wavelengths we can cover. Each module can fit an LED of any wavelength, given that it is compatible with the LED PCBs used in the setup, making it adaptable for each user's needs and accommodating a wider array of applications.

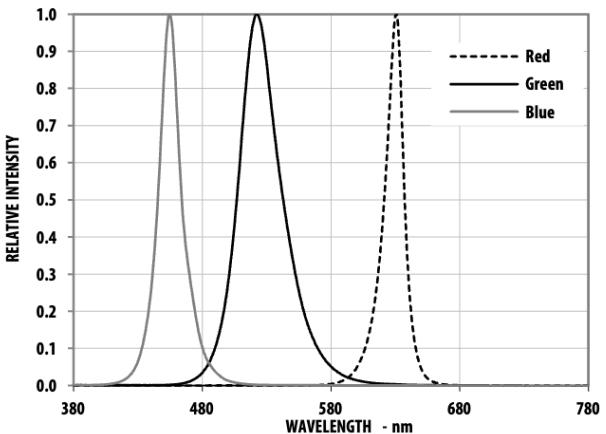


Figure 1: Spectrum of RGB LED with maximum peaks at 630 nm (red), 522 nm (green) and 455 nm (blue) [11].

The LED module is shown in Figures 2 and 3, comprising of both 3D-printed parts and off-the-shelf components, inspired by Gibson et al.'s design [12]. The LED is soldered to a small circular PCB with power wires attached. This is secured to a heatsink using thermal paste and adhesive to enable a secure fit and maximise thermal conduction. A lens mount holds an acrylic lens such that a focal length of 5mm is respected. A heatsink is connected to the lens mount with screws for adequate thermal management, with holes created through drilling, and then through tapping, to form a threaded hole.

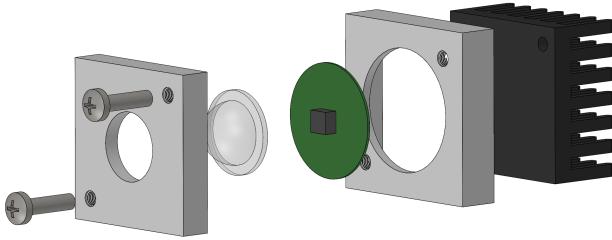


Figure 2: CAD assembly of LED Module.

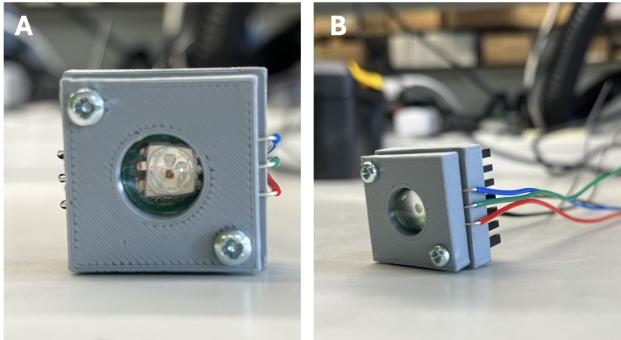


Figure 3: RGB LED Module (a) Planar View - LED module (b) Angle View - LED module.

Our device consists of 2 different LED module configurations: a single-wavelength module and a multi-wavelength RGB module. Both configurations are designed with modularity in mind, facilitating easy replacement when needed. The primary difference lies in the RGB LED module, which features six wires to accommodate the 3 LEDs, while the single-wavelength modules require only two wires. These modules are conveniently attached to the rest of the device using connectors, ensuring a straightforward and cost-effective replacement process. Additionally, the RGB module is equipped with a circular PCB specifically designed to accommodate the RGB LEDs. To streamline electrical connections, the wires attached to the module are colour-coded in red, green, and blue.

## 2.2. Motor Unit

The motor unit houses the electronic LED switching mechanism, as shown in Figures 4 and 5. We chose a servo motor for our rotation mechanism as it has a built-in closed-loop feedback system, allowing for precise positioning while remaining low-cost [13]. Four 3D-printed LED module holders were mounted onto a 3D-printed disc, allowing LED modules to slot in place. This was firmly secured atop a 180-degree servo motor using a screw to ensure stability during rotation. LED wires were allowed to pass through the disc to connect with screw terminals wired to a printed circuit board (PCB) beneath. The servo aligns the user-selected LED module with the optical fibre entry lens mounted to the motor unit wall (see Figure 5), directing light through the optical fibre to the microscope attachment. The optical fibre was attached to the motor box with a separation of 5mm from the fibre input lens, maintaining the focal length of the lens to maximise light focus from the LEDs.

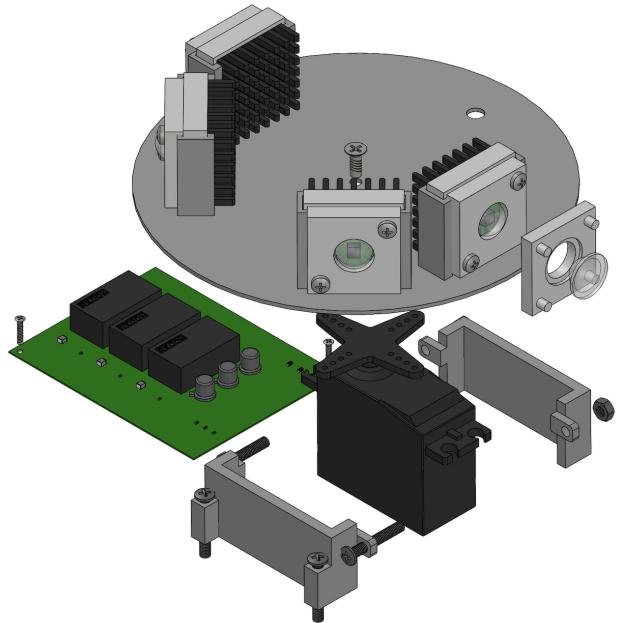


Figure 4: CAD assembly of motor box components. All components shown are housed in a 3D-printed box. LED modules are interchangeable.

