

Laser Pointer Turret Based Mosquito Air Defence System

Final Report

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in the Department of Electrical, Electronic and Computer Engineering

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Part 1. Preamble

This report describes work that I have completed in my final year project, developing a laser pointer turret based mosquito air defence system.

Project proposal and technical documentation

This main report contains an unaltered copy of the approved Project Proposal (as Part 2 of the report).

Technical documentation appears in Part 4 (Appendix).

All the code that I developed appears as a separate submission on the AMS.

Project history

This project does not extend on a previous project. The design and implementation is completely new.

I used library code for low level hardware interfacing with the camera and motors. The implementation of the Hungarian algorithm was taken from an existing software module. The rest of the work reported on here, is entirely my own.

Language editing

This document has been language edited by a knowledgeable person. By submitting this document in its present form, I declare that this is the written material that I wish to be examined on.

My language editor was Ms. M.B. Hartman.



Language editor signature

Monday 6th November, 2023

Date

Declaration

I, A.M. Hartman understand what plagiarism is and have carefully studied the plagiarism policy of the University. I hereby declare that all the work described in this report is my own, except where explicitly indicated otherwise. Although I may have discussed the design and investigation with my study leader, fellow students or consulted various books, articles or the internet, the design/investigative work is my own. I have mastered the design and I have made all the required calculations in my lab book (and/or they are reflected in this report) to authenticate this. I am not presenting a complete solution of someone else.

Wherever I have used information from other sources, I have given credit by proper and complete referencing of the source material so that it can be clearly discerned what is my own work and what was quoted from other sources. I acknowledge that failure to comply with the instructions regarding referencing will be regarded as plagiarism. If there is any doubt about

the authenticity of my work, I am willing to attend an oral ancillary examination/evaluation about the work.

I certify that the Project Proposal appearing as the Introduction section of the report is a verbatim copy of the approved Project Proposal.



A.M. Hartman

Monday 6th November, 2023

Date

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LIST OF ABBREVIATIONS

CAD	computer aided design
CCL	connected components labelling
CPU	central processing unit
CSI	camera serial interface
CUDA	compute unified device architecture
GPIO	general purpose input/output
GPU	graphics processing unit
GUI	graphical user interface
LED	light emitting diode
MIPI	mobile industry processor interface
PID	proportional-integral-derivative
PWM	pulse width modulation
RGB	red, green, blue
RPM	revolutions per minute
SORT	simple online and real-time tracking

Part 2. Project definition: approved Project Proposal

This section contains the problem identification in the form of the complete approved Project Proposal, unaltered from the final approved version that appears on the AMS.

For use by the Project lecturer**Feedback**

	Approved	Revision required
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To be completed by the student				
PROJECT PROPOSAL 2023				
		Project no	PdV3	Revision no
Title	Surname	Initials	Student no	Study leader (title, initials, surname)
Mr	Hartman	AM	20475323	Prof P. de Villiers
Project title	Laser pointer turret based mosquito air defence system			

Language editor details	Language editor signature
Vedre Hartman	
Student declaration	Study leader declaration
I understand what plagiarism is and that I have to complete my project on my own.	This is a clear and unambiguous description of what is required in this project. Approved for submission (Yes/No)
Student signature	Study leader signature and date
	

1. Project description

What is your project about? What does your system have to do? What is the problem to be solved?

The problem addressed in this project is the development of an automated system to shoot mosquitoes using a non-lethal laser turret. A non-lethal system is developed as a proof of concept. Mosquitoes carry dangerous diseases, such as malaria and dengue fever. Insect repellents are not 100% effective and need to be regularly reapplied to remain effective. Thus, the problem addressed in this project is to develop a new type of mosquito air defence system.

The concept is to detect mosquitoes using a camera and then "shoot" them down using a laser that is controlled by a turret system. In this project the mosquitoes will be in an enclosed tank. The project will entail the first principle design of an object detection algorithm that can recognise mosquitoes, a multi-target tracking algorithm which can track and make predictions for multiple targets, and a control system for the laser turret which can "shoot" at the target mosquito.

2. Technical challenges in this project

Describe the technical challenges that are *beyond* those encountered up to the end of third year and in other final year modules.

2.1 Primary design challenges

A fundamental challenge in the design of the laser pointer turret based mosquito air defence system is the reliable detection and localisation of mosquitoes. To achieve this, an algorithm must be developed that can associate detections of mosquitoes over time to track their movement. Additionally, a reliable prediction algorithm must be developed to predict the future state of mosquitoes based on their previous states. A core design challenge is to convert the position of a detection into an angular coordinate that the laser turret can target. The laser turret system must target a position with sufficient accuracy to illuminate the body of a mosquito while being able to move with enough speed to track it.

2.2 Primary implementation challenges

A primary implementation challenge is real-time detection and association of mosquito movements over time, with prediction of their future states, all on an embedded platform. A suitable model to represent mosquito motion must be selected to create an accurate state prediction model. Developing a control model for the laser turret and detecting the actual position of the laser is also a significant challenge. Implementing a turret system will sufficient speed and accuracy poses a critical challenge. Obtaining sufficient mosquitoes for testing and demonstration is an additional practical challenge.

3. Functional analysis

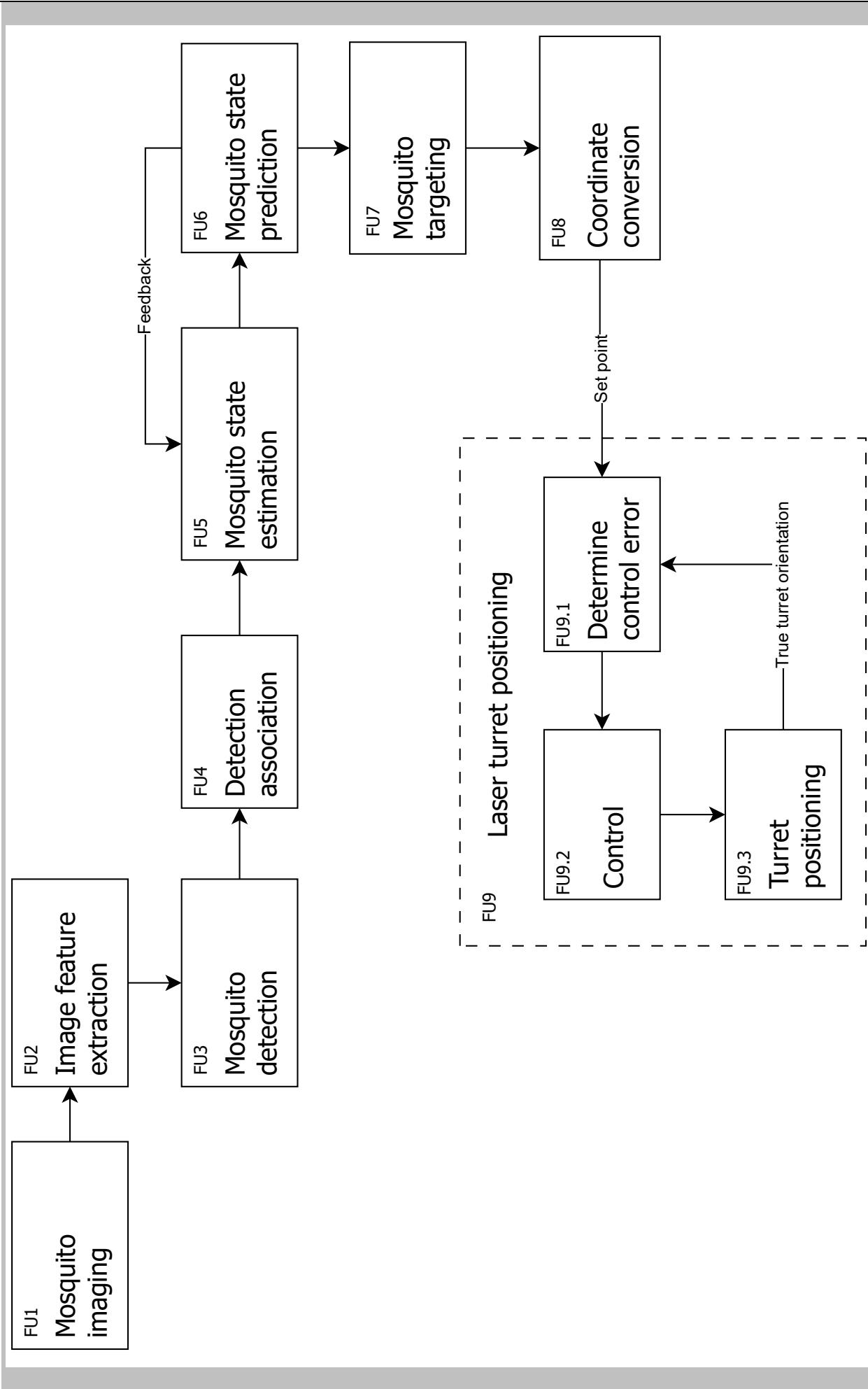
3.1 Functional description

Describe the design in terms of system functions as shown on the functional block diagram in section 3.2. This description should be in *narrative format*. DO NOT use a bullet list.