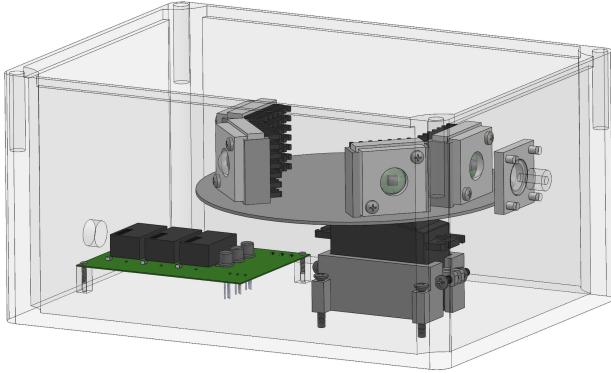


Figure 5: Complete view of the motor unit, with components housed inside a 3D printed box.

To keep our device reproducible and inexpensive, we designed a PCB to receive Pulse Width Modulation (PWM) signals from the Arduino and transmit them to the driver circuits powering the LEDs. The three single-wavelength LED modules are each operated by an RCD-24-1.00 constant current LED driver, which supplies a consistent current of up to 1A to ensure stable light output. The three drivers are capable of delivering equal current to any compatible LED colour, contributing to the device's modular design. Additionally, The RGB LED is controlled by a combination of transistors and resistors, delivering a constant current of 150mA as per the LED's specifications. A full circuit schematic is illustrated in Figure A1, with a more detailed list of components found in the Github repository.

### 2.3. Control Unit

For simplistic user control, our control unit is comprised of four buttons labelled with different colours, a liquid crystal display (LCD), and a slider as shown in Figure 6. Users have the flexibility to customise the labels according to their specific experimental requirements. The buttons determine LED selection, while the slider adjusts LED intensity. Inside the box, an Arduino Mega detects button presses and reads analogue slider values to adjust intensity. The extensive array of digital pins and enhanced processing capabilities of the Arduino Mega allowed us to efficiently manage various components of our device, including the motor, LCD, and LEDs. The LCD indicates the active LED and its intensity as a percentage to a whole integer, allowing results to be reproduced in further experiments and by other users. Powered by a 12V DC mains-connected supply, the control unit ensures convenient access to power.

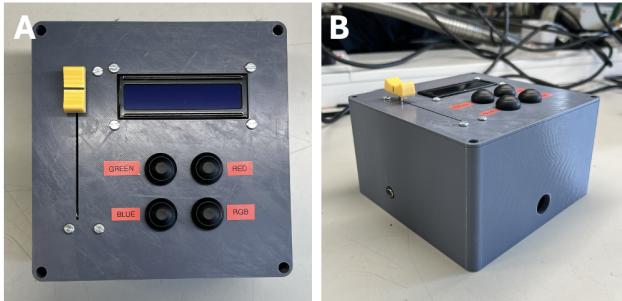


Figure 6: Control Box (a) Top view - Featuring the slider, four buttons and LCD. (b) Angled view showing the power port and output for wires connecting to the motor box.

### 2.4. Light Beam Delivery

To direct light from the LEDs to the microscope, we integrated a collimating lens of a focal length of 5mm into the housing unit, directing light into one end of a multimode optical fibre, as shown in Figure 7. This is known as the fibre entry lens. The multimode type fibre was selected as they are designed to better accommodate the broad spectrum of light emitted by LEDs compared to single-mode optical fibres [14]. We connected the opposite end of the fibre to a 3D-printed microscope attachment. This housed another collimating lens to direct light transmitted through the fibre into the fluorescence microscope. To prevent light loss and attachment instability, we fitted a rubber O-ring seal, which fit securely to a Thorlabs threaded tube specific to the light socket dimensions of the fluorescence microscope (see Figure 8). However, diameter measurements can be adjusted for adaptation to other microscopes for versatile use.

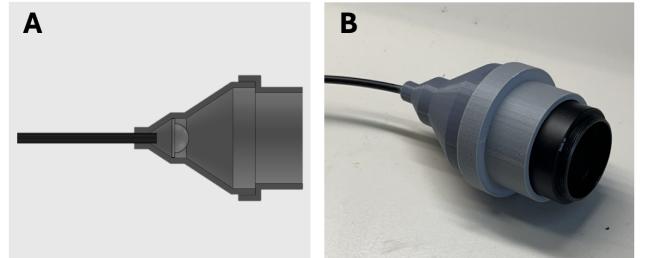


Figure 7: Light delivery system. (a) CAD showing collimating lens inside 3D printed attachment. (b) Secure fit to Thorlabs microscope attachment.

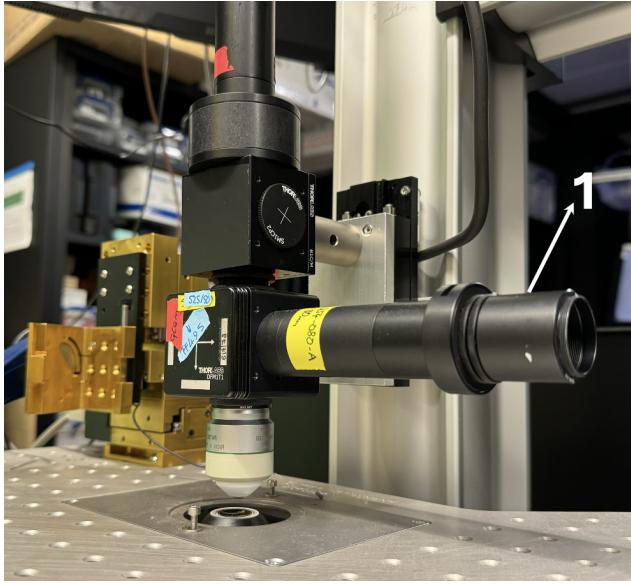


Figure 8: Fluorescence Microscope, showing attachment site. Thorlabs attachment, connecting the microscope with our device when attached (1).

## 2.5. Programming

To make the reproduction of our device easy, the code design allows for calibration of the device so the LED modules align accurately with the output. Moreover, the code allows for a variety of Arduino boards to be used, as well as other compatible with the C++ environment. We have incorporated the online platform GitHub to effectively monitor any changes when writing the code.

## 2.6. Testing

Testing procedures were performed to evaluate the quality and functionality of the light source device. We explored angular tolerance, current testing of the LED driver and LED driver control and how they were vigorously tested to check performance and reliability.