The system will image the mosquito enclosure (FU1). The system will then extract the features from the image (FU2). The system will detect all the moving mosquitoes in the enclosure (FU3). The system will then associate the mosquito detections over time to determine the past movement of the mosquitoes (FU4). The system will then determine the current state of the mosquitoes using the movement history (FU5). The system will then use the current state of the mosquitoes and a model for the movement of mosquitoes to predict the future state of the mosquitoes (FU6). The system will then select a mosquito to target (FU7). The position of the target mosquito is then converted from rectangular coordinates into angular coordinates that can be targeted by the laser turret (FU8). The laser turret must then move to the target position. The system must then detect the actual position of the laser. This will be used as feedback to adjust the position of the laser to reach the target position (FU9).

3.2 Functional block diagram

(this should not be a flow diagram)



4. System requirements and specifications

These are the core requirements of the system or product (the mission-critical requirements) in table format **IN ORDER OF IMPORTANCE**. Requirement 1 is the most fundamental requirement.

	Requirement 1: the fundamental functional and performance requirement of your project	Requirement 2 (Number 2 in the order of importance)	Requirement 3
1. Core mission requirements of the system or product: Focus on requirements that are core to solving the engineering problem. These will reflect the solution to the problem.	The system must track and illuminate mosquitoes with a laser in an enclosure.	Detect moving mosquitoes in the enclosure.	Track mosquitoes over time. (Associate mosquitoes detections between frames.)
2. What is the target specification (in measurable terms) to be met in order to achieve this requirement?	The system must be able to illuminate a mosquito every 5 seconds.	The system must have a 0.9 probability of detection and a 0.05 probability of false alarm. Detection will be performed at an update interval of 500ms.	After 5 seconds there must be a minimum of 0.9 probability of correct association in each step of tracking the mosquitoes.
3. Motivation: Defend the specific target specification selected, i.e. the value. Why will meeting the specification given in point 2 above solve the problem?	5 seconds is a reasonable amount of time to acquire the next mosquito and reposition the laser to be ready for the next "shot".	90% is a high probability of detection and 5% is low enough that little time will be wasted on false alarms (mosquitoes that do not exist).	The system must be able to associate mosquitoes from one frame the next to target the mosquitoes. 90% is high yet reasonable probability of correct association. 90% is an acceptable rate for most tracking systems.
4. How will you demonstrate at the examination that this requirement and specification (points 1 and 2 above) have been met? Be explicit about how you will prove these were met.	The display will indicate the time that has elapsed since the targeting began until the mosquito has been illuminated. The constant illumination of mosquitoes by the laser will demonstrate correct functioning of the system.	The system will have a display that shows the video feed with the mosquitoes identified. This can be paused and inspected to verify that the requirement is met.	The display will show the tracks (lines) that follow a specific mosquito over time.
5. Your own design contribution: what are the aspects that you will design and implement yourself to meet the requirement in point 2? If none remove this requirement.	The image processing system, the prediction algorithm of the mosquitoes future location, the targeting algorithm, and the control system for the laser turret.	The detection algorithm will be developed by the student and implemented on an embedded microprocessor.	The target tracking algorithm will be developed by the student.
6. What are the aspects to be taken off the shelf to meet this requirement? If none, clearly indicate "none". Explicitly indicate what tasks library functions will be used for (if relevant to the project).	The embedded platform, the camera, the laser, the motors, the motor drivers, and the power supply will be off the shelf.	The embedded platform, the camera, and the display will be off the shelf.	The embedded platform will be off the shelf.

System requirements and specifications page 2

	Requirement 4	Requirement 5	Requirement 6
1. Core mission requirements of the system or product: Focus on requirements that are core to solving the engineering problem. These will reflect the solution to the problem.	Control the position of the laser to illuminate the target position (set point).		
2. What is the target specification (in measurable terms) to be met in order to achieve this requirement?	The laser must be able to illuminate the set point within 2 seconds accurate to within 1mm.		
3. Motivation: Defend the specific target specification selected, i.e. the value. Why will meeting the specification given in point 2 above solve the problem?	The laser must be able to reach the set point within one second such that the overall system specification is reached. A typical mosquito is 2mm wide thus the precision must be at least half this.		
4. How will you demonstrate at the examination that this requirement and specification (points 1 and 2 above), have been met? Be explicit about how you will prove these were met.	The system will draw a 1mm circle around the set point and indicate if the laser reached this target within 2 seconds.		
5. Your own design contribution: what are the aspects that you will design and implement yourself to meet the requirement in point 2? If none, remove this requirement.	The turret model and control system with set point, settling time, and overshoot will be developed by the student.		
6. What are the aspects to be taken off the shelf to meet this requirement? If none, indicate "none". Explicitly indicate what tasks library functions will be used for (if relevant to the project).	The motors, turret housing, motor drivers, and the power supply will be off the shelf. The laser will be off the shelf.		

5. Field conditions

These are the REAL WORLD CONDITIONS under which your project has to work and has to be demonstrated.

	Real world field condition 1	Real world field condition 2	Real world field condition 3
Field condition requirement. In which field conditions does the system have to operate? Indicate the one, two or three most important field conditions.	The mosquitoes will be in an enclosed tank where the lighting conditions will be controlled.	If mosquitoes cannot be obtained a suitable substitute will be used.	
Field condition specification. What is the specification (in measurable terms) for this field condition?	The tank must be at least 1 metre wide. All the sides of the tank except the front facing side will have a white lining.	The substitute will be a similar flying insect.	

6. Student tasks

6.1 Design and implementation tasks

List your primary design and implementation tasks in bullet list format (5-10 bullets). These are not product requirements, but your tasks.

- The student needs to develop a mosquito detection algorithm.
- The student needs to develop a detection association algorithm.
- The student needs to develop a mosquito state prediction algorithm.
- The student needs to design a control system and interface for the laser turret.
- The student needs to select appropriate hardware for the laser turret.
- The student needs to select an appropriate camera.
- The student needs to acquire a laser that will be able to kill mosquitoes.

6.2 New knowledge to be acquired

Describe what the theoretical foundation to the project is, and which new knowledge you will acquire (*beyond* that covered in any other undergraduate modules).

- The student needs to learn how to develop computer vision algorithms.
- The student needs to learn how to associate, track, and predict the movement of objects.
- The student needs to learn how to model a laser turret.
- The student needs to learn how to interface and control a turret system.
- The student needs to learn how to interface and work with live video.
- The student needs to learn how to control motors.

Part 3. Main Report

1. Literature study

Malaria is still one of the leading causes of death in low-income countries according to the World Health Organisation [1]. Mosquitoes that do not carry diseases are also a general nuisance in the everyday life of people living in mosquito-prone areas. The main defence mechanism employed against mosquitoes are mosquito repellents. Mosquito repellents do provide a certain degree of relief against pestering mosquitoes, however repellents only provide temporary relief. Electric insect killers is the other main defence mechanism employed against mosquitoes. These devices use ultraviolet light to attract insects and electrocute them when they come into contact with an electrified grid or a similar mechanism. The devices are obtrusive and ineffective on mosquitoes that were not attracted by the ultraviolet light. Therefore, it is necessary to pursue improvement in our defence against mosquitoes. A laser turret based mosquito defence system could prove to be an unobtrusive and effective defence mechanism against mosquitoes.

The successful development of such a mosquito defence system will require accurate detection and tracking of mosquitoes. The tracking of mosquitoes is a challenging task because of the small size of mosquitoes and their erratic flight patterns. The detection and tracking solutions investigated will be based on camera imaging. There are two main approaches to object tracking: appearance-based tracking and tracking-by-detection. Appearance based tracking approaches utilise the appearance of the object directly in the tracking process, while tracking-by-detection approaches rely on an external object detectors.

Deep learning object detection algorithms have been shown to be effective in detecting objects based on appearance. Creating a deep learning detection algorithm require large sets of training data. Collecting a large set of mosquito images for training will be a challenging task. A popular deep learning object detection and identification system is the YOLOv3 algorithm. Appearance based detection can also be applied using a pattern matching approach. In general pattern matching is searching and checking images for the presence of other given images (patterns) to find and mark the patterns' locations (if any) within the given images. Appearance based detection models require high quality image data since the detection is based on appearance. This can be highly beneficial when features can be extracted from an object's appearance or the object's orientation can be estimated based on its appearance. The study conducted by Hurtik et al. [2] presents results based on F-transform pattern matching. The best operating frame rate that was achieved in [2] was 0.43 frames per second. This is far too slow to be used in a real-time tracking applications. A frame rate of at least 5 frames per second is required to achieve good real-time performance especially when the tracking subject exhibits erratic behaviour such as a mosquito. Appearance based detection and tracking approaches are only viable for mosquitoes when imaged close-up. A laser turret mosquito targeting system is not feasible when close-up imaging is required to detect and track mosquitoes. This is because the laser turret will be required to target mosquitoes over a large area in order for it to be effective. Therefore, appearance based detection and tracking approaches will not be suitable for the proposed mosquito defence system.

An alternative to the appearance based detection approaches is to detect objects by isolating the background and foreground of the image [3]. The laser turret based mosquito defence system will be developed to operate in a controlled environment. The background of the environment

will exhibit little to no change and will be uniform. This will enable the background of the image to be isolated from the foreground. The foreground of the image should only contain the objects of interest. In [4], a dual foreground and background model is proposed to improve mosquito detection accuracy. This should not be required for laser turret mosquito defence system since the mosquitoes will be in a controlled environment. Detected objects that are too close to one another are split into two, and abnormally small objects are merged in [4].

Tracking-by-detection approaches are more suitable for the proposed mosquito defence system. Tracking-by-detection approaches are based on the detection of objects in a scene and the tracking of the detected objects. Tracking-by-detection can be performed using particle filter-based tracking. A particle filter considers the proximity and behaviour of other targets. In the case of social insect tracking, it is known that two targets cannot occupy the same space, and targets will actively avoid collisions. The joint particle tracker proposed in [5] is highly accurate but unfortunately, it suffers from exponential complexity. This computational complexity is not feasible in real-time multi-target tracking system.

The simple online and real-time tracking (SORT) algorithm proposed in [6] has a main focus to associate objects efficiency for online and real-time applications. The SORT uses the combination of a Kalman filter and the Hungarian algorithm. The Kalman filter is an optimal linear state estimator. The Hungarian algorithm is an optimal assignment algorithm. The performance of the SORT algorithm can be seen in Figure 1. The SORT algorithm employs a

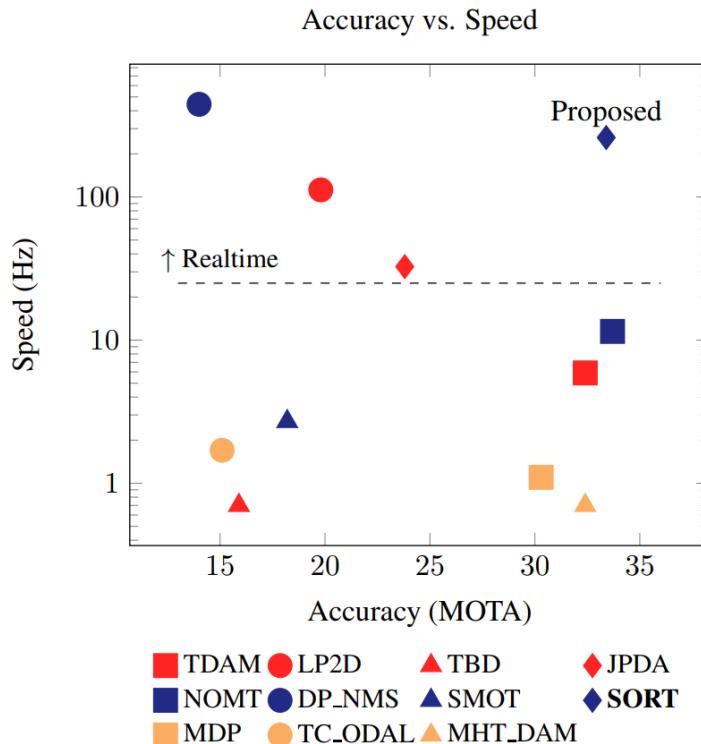


Figure 1.
Performance of the SORT algorithm [6].

Kalman filter for each object that is being tracked. The Kalman filter is used to predict the future location of the object. The Hungarian algorithm is used to assign detections to tracks.

The Kalman filter requires a series of matrix operations to be performed for each object that is being tracked. The Hungarian algorithm has a time complexity of $O(n!)$. The computational complexity of the SORT tracking makes it suitable for the proposed mosquito defence system.

The laser pointer turret based mosquito air defence system will be developed using a tracking-by-detection paradigm. The appearance based detection approaches are not suitable for the proposed system because of the small size of mosquitoes and the large area that the laser turret will be required to cover. The mosquito detection system will be design using a background and foreground isolation approach similar to the approaches described in [3] and [4]. The computational complexity of particle filter based tracking approaches make them infeasible for real-time requirements of the system. The tracking system will be based on the SORT algorithm proposed in [6]. The SORT algorithm is ideally suited for laser turret mosquito defence system since it was designed to be implemented in online real-time systems.

2. Approach

The aim of this project was to develop a system that would track and illuminate mosquitoes with a laser. The system will detect mosquitoes using a camera and the laser will be controlled by a turret system. The system is implicitly required to operate in real-time in order to track and illuminate mosquitoes with a laser. This was taken into consideration in all the design aspects of the system. The project entails the first principles design of the following:

- A laser turret that can change the position of a laser beam.
- A control system that can control the laser turret.
- An object detection algorithm that can detect mosquitoes.
- An object detection algorithm that can detect the reflections of the laser beam.
- A multi-target tracking algorithm that can track multiple mosquitoes and predict their future locations.

The laser turret was inspired by two-axis laser scanners that use two mirrors to direct a laser beam in two dimensions as illustrated in Figure 8. The advantages of this approach compared to moving that laser diode itself is that the mirrors are rotated about their centre of mass which reduces the torque required to rotate the mirrors. This enables the laser turret to rapidly change the position of the mirrors and in turn the position of the laser beam. The drawback of this approach is that there will be additional scattering of the laser beam due to imperfections in the mirrors. This will not have significant impact on the system, therefore, this approach was chosen for the laser turret. A closed-loop proportional-integral-derivative (PID) control system will be used to control the laser turret. The laser position feedback for the control system will be provided by the laser detection system.

The object detection algorithm to detect mosquitoes can be implemented using a deep learning approach that will enable the identification and appearance matching of mosquitoes. This approach is computationally expensive and will require quality high-resolution images of mosquitoes. A less computational expensive approach is to use image segmentation techniques to separate the mosquitoes from the background of the image. An image segmentation approach greatly reduces the computational complexity at the expense of flexibility and robustness. Another trade-off to consider is that this approach will not be able to distinguish between mosquitoes and other objects similar in appearance. Image segmentation does not require the same quality and resolution images as a deep learning approach since it will not distinguish between objects of similar appearance. The benefits of an image segmentation approach outweigh the trade-offs compared to a deep learning approach for this project. Therefore, the image segmentation approach was chosen for this project.

The same considerations were made for the object detection algorithm to detect the reflections of the laser beam. An image segmentation approach was chosen for the same reasons as discussed above.

The multi-target tracking algorithm is required to track and predict the locations of mosquitoes. This can be efficiently achieved using a Kalman filter for one object. The Kalman filter is a recursive algorithm that can be used to estimate the state of a system that is subject to random noise. The Kalman filter is able to recursively predict the future state of a system,

which is required to predict the future locations of a mosquito. This can be extended to track multiple objects using the SORT algorithm that combines the Kalman filter and the Hungarian algorithm. The Hungarian algorithm is an optimal assignment algorithm that can be used to assign detections to tracks. The SORT algorithm is less computationally complex than other multi-target tracking algorithms while maintaining a comparable or higher accuracy [6].