### 2.6.1. Angular Tolerance

Obtaining precise angles with rotation is essential for the accurate delivery of light into the optical fibre to minimise light loss into the microscope. An angular tolerance test was carried out to evaluate the error in the angular rotation of the servo motor when switching between LEDs. The experiment was set up as shown in Figure 9. A single blue LED module was centred on a manually operated rotating stage positioned within the prototype motor box, mimicking the rotating mecha-

nism of our circular board design. The LED was connected to a power supply providing the maximum safe current to obtain maximum intensity emission. The maximum intensity of RGB channels was obtained by applying maximum current through each channel one at a time, with 0 amps through the remaining channels. The lens and light fibre were attached to the motor box accordingly with our design, with the total intensity output at the end of the 3D printed attachment recorded using a ThorLabs photodiode power sensor, with the sensor mounted onto a post holder. Power output was measured in mW at 10-degree angle intervals. The experiment was repeated five times for the blue LED module and averaged to find the mean results.

### 2.6.2. LED Driver current testing

Light sources play a critical role in fluorescence microscopy, where stable light output at desired intensities is essential for accurate imaging. In this experiment, we aimed to assess the performance of the constant current driver, RCD-24-1.00, to ensure it meets the requirement of providing safe and consistent current to LEDs used in fluorescence microscopy. Specifically, we focused on observing the behavior of the driver when powering a green LED, as green fluorescence is commonly utilised in microscopy applications. By supplying 12V directly to the LED driver and recording the current every 10 seconds using a multimeter, we seek to determine the driver's ability to maintain a constant current output over time. This investigation is crucial for validating the reliability of our design and ensuring optimal performance in fluorescence microscopy applications.

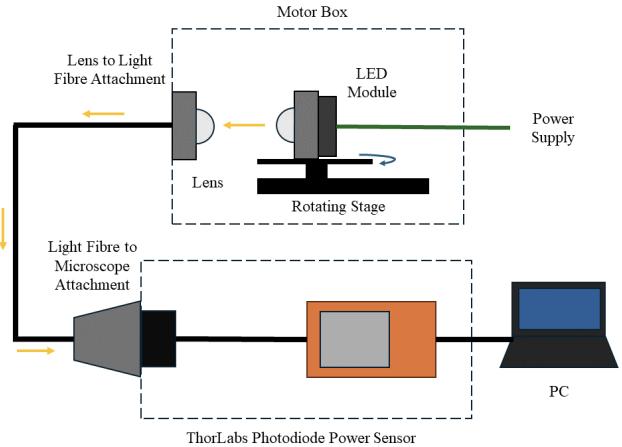


Figure 9: Schematic of angular tolerance test setup.

### 2.6.3. LED Driver control

The precise modulation of light intensity in fluorescence microscopy experiments is fundamental in achieving reproducible results and linear excitation of fluorophores. To evaluate the capability of the driver in facilitating this control, we conducted a series of experiments. By supplying 12V to the LED driver and integrating a pulse-width modulation (PWM) signal from an Arduino, we aimed to explore the full range of current outputs available. PWM signals were systematically varied in intervals of 25, ranging from 0 to 255 (8-bit PWM resolution), to assess the driver's current output across a range of intensities. Furthermore, to ensure adaptability to different LED colors, we measured the current across three distinct LEDs - red, white, and blue - using multimeters. This comprehensive evaluation seeks to ascertain the LED driver's suitability for providing precise and adaptable light intensity control in fluorescence microscopy applications.

## 3. Results

We have demonstrated a simple and cost-effective solution to the current problem of expensive light sources in fluorescence microscopy meeting the following criteria. Our light source device design is shown in Figure 10 is:

- Low-cost, utilising affordable and easily accessible off-the-shelf components
- Multiwavelength, with four easily interchangeable LED modules of adjustable intensity, having commonly used wavelengths of 405 nm, 470 nm, 530 nm and broad-spectrum RGB LED (380-690 nm)
- Compact, with simplistic control mechanisms for any lay user
- Adaptable to existing microscopy systems

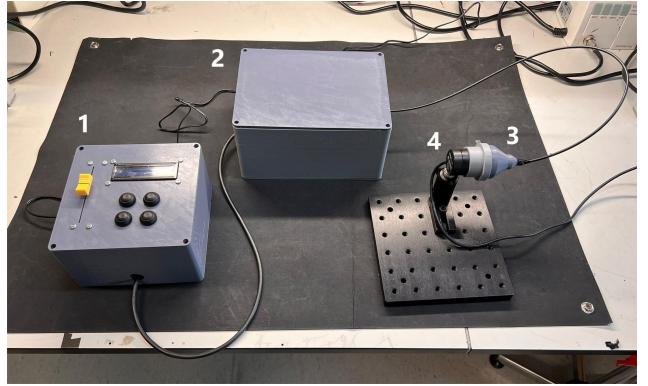


Figure 10: Completed light source device. 1) Control unit. 2) Motor unit. 3) Light path. 4) Device attachment to Thorlabs photodiode power sensor attachment, to demonstrate its secure fit.

### 3.1. Angular Tolerance

Angular tolerance was measured for the blue LED ( $n=5$ ). As expected, intensity peaked at 0 degrees with a symmetrical unimodal distribution. A minimum relative intensity of 0.92 was achieved even with an angle of  $\pm 5^\circ$  degrees.

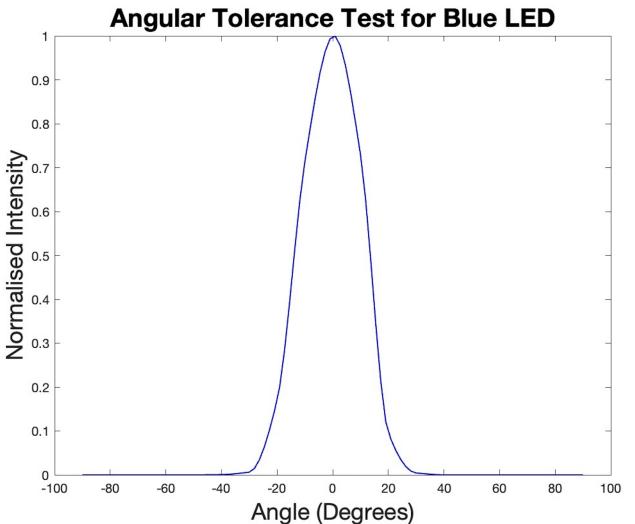


Figure 11: Angular tolerance test with blue LED using complete device set up. Intensity was measured at the output of the microscope attachment.