A high-level overview of the system can be seen in Figure 2. The system was designed to operate in a controlled environment.

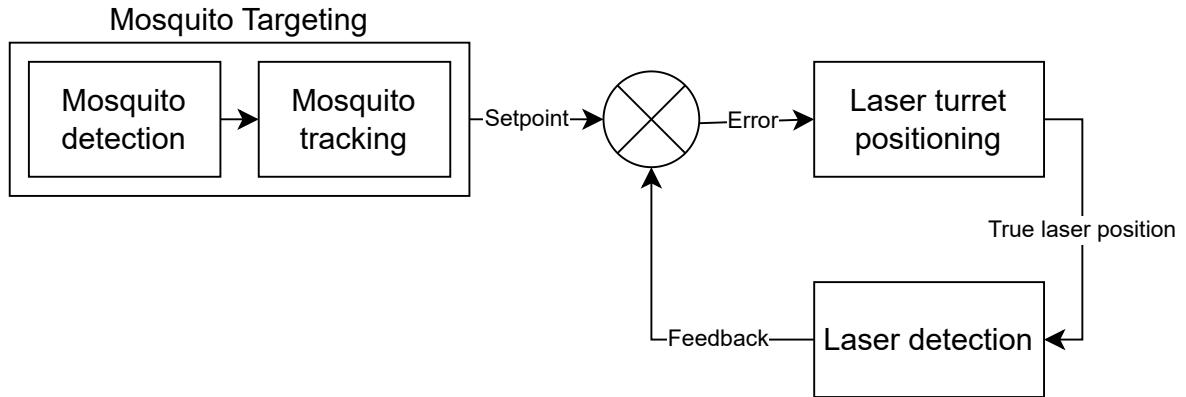


Figure 2.
Overview of the system.

3. Design and implementation

3.1 Design summary

This section summarises the project design tasks and how they were implemented (see Table 1).

Deliverable or task	Implementation	Completion of deliverable or task, and section in the report
The laser turret and laser turret control system had to be designed and implemented by the student.	The laser turret and laser turret control system were designed and implemented from first principles.	Completed. Sections 3.3 to 3.6
The mosquito and laser detection algorithm had to be designed and implemented on an embedded platform by the student.	The mosquito and laser detection algorithm was designed and implemented from first principles.	Completed. Sections 3.5 and 3.6
The mosquito tracking and prediction algorithm had to be developed and implemented by the student.	The mosquito tracking algorithm and prediction was developed and implemented from first principles.	Completed. Sections 3.5 and 3.6
An appropriate camera had to be selected by the student.	An appropriate camera was selected by the student.	Completed. Section 3.3.2

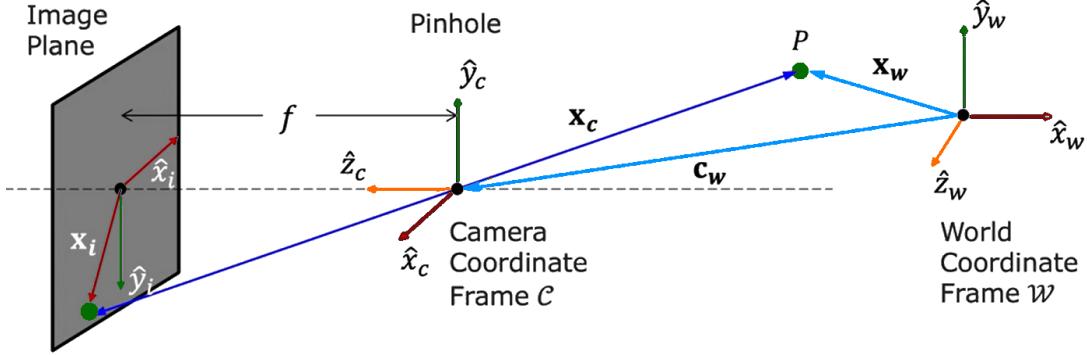
Table 1.
Design summary.

3.2 Theoretical analysis and modelling

3.2.1 Mapping pixel co-ordinates to metric co-ordinates

To control the laser, its position must be known in the world co-ordinate frame. The laser position was measured using a camera, thus the camera's pixel co-ordinate frame must be mapped to the world co-ordinate frame. To perform this mapping a camera model is required. The forward imaging model of a camera is shown in Figure 3.

Using the forward imaging model the pixel distance was mapped to the metric distance for

**Figure 3.**

Forward imaging model of a camera. This figure was modified from [7].

the x -axis with

$$X = Z \times \left(\frac{x - x_{ref}}{f_x} \right), \quad (1)$$

where Z is the depth camera with respect to the world co-ordinate frame, x is the pixel of interest, x_{ref} is the reference pixel, and f_x is the effective focal length of the camera. Similarly, the pixel distance was mapped to the metric distance for the y -axis. The effective focal length of the camera f_x was determined through camera calibration. The mapping is performed for the y -axis.

3.2.2 Morphological operations

Erosion is a fundamental morphological operation used to remove small structures or details from a binary image. It is defined as the basic set operation of moving a structuring element (usually a smaller binary matrix) over the input binary image and finding the intersection of the structuring element with the image. This operation can be mathematically expressed as

$$(A \ominus B)(x, y) = \bigcap \{A(x+i, y+j) | (i, j) \in B\}, \quad (2)$$

where

- A is the input binary image.
- B is the structuring element.
- \ominus represents the erosion operation.
- (x, y) are the pixel co-ordinates in the resulting image.

Dilation is another fundamental morphological operation, but it is used to enhance or grow the features in a binary image. Dilation can be defined as the set operation that moves the structuring element over the input image and computes the union of the element with the parts of the image where the structuring element "hits". The mathematical expression for dilation is as follows:

$$(A \oplus B)(x, y) = \bigcup \{A(x+i, y+j) | (i, j) \in B\} \quad (3)$$

where

- A is the input binary image.

- B is the structuring element.
- \oplus represents the dilation operation.
- (x,y) are the pixel co-ordinates in the resulting image.

The erosion and dilation operations are illustrated in Figure 4.



(a) The erosion of the dark-blue square by a disk, resulting in the light-blue square. **(b) The dilation of a dark-blue square by a disk, resulting in the light-blue square with rounded corners.**

Figure 4.

The figure shows an example of erosion and dilation. This figure was modified from [8].

Opening is a compound morphological operation that consists of an erosion followed by a dilation using the same structuring element. It is primarily used to remove noise and small objects from a binary image. The opening of an image A by a structuring element B is defined as

$$A \circ B = (A \ominus B) \oplus B, \quad (4)$$

where

- A is the input binary image.
- B is the structuring element.
- \circ represents the opening operation.

Closing is another compound morphological operation that consists of dilation followed by an erosion using the same structuring element. It is used to close small holes and gaps in objects and to connect nearby objects. The closing of an image A by a structuring element B is defined as

$$A \bullet B = (A \oplus B) \ominus B, \quad (5)$$

where

- A is the input binary image.
- B is the structuring element.
- \bullet represents the closing operation.

Opening and closing are both idempotent operations, meaning that repeated openings or closing have no effect on the image. Opening and closing is illustrated in Figure 5.



(a) The opening of the dark-blue square by a disk, resulting in the light-blue square with round corners.

(b) The closing of the dark-blue shape (union of two squares) by a disk, resulting in the union of the dark-blue shape and the light-blue areas.

Figure 5.

The figure shows and example of opening and closing. This figure was modified from [8].

3.2.3 Kalman filter

The Kalman filter is a recursive algorithm that estimates the state of a system from a series of noisy measurements. The Kalman filter is based on a linear dynamical system model, which is defined by the following equations:

$$\begin{aligned} \mathbf{x}_k &= \mathbf{Ax}_{k-1} + \mathbf{Bu}_{k-1} + \mathbf{w}_{k-1}, \\ \mathbf{z}_k &= \mathbf{Hx}_k + \mathbf{v}_k, \end{aligned} \quad (6)$$

where

- \mathbf{x}_k is the state vector at time k .
- \mathbf{z}_k is the measurement vector at time k .
- \mathbf{A} is the state transition matrix.
- \mathbf{B} is the control matrix.
- \mathbf{u}_k is the control vector at time k .
- \mathbf{w}_k is the process noise vector at time k .
- \mathbf{H} is the observation matrix.
- \mathbf{v}_k is the measurement noise vector at time k .