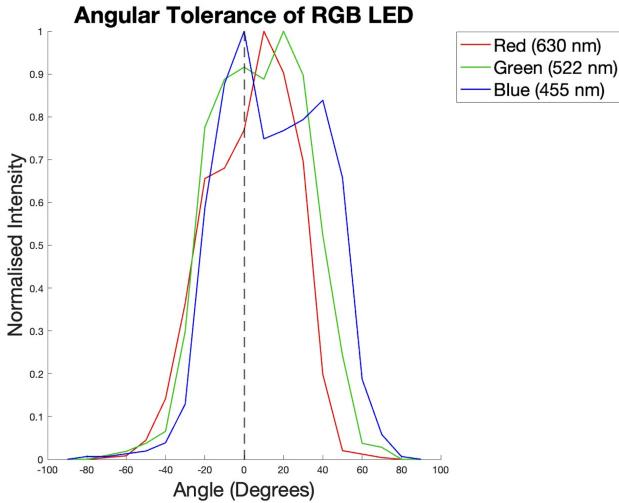


Figure 12: Angular tolerance test results for RGB LED. Shifted appearance of red, green, and blue channels respective to their placement in the RGB LED.

### 3.2. LED Driver Current Testing

The maximum current output of the LED driver RCD-24-1.00 was measured over a period of five minutes. The first 4.5 minutes presented a stable current with an average of  $994.6 \text{ mA} \pm 0.5 \text{ mA}$  (95% confidence interval) with maximum fluctuations of 2mA. However, after 4.5 minutes the green LED stopped operating and the driver stopped providing current as illustrated in figure x.

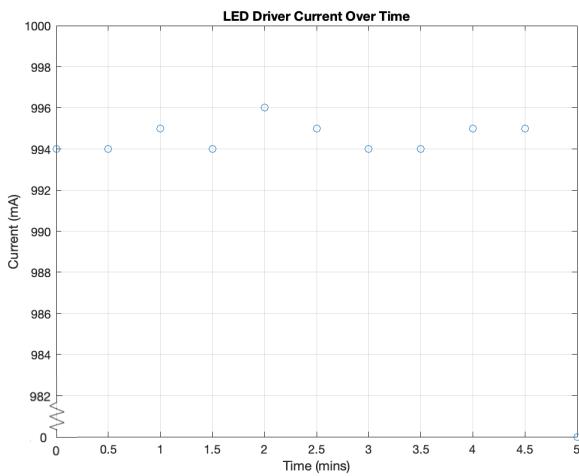


Figure 13: LED Driver Current Test - Current supplied by the RCD-24-1.00 LED driver to a green LED for a duration of 5 minutes.

### 3.3. LED Driver Control

The current output of the LED driver RCD-24-1.00 was measured as a function of PWM input supplied by an Arduino. For all LEDs, the driver behaved linearly from PWM inputs of 50 to 225, with 225 inducing the highest current. Additionally, at 0 PWM, the driver supplied maximum current to all 3 LEDs, and at 255 PWM, the driver supplied 0mA. This yielded a complete range of current output. Furthermore, the driver consistently provided the same current output across all LED colors throughout the entire PWM range.

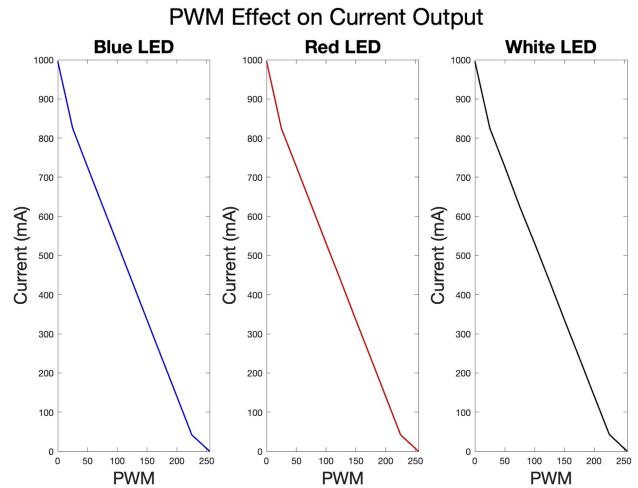


Figure 14: Variation of current across 3 different wavelength LEDs - red, blue and white - in response to changes in PWM (0-255) supplied to LED driver RCD-24-1.00.

## 4. Discussion

### 4.1. LEDs

Our main goal was to overcome the problems of manual switching in light sources for fluorescence microscopy while maintaining low costs to improve accessibility to research. Creating low-cost sources for versatile applications has proved challenging in current solutions, as a trade-off between price and functionality often occurs[6]. However, a successful component has been the realisation of LEDs as a low-cost, yet advantageous light source compared to the conventional use of mercury arc and halogen lamps [2]. In addition to their greater stability and longer lifetime, LEDs emit specific wavelengths of light with relatively narrow band spectrums (20-50μm), varying slightly with different LEDs [15], removing the need for complex and expensive filtering with conventional sources. Ideally, for high-quality imaging, filters would be included to match the absorption spectrum of the fluorophore more

closely. Still, for low-cost applications, the relatively narrow LED bandwidth is sufficient (with an expected trade-off of some additional noise and background auto-fluorescence). Hence, these have been integrated into many current low-cost solutions.

Although low-cost smartphone-based solutions have utilised LED sources for applications including cell imaging [6] and diagnosis of disease such as tuberculosis [9][16][17], their applications are often restricted to basic biomedical imaging, or specific diagnostic tests. A key limitation preventing this is the lack of wavelength options able to be achieved by these devices. Many offer a single wavelength LED only [16][17], and those with multiple wavelengths are unable to be changed, restricting the user. A development from this problem was Gibson et al.'s creation of the ModLight device - a novel low cost, multi-wavelength light source for fluorescence microscopy which improves the versatility of wavelength switching beyond that offered by current solutions mentioned [12]. Their design employs interchangeable LED modules and mirrors for LED selection, allowing the user to excite more fluorophores and cover a wider range of applications. However, while promising and effective in their microscopy testing of cell imaging, the manual switching of mirrors for LED selection in their design lends inefficiency and inconvenience for the user.

We developed their multi-wavelength concept further by harnessing the advantage of electronic switching of LEDs in our device. Like their design, our device houses up to four interchangeable LEDs at a time, already improving wavelength selection beyond that of many commercial light sources available. This may facilitate the diagnosis of a wider range of diseases and use in more biomedical applications. To then eliminate the need for manual switching of mirrors for LED selection, we instead incorporated a servomotor rotation mechanism to allow LEDs to be switched easily at the touch of a button - a more user-friendly, and efficient approach. Our low-cost 180 degree servomotor rotates to position the LED modules in alignment with the output lens to direct light into the optical fibre. It boasts an embedded closed-loop system to minimise rotation error [13][18] and holds any position between 0 and 180 degrees [19]. Precise rotation is critical in our design, as alignment must be accurate to minimise light loss into the fibre for maximum light output. We note a small rotation error in the servo of  $\pm 1^\circ$  [20], however, this has a negligible effect on our device design for single-wavelength LEDs, demonstrated through our angular tolerance test. Results for this were as expected for the blue LED, in accordance with the approximately Gaussian spectral shape of LEDs [21], as intensity peaked at 0 degree alignment, with a unimodal distribution. Even if the servo error were to reach  $\pm 5^\circ$ , 92% intensity is still achieved. We recognise errors could be reduced further in the rotation mechanism by incorpo-

rating additional feedback mechanisms such as position detectors [18]. These would enable precise adjustments to counteract any deviations from the desired position. Fine-tuning the control algorithms within the Arduino microcontroller can optimise response times and minimise overshoot, ensuring smoother and more accurate movements. This is a desirable approach to consider in future if it can be obtained at a reasonable cost, as precise alignment in this design is essential for creating a high-quality solution.

Regarding the RGB LED, results differed for the angular tolerance test as shown in Figure 12. It's important to note that our decision to implement an RGB LED was to explore its functionality as a novel approach. The user can theoretically select any wavelength from its wide spectrum, which seems ideal, however, it isn't used in high-end microscopy due to several limitations. The first is shown through this angular tolerance testing where a shift in the distributions of each channel is seen, instead of an ideal peak at  $0^\circ$  and similar distributions for all. This is a limitation reflected in the design of the RGB LED, where the three individual colour channels are slightly distanced from each other in the same way they are distributed in the graph: a centred green channel, and a red and blue channel either side (shown as translated left and right in 12. This causes a misalignment of LED light emission into the module lens and consequently the fibre entry lens, so it does not allow equal focusing of light for all colours. This limitation needs further exploration to investigate possible modifications to the RGB module design to prevent this phenomenon. It can also lead to uneven spectral distribution when channels are mixed and colour inaccuracies due to the misalignment, with some wavelengths of light unable to be emitted at high intensities (see Figure 1). While these limitations may limit our ability to excite fluorophores at high quality, it still provides more versatile wavelength selection than singular wavelength LEDs. However, fluorescence microscopy testing still needs to be carried out to evaluate if light emission is precise and accurate enough with the RGB LED for basic imaging experiments.

## 4.2. LED Drivers

For reliable quantitative imaging, it is crucial to minimise variations in incident light power. This ensures that changes in light intensity in the images are due to biological processes and not instrument instability [3]. Our current tests revealed that the RCD-24-1.00 LED driver consistently maintained a stable output, delivering a constant current of 995mA to the LED with negligible fluctuations. Despite the LED driver datasheet [22] specifying an output range of 1000mA-1200mA for a 12V input, our observed value of 995mA falls slightly short. However, this deviation does not

adversely affect light intensity due to inherent limitations on LED current. As the experiment progressed, the LED's failure became apparent due to prolonged exposure to its maximum rated current of 1A. This prolonged exposure generated significant heat, leading to thermal stress and degradation of the LED's semiconductor material. This observation underscores the insufficient heat management of the LEDs, necessitating a more cautious approach in design implementation. Consequently, to ensure safer and sustainable usage of the LEDs, a more conservative design choice was adopted, limiting the range of intensities to 90% of the LED's maximum current. This adjustment enables more effective heat dissipation and minimises the risk of thermal stress-related failures in future experiments. Looking ahead, it is imperative to repeat the test over an extended period with varying currents to assess the stability of light output under different intensity levels. This comprehensive approach will provide valuable insights into the performance and reliability of the LEDs under real-world operating conditions, guiding further improvements in experimental design and implementation.

### 4.3. Thermal Management

In alignment with the optimisation of LED drivers for stable performance, effective thermal management is crucial for safety and longevity. Heat dissipation mechanisms such as heatsinks, and thermal paste were employed to prevent excessive temperature build-up. Heatsinks absorb and dissipate heat away from the LED, reducing the risk of overheating and potential damage to surrounding components. Thermal paste enhances thermal conductivity between the LED and heatsink, improving heat transfer efficiency. Using 3D printing materials other than PLA (such as Polycarbonate (PC), Thermoplastic polyurethane (TPU)) [23] is another applicable method. Proper thermal management ensures stable LED performance, minimises the risk of thermal runaway, and prolongs the lifespan of the LED. By mitigating heat-related hazards, these safety measures uphold operational integrity and user protection in LED applications. Additionally, risks are elaborated upon in Figure B2.

### 4.4. Intensity Control

We also recognise the importance of precision in intensity adjustment, to ensure experiments are reproducible. This was achieved by employing a slider for intensity control, with an LCD that presents the intensity value to the user to a whole percentage. Enhancing user experience and ensuring reproducibility could be further optimised by integrating an input keyboard in-

terface for precise intensity control by the user, offering finer granularity and eliminating potential sensitivity issues associated with sliders. To maintain low cost, smartphones could be also used for this purpose, given their high prevalence in low-income countries and extensive use in many low-cost fluorescence microscopy solutions. [2].

Linear control and a wide dynamic range of light intensities are indispensable in fluorescence microscopy, as they ensure accurate and high-quality imaging results [24]. To assess the LED driver's capability for intensity control, we conducted experiments to measure its current output across a range of PWM values (0-255). The obtained results, while generally demonstrating a linear relationship between PWM values and current output, revealed notable deviations at the beginning and end of the PWM cycle. These deviations were a sudden change in gradient, indicating non-linear behaviour in the LED driver's response to minimal and maximal PWM values. This non-linearity could have arisen from various factors, including limitations in the LED driver's control circuitry and imperfections in the Arduino's PWM control mechanism. Abrupt changes in light intensity can lead to photobleaching and phototoxicity, causing irreversible damage to fluorescent probes and biological samples [25]. Linear control allows for gradual and controlled adjustments in light intensity, minimising the risk of sample damage while maximising image quality and longevity. To mitigate the effects of non-linear behaviour in intensity control, a more precise source of PWM modulation can be used and alternative LED driver designs with enhanced linearity and dynamic range can be explored.