The Kalman filter algorithm can be divided into two phases: the prediction phase and the update phase. The equations for the prediction phase is

$$\begin{aligned} \hat{\mathbf{x}}_k^- &= \mathbf{A}\hat{\mathbf{x}}_{k-1} + \mathbf{B}\mathbf{u}_{k-1}, \\ \mathbf{P}_k^- &= \mathbf{AP}_{k-1}\mathbf{A}^T + \mathbf{Q}, \end{aligned} \quad (7)$$

where

- $\hat{\mathbf{x}}_k^-$ is the a priori state estimate at time k .
- \mathbf{P}_k^- is the a priori error covariance matrix at time k .
- \mathbf{Q} is the process noise covariance matrix.

The equations for the update phase is

$$\begin{aligned}\mathbf{K}_k &= \mathbf{P}_k^- \mathbf{H}^T (\mathbf{H} \mathbf{P}_k^- \mathbf{H}^T + \mathbf{R})^{-1}, \\ \hat{\mathbf{x}}_k &= \hat{\mathbf{x}}_k^- + \mathbf{K}_k (\mathbf{z}_k - \mathbf{H} \hat{\mathbf{x}}_k^-), \\ \mathbf{P}_k &= (\mathbf{I} - \mathbf{K}_k \mathbf{H}) \mathbf{P}_k^-,\end{aligned}\quad (8)$$

where

- \mathbf{K}_k is the Kalman gain at time k .
- $\hat{\mathbf{x}}_k$ is the a posteriori state estimate at time k .
- \mathbf{P}_k is the a posteriori error covariance matrix at time k .
- \mathbf{R} is the measurement noise covariance matrix.

The Kalman filter, initialised with an initial state estimate $\hat{\mathbf{x}}_0$ and error covariance \mathbf{P}_0 , is a recursive, adaptive, and linear estimator that optimally minimises the mean square error for real-time state estimation of linear systems with computational efficiency.

3.3 Hardware design

The hardware block diagram is presented in Figure 6. The hardware consists primarily of a laser turret, a camera, a mosquito enclosure, and an embedded processing platform. The laser turret is used to move the laser beam across the mosquito enclosure. The camera is used to detect the laser beam and the mosquitoes. A bracket is used to position the laser turret and the camera relative to the mosquito enclosure. The embedded processing platform is used to control the laser turret and perform the image processing required for the laser detection and mosquito detection.

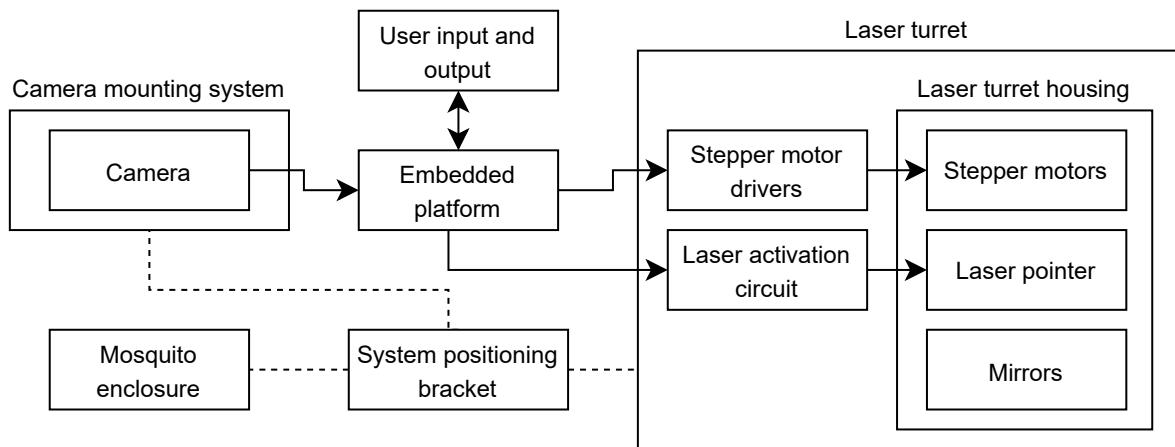


Figure 6.
Hardware block diagram.

3.3.1 *Embedded platform selection*

To select an embedded platform for the project the following requirements were considered:

Processing power

The embedded platform must be able to perform the image processing required for the laser detection and mosquito detection in real-time. Image processing is computationally intensive, but can largely benefit from parallelisation. Therefore, an embedded platform with a graphics processing unit (GPU) will be preferred.

Memory

The embedded platform must have sufficient memory to store the multiple images along with the required algorithms. A 1080p image with three 8-bit colour channels requires 6 MB of memory.

Hardware interfaces

The embedded platform must be compatible with camera interfaces. It must also have sufficient general purpose input/output (GPIO) pins to interface with the stepper motor drivers. The embedded platform must also have support for a display output and a keyboard and mouse input to provide a user interface to control the system.

Availability and support

It is important to select an embedded platform that is readily available. It is important to select an embedded platform with large body of knowledge available and sufficient scientific support community since this is an individual project without access to people with expertise with the embedded platform.

The Nvidia Jetson Nano was chosen as the embedded platform for the project. The Nvidia Jetson Nano is a single-board computer with a GPU and a quad-core central processing unit (CPU). The Nvidia Jetson Nano has a mobile industry processor interface (MIPI) camera serial interface (CSI)-2 camera interface and has 40 GPIO pins. The Jetson Nano has a quad-core ARM Cortex-A57 MPCore processor, an Nvidia Maxwell GPU with 128 compute unified device architecture (CUDA) cores, and 4 GB of LPDDR4 memory. It also features an HDMI display output and a USB 3.0 port. The Nvidia Jetson Nano is readily available and has a large body of knowledge available and sufficient scientific support community.

3.3.2 *Camera selection*

To minimise the computational complexity of the image processing required for the laser detection and mosquito detection a low video resolution will be used. The video resolution will not need to exceed 1080p. The camera must be able to capture images at a frame rate of at least 30 frames per second. The camera must also be compatible with the MIPI CSI-2 interface on the Nvidia Jetson Nano.

The Raspberry Pi Camera Module V2 was chosen as the camera for the project. The Raspberry Pi Camera Module V2 is an 8 MP camera that can capture images at a frame rate of 30 frames

per second at 1080p. The Raspberry Pi Camera Module V2 is compatible with the MIPI CSI on the Nvidia Jetson Nano. The Raspberry Pi Camera Module V2 is readily available and has a large body of knowledge available and sufficient scientific support community.

3.3.3 Mosquito enclosure

The mosquito enclosure will be a rectangular prism as shown in Figure 7. The front facing surface will be transparent and the rest of the surfaces will be white. The enclosure will be fitted with internal lighting to ensure contrast between the background and the mosquitoes and to minimise the camera noise.

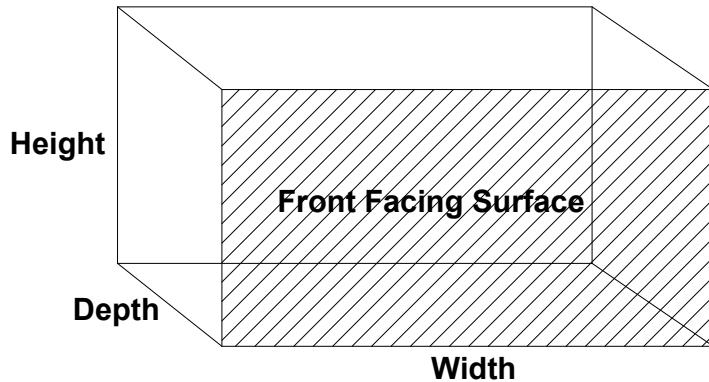


Figure 7.
Mosquito enclosure.

3.3.4 Laser turret

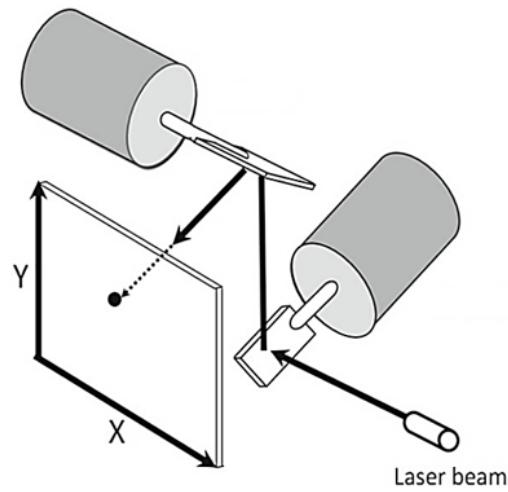
The laser turret design was inspired by commercial two-axis laser scanners. The position of the laser beam is controlled by adjusting the angles of two mirrors. This is illustrated in Figure 8. The mirrors are connected directly to the output shaft of the motors. The laser turret will be positioned orthogonally to the xy -plane of the mosquito enclosure. The point where the laser beam shines orthogonal to the xy -plane of the mosquito enclosure is considered the origin of the laser. This will occur when the two mirrors are at 45° relative to the laser beam.

When a single axis of the laser turret is considered it can be seen that a right triangle is formed between the laser turret and the xy -plane mosquito enclosure as shown in Figure 9. Using the properties of a right triangle the laser beam angle θ required to shine the laser a distance d relative to the origin of the laser can be calculated using

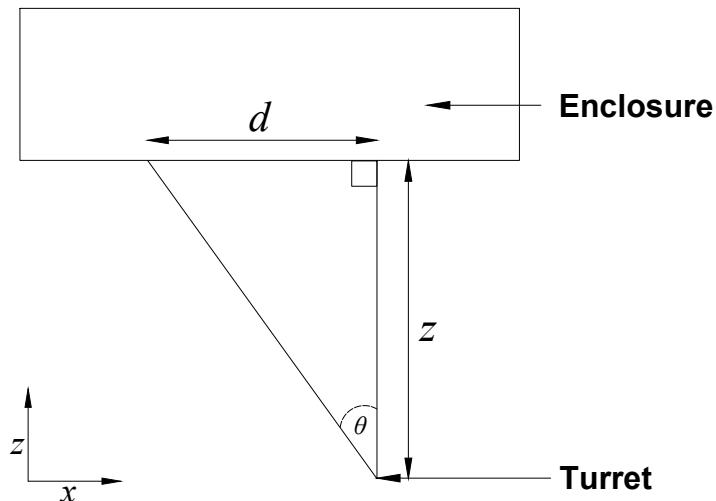
$$\theta = \arctan\left(\frac{d}{z}\right), \quad (9)$$

where z is the distance between the turret and the back wall of the mosquito enclosure.

The lateral step size of the laser must be a maximum of $d_{min} = 2$ mm. This will ensure that the laser will be able to illuminate every position in the mosquito enclosure since the laser itself will be a few millimetres wide.

**Figure 8.**

Two-axis laser scanner schematic. This figure was modified from [9].

**Figure 9.**

The right triangle formed between the laser turret and the mosquito enclosure.

The required lateral speed is determined in accordance with the field specifications. The longest length of the mosquito enclosure d_{max} will be 1 m. To ensure that the laser can illuminate any setpoint inside the mosquito enclosure within 2 s of receiving a step input, it was assumed that the laser must be able to move with a velocity v_{laser} of least 1 m s^{-1} opposed to the 0.5 m s^{-1} required to move the 1 m length of the mosquito enclosure within 2 s. This was done to accommodate for the settling time of the laser turret control system.

3.4 Hardware implementation

3.4.1 Mosquito enclosure

The mosquito enclosure was constructed from a second hand glass fish tank. All the surfaces other than front facing surface was retrofitted with a white lining. Internal light emitting diodes (LEDs) were added to the enclosure, shining from the top and bottom surfaces to minimise shadows on the back surface the enclosure, to ensure contrast between the background and the mosquitoes and to minimise the camera noise.

3.4.2 System positioning

The laser turret and the camera was placed outside the mosquito enclosure in known positions relative to the enclosure. The bracket, shown in Figure 10, was built to hold the laser turret and the camera in place relative to the mosquito enclosure. The laser turret and camera will be mounted on the bracket using 3D printed clamps.

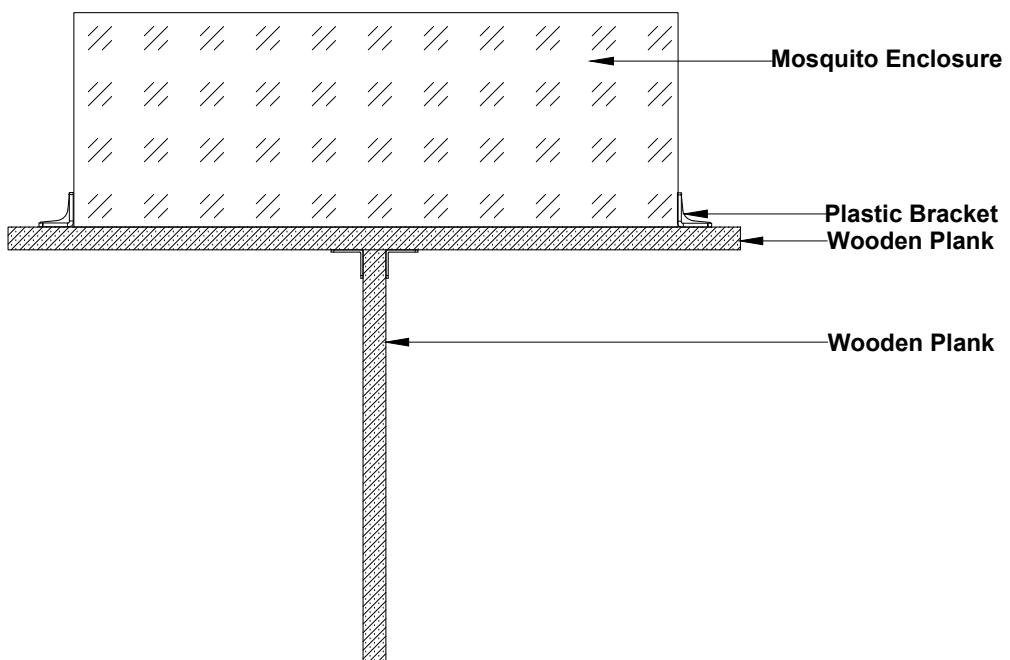


Figure 10.
System positioning bracket.

3.4.3 Camera mounting

The camera was mounted on the bracket in Figure 10 using a 3D printed camera mount. The camera mount was designed to be adjustable to ensure that the camera can be positioned in the centre of the mosquito enclosure. The camera mounts were designed in computer aided design (CAD). The camera mount is shown in Figure 11.

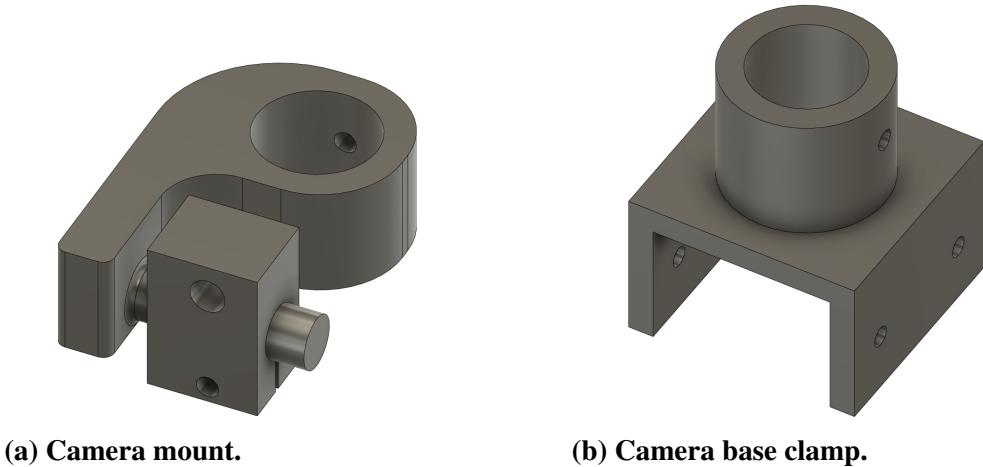


Figure 11.
The camera mount and camera base clamp.