### 4.5. Future Directions

As a short-term goal, validation of our device using fluorescence microscopy imaging experiments still needs to be conducted to determine its effectiveness and applications. We aim to image fixed rat neuron cells expressing the common green fluorescent protein with our light source, and compare captured images to those obtained using conventional light sources and high-end commercial LED sources. It's important to determine the quality of images, as high-end use such as within the academic field, requires high sensitivity and reading efficiency.

Additionally, our low-cost and open-source design is essential for improving accessibility to these low-income settings [26]. We could take this further by integrating it into a completely accessible, fluorescence microscopy system. As a result, our longer-term aim is to curate a solution utilising an OpenFlexure microscope - a customisable, open-source optical microscope [27], lending to even cheaper complete microscopy systems. Out-

reach to other companies who offer open-source and low-cost parts may pave the way to high-quality, low-cost solutions and eventually create a light-source device compatible with high-end academic research. Ultimately, the aim is to improve accessibility to microscopy, and collaboration may be forefront to achieving this.

## 5. Conclusion

In conclusion, our innovative approach addresses the challenge of expensive light sources in fluorescence microscopy by presenting a simple, cost-effective solution. Utilising readily available off-the-shelf components, our light source device offers multiwavelength capabilities with interchangeable LED modules, providing versatility beyond many commercial alternatives. The compact design, coupled with user-friendly controls, ensures accessibility to a broad range of users, while integration into existing microscopy systems enhances adaptability. LED technology not only offers superior stability but also eliminates the need for complex optics and expensive filters, making our solution both efficient and economical.

Despite the potential limitations of using RGB LEDs, our testing indicates promising results, albeit requiring further research for validation. The integration of precise servomotor mechanisms for LED selection, intensity control, and effective thermal management ensures optimal performance and safety. Looking forward, validation through fluorescence microscopy imaging experiments remains a priority to evaluate success in its applications and construct improvements as needed. Collaboration with open-source platforms and companies may enhance accessibility and pave the way for broader applications, ultimately contributing to improved healthcare and scientific research worldwide. Our low-cost, open-source design represents a significant step towards democratising microscopy, offering the potential to revolutionise accessibility and affordability in both educational and diagnostic settings.

## 6. Appendix

### A. Electronics Schematics

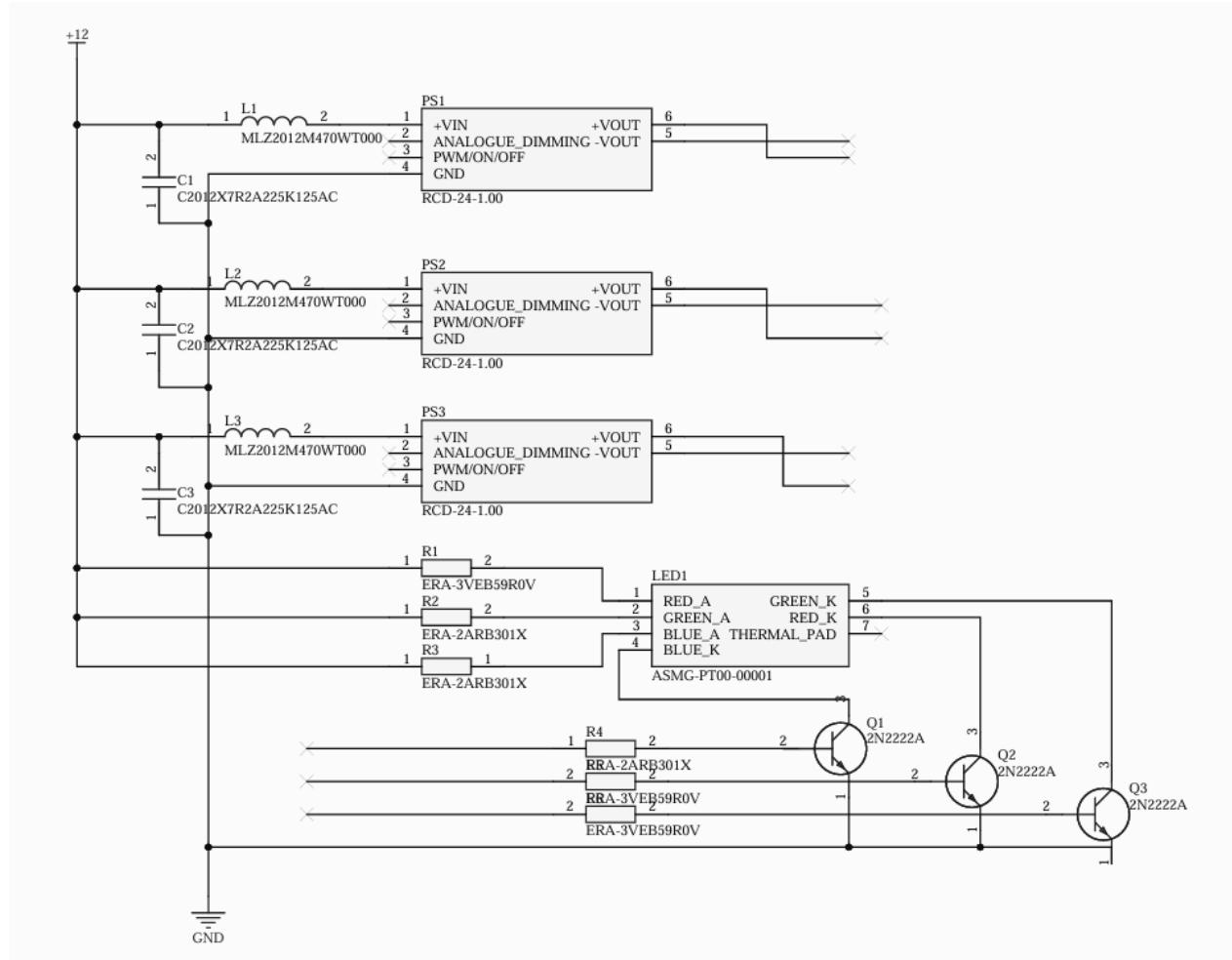


Figure A1: Motor PCB schematic showing 3 LED drivers for the control of 3 common wavelength LEDs, and an RGB driver circuit for RGB control.

## B. Risk Assessment

Key: S (Severity), O (Occurrence), D (Detection); RPN (Risk Priority Number) =  $S \times O \times D$ .