3.4.4 Laser turret

The specific geometry of the laser turret was designed with the goal to practically obtain a sufficiently small lateral step size of the laser on the back wall of the mosquito enclosure, while maintaining sufficient speed. The dimensions of the mirrors were chosen for practicality as $30 \times 15 \times 3$ mm.

a. Angular step size

The turret axis on which the laser beam is first incident on will be referred to as the first axis and the other axis will be referred to as the second axis for the remainder of this discussion. The rotation range of the first axis is bounded by the geometry of the turret since the laser beam reflected from the first axis must be incident on the second axis. With the chosen mirror dimensions, the maximum angle through which the first axis can rotate is 40° , which rotates the laser beam through 80° . This was determined geometrically in the scale drawing in Figure 12. To accommodate for the mounting and alignment of the mirrors as well as other imperfections it was decided to consider a maximum rotation of 20° , resulting in $\theta_{laser}^{max} = 40^\circ$. The rotation range of the second axis is not bounded by the geometry of the laser turret since the laser beam reflected from the second axis is incident on the mosquito enclosure. Therefore, the laser turret will be oriented such that the first axis moves the laser beam parallel to the

shorter height of the mosquito enclosure and the second axis moves the laser beam parallel to the longer width of the mosquito enclosure.

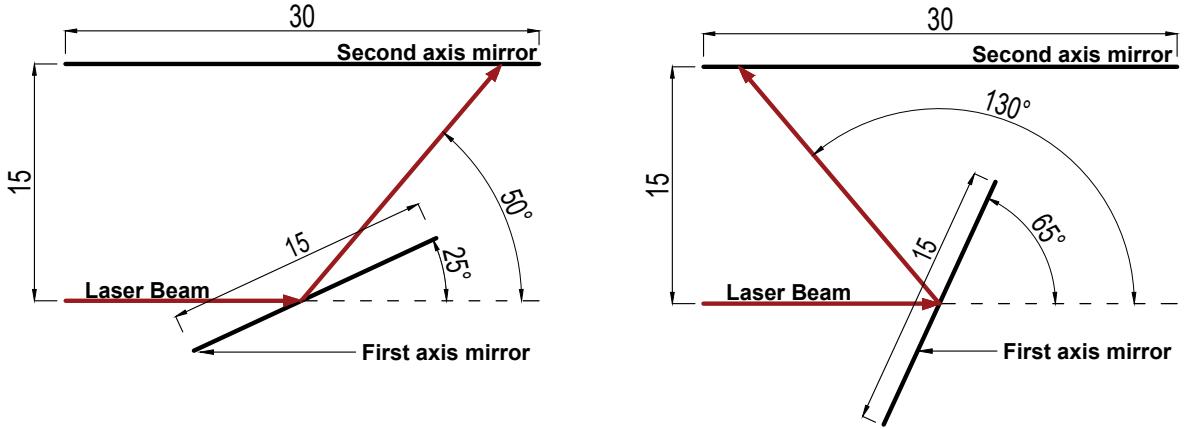


Figure 12.
The rotation range of the first axis with chosen mirror dimensions.

The minimum distance z_{min} between the laser turret and the mosquito enclosure can be determined by rearranging Equation 9 to give

$$z_{min} = \frac{d}{\tan(\theta_{laser}^{max})} = \frac{38\text{cm}}{\tan(40^\circ)} = 45.3\text{cm}, \quad (10)$$

where $d = 38\text{ cm}$ is the height of the mosquito enclosure and $\theta_{laser}^{max} = 40^\circ$ is the maximum angle through which the first axis of the laser can rotate. The maximum step resolution θ_{step}^{max} of the motors can be calculated by substituting z_{min} and the required lateral step size d_{min} into an equation derived from Equation 9 given by

$$\theta_{step}^{max} = \frac{1}{2} \arctan\left(\frac{d_{min}}{z_{min}}\right) = \frac{1}{2} \arctan\left(\frac{2\text{mm}}{45.3\text{cm}}\right) = \frac{0.253^\circ}{2} = 0.126^\circ. \quad (11)$$

The division by two in Equation 11 is done to compensate for the fact the laser beam angle is double the mirror angle.

b. Angular speed

The maximum angular speed ω_{max} required by the motors can be determined with $d_{max} = 1\text{ m}$, $v_{laser} = 1\text{ m s}^{-1}$, and $z_{min} = 45.3\text{ cm}$. The maximum angle through which the turret must rotate is

$$\theta_{motor}^{max} = \frac{1}{2} \arctan\left(\frac{d_{max}}{z_{min}}\right) = \frac{1}{2} \arctan\left(\frac{1\text{m}}{45.3\text{cm}}\right) = \frac{65.6^\circ}{2} = 32.8^\circ. \quad (12)$$

The maximum angular speed required to move the laser beam at the lateral speed $v_{laser} = 1\text{ m s}^{-1}$ is

$$\omega_{max} = v_{laser} \times \theta_{motor}^{max} = 32.8^\circ \text{ s}^{-1} = 0.572 \text{ rad s}^{-1}. \quad (13)$$

The results in a required motor revolutions per minute (RPM) of

$$\omega_{max} = 0.572 \text{ rad s}^{-1} \times \frac{60}{2\pi} = 5.5 \text{ RPM}. \quad (14)$$

c. Torque

The required torque τ was calculated using

$$\tau = I\alpha, \quad (15)$$

where I is the moment of inertia of the load, which is the mirror, and α is the required angular acceleration.

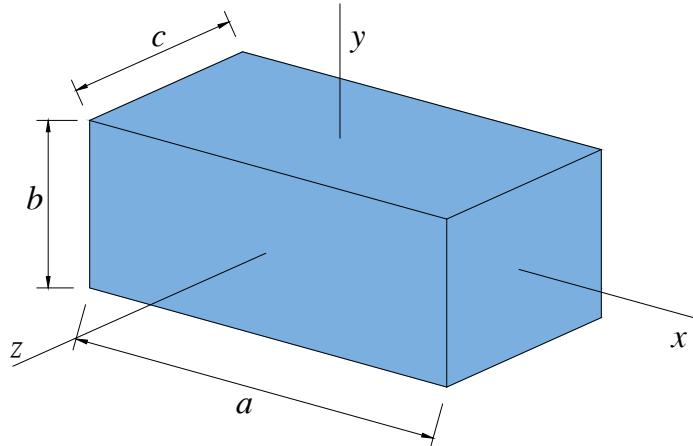


Figure 13.
Axes and dimensions of a rectangular prism.

The moment of inertia of the mirror was calculated using the equation for the moment of inertia of a rectangular prism with rotation about its x -axis as seen in Figure 13 given by

$$I = \frac{1}{12}M(b^2 + c^2), \quad (16)$$

where M is the mass of the rectangular prism and b and c are the dimensions of the rectangular prism. The mass of the rectangular prism M will be calculated using the density of glass $\rho = 2500 \text{ kg m}^{-3}$ and the volume of the rectangular prism V given by

$$V = abc, \quad (17)$$

where a , b , and c are the dimensions of the rectangular prism. The dimensions of the rectangular prism are given by the chosen mirror dimensions as $a = 30 \text{ mm}$, $b = 15 \text{ mm}$, and $c = 3 \text{ mm}$. The mass of the mirror M is

$$M = \rho V = 2500 \text{ kg m}^{-3} \times (30 \text{ mm})(15 \text{ mm})(3 \text{ mm}) = 3.38 \text{ g}. \quad (18)$$

Thus, the moment of inertia of the mirror is

$$I = \frac{1}{12}M(b^2 + c^2) = \frac{1}{12}(3.38 \text{ g})((15 \text{ mm})^2 + (3 \text{ mm})^2) = 6.59 \times 10^{-8} \text{ kg m}^{-2}. \quad (19)$$

The required angular acceleration of the motor α is calculated with

$$\alpha = \frac{\Delta\omega}{\Delta t}, \quad (20)$$

where $\Delta\omega = \omega_{max} - 0$ is the change in angular velocity and Δt is the change in time. The change in time Δt was determined by assuming the laser must be able to accelerate from a stand still to $v_{laser} = 1 \text{ ms}^{-1}$ extremely rapidly to ensure that the motors could respond to the

irregular flight pattern of a mosquito. It was assumed that this acceleration must occur within 10 ms. Thus, the required angular acceleration α is

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{0.572 \text{ rad s}^{-1}}{0.01 \text{ s}} = 57.2 \text{ rad s}^{-2}. \quad (21)$$

Given the calculated moment of inertia and angular acceleration the required torque τ is

$$\tau = I\alpha = 6.59 \times 10^{-8} \text{ kg m}^{-2} \times 57.2 \text{ rad s}^{-2} = 3.77 \times 10^{-6} \text{ Nm}. \quad (22)$$

d. Motor and driver selection

Typical stepper motors have a basic step angle of 1.8° . This does not meet the required step resolution $\theta_{step}^{max} = 0.253^\circ$, however the step angle can be reduced by using microstepping. Microstepping works by interpolating the pulse width modulation (PWM) signal to the stepper motor driver to produce intermediate step positions between the basic step positions. Stepper motor drivers that support up to 16 microsteps are readily available. Drivers that support up to 256 microsteps are also available. The step angle θ_{step} of a stepper motor using 16 microsteps is

$$\theta_{step} = \frac{1.8^\circ}{16} = 0.1125^\circ, \quad (23)$$

which is sufficient to meet the required maximum step resolution $\theta_{step}^{max} = 0.127^\circ$. Therefore, a typical stepper motor with a basic step angle of 1.8° operated using at least 16 microsteps will be sufficient.