Risk	Consequence	S1	O1	D1	RPN before	Prevention	S2	O2	D2	RPN after
LED overheating	A fire might breakout	6	3	2	36	Attaching heatsinks to the LED PCB	2	3	2	12
Light loss	Poor image formation by the microscope	3	4	2	24	Introducing a rubber seal to tightly hold the microscope attachment	1	2	2	4
Material shortages	This causes delays in the production of the device and increased costs due to fast-tracked shipping	2	5	3	30	Ordering excess materials to always have supply and diversifying suppliers	1	2	1	2
Exposure to hazardous electrical components during assembly	Injuries to team members and damage to the equipment	6	3	3	54	Using personal protective equipment (PPE) and conducting training	3	2	1	6
Unexpected project expenses	Might lead to project cancellation	3	3	2	18	Regular monitoring of the project expenses and having contingencies for unexpected costs	1	2	1	2
Increased energy consumption	Higher expenses leading to increased operating costs	3	3	3	9	Turning off LEDs when not in use and purchasing ones with high efficiency ratings	1	1	2	2

Figure B2: Risk assessment. Provides an evaluation of potential risks and their likelihood and impact, helping the team to make informed decisions.

## C. Project Management

Throughout the project, we encountered several departures from our initial project planning as outlined in the project pitch. One significant challenge arose when one of our team members unexpectedly departed from the project. That disrupted the team dynamics and necessitated a reassessment of roles and responsibilities to ensure project continuity. As a result, we experienced delays in certain tasks as we had to redistribute the workload. Project milestones that we have described at the beginning of the project in a form of a gantt chart, shown in Figure D3, had to be adjusted as well. Additionally, the departure led to a temporary gap in specific expertise, requiring us to allocate additional resources to gain the knowledge necessary to complete all the tasks. Despite these challenges, we successfully navigated through the obstacle by fostering open communication, redefining project milestones, and reassigning tasks effectively. These events served as a valuable learning experience, highlighting the importance of contingency planning and adaptability in project management. Moving forward, we will implement strategies to mitigate the impact of potential changes in the face of unexpected challenges.

From this experience, we have learned 3 key management lessons:

**Adaptability is Key:** The departure of a team member underscored the importance of adaptability in project management. We learned that unforeseen circumstances can arise at any stage of a project, necessitating flexibility in our approach. By remaining agile and responsive to change, we were able to reorganise our resources, redistribute tasks, and maintain project progress despite the disruption. Moving forward, we will prioritise building a team culture that embraces adaptability, equipping team members with the skills and mindset needed to navigate unexpected challenges effectively.

**Communication is Vital:** Effective communication emerged as a critical factor in managing unexpected events during the project. The departure of a team member highlighted the importance of clear and transparent communication channels within the team. We learned that regular updates, open discussions, and proactive problem-solving are essential for addressing issues promptly and minimising the impact of disruptions. By fostering a culture of open communication, we can ensure that all team members are informed, engaged, and aligned with project goals.

**Redundancy and Resilience:** Loss of a team member underscored the need to build redundancy and resilience into project plans. We recognized that relying heavily on individual expertise or resources can leave the project vulnerable to disruptions. Moving forward, we will implement strategies to diversify skill sets, cross-train team members, and establish backup plans to mitigate the impact of potential departures or unforeseen events. By building redundancy and resilience into our project management approach, we can better withstand disruptions and maintain continuity in project execution, ensuring successful outcomes even in the face of adversity.

## D. Gantt Chart

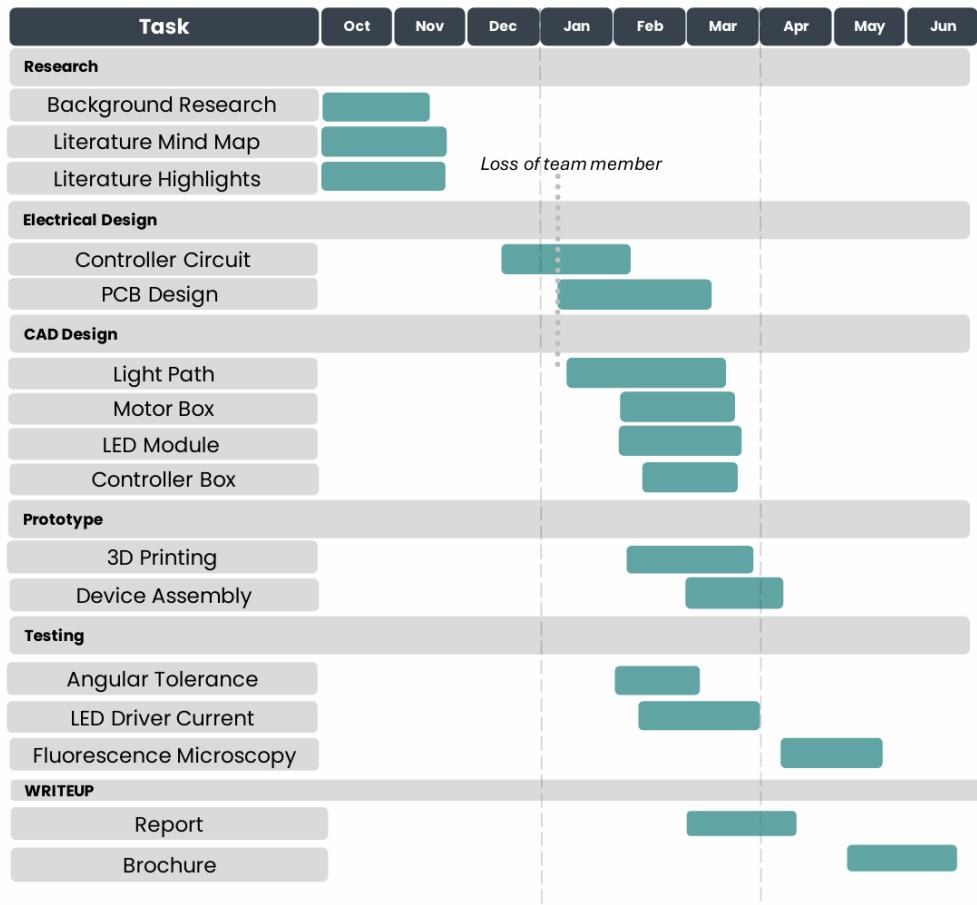


Figure D3: Gantt Chart - Indicating the loss of a team member, and our key milestones. The group was split into sub-teams, and roles were allocated. Planning was restructured accordingly when this occurred.

## References

- [1] Christie Bader. et al. Shane M. Hickey, Ben Ung. Fluorescence microscopy—an outline of hardware, biological handling, and fluorophore considerations. *Cells*, 11(1):35, 2021.
- [2] Omar Ormachea, Alex Villazon, Patricia Rodriguez, and Mirko Zimic. A smartphone-based low-cost inverted laser fluorescence microscope for disease diagnosis. *Biosensors*, 12(11):960, 2022.
- [3] Firas Mubaid, Daniel Kaufman, Tse-Luen Wee, Dong-Son Nguyen, David Young, Maria Anghelopoulou, and Claire M.Brown. Fluorescence microscope light source stability. *Histochemistry and Cell Biology*, 151:357–266, 2019.
- [4] Jianchen Zi and Hai Bi. Fluorescence microscope light source based on integrated led. *Light: Science and Applications*, 12(1), 2023.
- [5] Hongying Zhu, Oguzhan Yaglidere, Ting-Wei Su, Derek Tseng, and Aydogan Ozcan. Cost-effective and compact wide-field fluorescent imaging on a cell-phone. *Lab on a Chip*, 11(2):315–322, 2011.
- [6] Samuel B. Tristan-Landin, Alan M. Gonzalez-Suarez, Rocio J. Jimenez-Valdes, and Jose L. Garcia-Cordero. Facile assembly of an affordable miniature multicolor fluorescence microscope made of 3d-printed parts enables detection of single cells. *PLOS ONE*, 14(10), 2019.
- [7] Jessica Minion, Madhukar Pai, Andrew Ramsay, Dick Menzies, and Christina Greenaway. Comparison of led and conventional fluorescence microscopy for detection of acid fast bacilli in a low-incidence setting. *PLoS ONE*, 6(7), 2011.
- [8] H.A. Habeeb, M.R. Alkarhari, F.R. Ramli, R. Hasan, and S. Maidin. *Strength and porosity of additively manufactured PLA using a low cost 3D printing*. Centre for Advanced Research on Energy, 2016.
- [9] Thomas Hänscheid. The future looks bright: Low-cost fluorescent microscopes for detection of mycobacterium tuberculosis and coccidia. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, 102(6):520–521, 2008.
- [10] Erik A. Rodriguez, Robert E. Campbell, John Y. Lin, Michael Z. Lin, Atsushi Miyawaki, Amy E. Palmer, Xiaokun Shu, Jin Zhang, and Roger Y. Tsien. The growing and glowing toolbox of fluorescent and photoactive proteins. *Trends in Biochemical Sciences*, 42(2):111–129, 2017.
- [11] ASMG-PT00-00001. <https://shorturl.at/kox7>, 2018.
- [12] Graham M. Gibson, Robert Archibald, Mark Main, and Akhil Kallepalli. Modular light sources for microscopy and beyond (ModLight). *HardwareX*, 13, 2023.
- [13] A.S. Sadun, Jamaludin Jalani, and J.A. Sukor. A comparative study on the position control method of dc servo motor with position feedback by using arduino. 11:10954–10958, 01 2016.
- [14] Cameron Smith. Single mode vs. multimode fiber... what's the difference? <https://shorturl.at/bvYGS>, 2020. Accessed: 10.04.2024.
- [15] Ibrahim Al-Bahadly and Rashid BERNDT. Led-based color sensing system. *Sens. Transducers J.*, 114:132–150, 03 2010.
- [16] Asa Tapley, Neil Switz, Clay Reber, J. Lucian Davis, Cecily Miller, John Baptist Matovu, William Worodria, Laurence Huang, Daniel A. Fletcher, and Adithya Cattamanchi. Mobile digital fluorescence microscopy for diagnosis of tuberculosis. *Journal of Clinical Microbiology*, 51(6):1774–1778, 2013.
- [17] Andrew R. Miller, Gregory L. Davis, Z. Maria Oden, Mohamad Reza Razavi, Abolfazl Fateh, Morteza Ghazanfari, Farid Abdolrahimi, Shahin Poorazar, Fatemeh Sakhaie, Randall J. Olsen, and et al. Portable, battery-operated, low-cost, bright field and fluorescence microscope. *PLoS ONE*, 5(8), 2010.
- [18] Guoliang Zhong and Jiang Liangzhong. Design of the closed loop speed control system for dc motor. *Computer and Information Science*, 2, 02 2009.
- [19] Parallax standard servo. [https://uk.robotshop.com/products/parallax-standard-servo?gad\\_source=1](https://uk.robotshop.com/products/parallax-standard-servo?gad_source=1), 2011. Accessed: 10.04.2024.
- [20] Julie Liner. Limbi servo angle accuracy (rotational tolerance) test plan. <https://shorturl.at/afKL7>, 2019. Accessed: 10.04.2024.
- [21] Ivan Moreno, Chang-Yu Tsai, David Bermudez, and Ching-Cherng Sun. Simple function for intensity distribution from leds - art. no. 66700h. *Proceedings of SPIE - The International Society for Optical Engineering*, 6670, 09 2007.
- [22] Rcd-24 series. <https://recom-power.com/en/products/led-driver/led-driver-dc-dc/rec-s-RCD-24.html?0>, 2016. Accessed: 10.04.2024.

- [23] Irina Bute, Sergejs Tarasovs, Sergejs Vidinejevs, Laima Vevere, Jevgenijs Sevcenko, and Andrey Aniskevich. Thermal properties of 3d printed products from the most common polymers. *The International Journal of Advanced Manufacturing Technology*, 124(7–8):2739–2753, 2022.
- [24] Liang Gao, Lin Shao, Bi-Chang Chen, and Eric Betzig. 3d live fluorescence imaging of cellular dynamics using bessel beam plane illumination microscopy. *Nature Protocols*, 9(5):1083–1101, 2014.
- [25] Jaroslav Ichá, Michael Weber, Jennifer C. Waters, and Caren Norden. Phototoxicity in live fluorescence microscopy, and how to avoid it. *BioEssays*, 39(8), 2017.
- [26] Joshua Balsam, Miguel Ossandon, Hugh Alan Bruck, Irina Lubensky, and Avraham Rasooly. Low-cost technologies for medical diagnostics in low-resource settings. *Expert Opinion on Medical Diagnostics*, 7(3):243–255, 2013.
- [27] The openflexure project. <https://openflexure.org/>. Accessed: 10.04.2024.