A drawback of using microstepping is that the effective torque of the stepper motor is reduced with each increase in microstepping. The torque reduction due to microstepping can be calculated with

$$\tau_{eff} = \tau_{rated} \sin\left(\frac{\pi S}{2}\right), \quad (24)$$

where

- τ_{eff} is the effective torque of the stepper motor for a specific amount of microstepping.
- τ_{rated} is the rated torque of the stepper motor.
- S is the reciprocal of the number of microsteps.

The effective torque of a stepper motor for the full range of microsteps available is tabulated in Table 2. It can be seen that microstepping has a drastic impact on the effective torque of stepper motors. Thus, the required torque will need to be calculated for the chosen microstepping operation.

The DRV8825 stepper motor driver was chosen since it is readily available and supports up to 32 microsteps. The DRV8825 stepper motor driver has a maximum current rating of 2.5 A and a maximum voltage rating of 45 V. The maximum microstepping mode will be utilised for increased resolution in the control of the laser. The required torque with 32 microsteps is

$$\tau_{required} = 3.77 \times 10^{-6} \text{ Nm} \times \frac{100\%}{4.91\%} = 7.68 \times 10^{-5} \text{ Nm}. \quad (25)$$

A bipolar NEMA8 stepper motor with specifications shown in Table 3 and a pull-out torque curve at half step shown in Figure 14 was chosen as the motors for the laser turret. From the pull-out torque curve in Figure 14, the maximum rated speed of the motor is given as 13 000

Microsteps	Effective torque
1	100%
2	70.71%
4	38.27%
8	19.51%
16	9.8%
32	4.91%
64	2.45%
128	1.23%
256	0.61%

Table 2.
Effective torque of stepper motor for full range of microsteps.

Basic step angle	1.8°
Holding torque	180 g cm = 1.77×10^{-2} Nm
Rated voltage	3.9 V
Rated current	0.6 A

Table 3.
Specifications of the NEMA8 stepper motor.

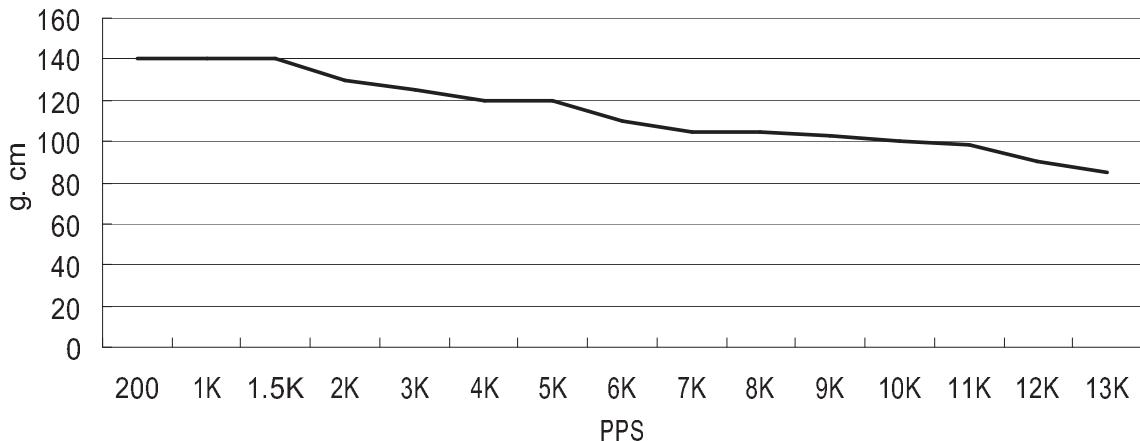


Figure 14.
Pull-out torque curve of the stepper motor at half step with 24 V and 0.6 A.

points per second at half step 0.9° which is

$$13000 \div \frac{360^\circ}{0.9^\circ} = 32.5 \text{ RPM}, \quad (26)$$

with a pull-out torque greater than 100 g cm = 9.8×10^{-3} Nm. The effective torque of the stepper motor at maximum speed with 32 microsteps is

$$\tau_{eff} = 9.8 \times 10^{-3} \text{ Nm} \times 4.91\% = 4.81 \times 10^{-4} \text{ Nm}. \quad (27)$$

The effective torque of the stepper motor at maximum speed is greater than the required torque

for the laser turret, therefore the NEMA8 stepper motor is suitable for the laser turret and was also chosen for its compactness which can be seen in Figure 15.

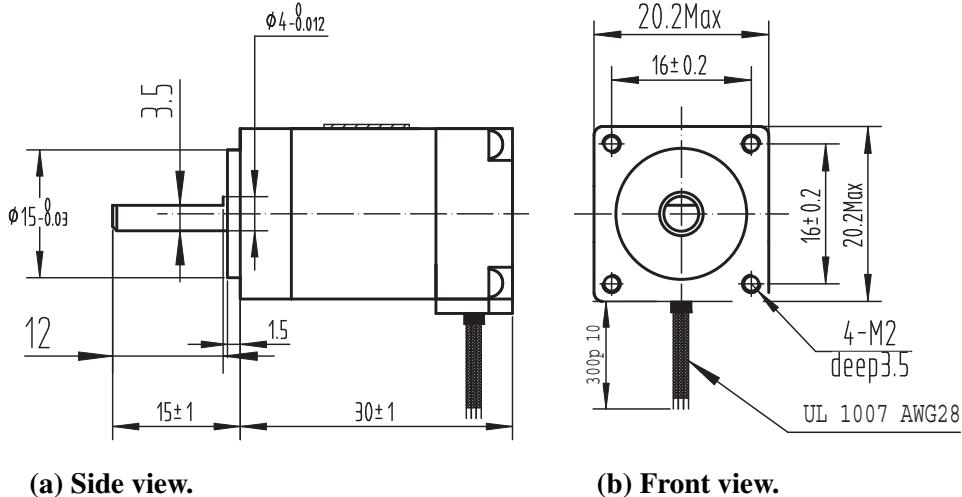


Figure 15.
Dimensions of the NEMA8 stepper motor.

e. Laser selection and activation circuit

A low-powered 5 mW red laser with adjustable focus was chosen for the laser turret. The laser has an operating voltage range of 2.8 – 5.2 V. A low-powered laser was chosen for safety. The adjustable focus enabled the laser beam to be focused to a small area on the back wall of the mosquito enclosure. The laser must be red since the image processing will be done using only the red channel of the red, green, blue (RGB) video frame.

The 3.3 V GPIO of the Nvidia Jetson Nano cannot supply enough current to power the laser. A switching transistor circuit was designed to enable the laser to be turned on and off from the Nvidia Jetson Nano GPIO. The schematic for the switching transistor circuit can be seen in Figure 16. When the input signal is high the transistor is switched on and the laser is powered. When the input signal is low the transistor is switched off and the laser is not powered. In Figure 16, R_1 is a pull-down resistor to ensure that the input signal is low when the Nvidia Jetson Nano is not driving the input signal. R_1 was chosen as $56\text{k}\Omega$ to limit the current drawn from the Nvidia Jetson Nano GPIO. With $R_1 = 56\text{k}\Omega$ the current drawn from the GPIO is $\frac{3.3\text{V}}{56\text{k}\Omega} = 59\mu\text{A}$. R_2 and D_1 represent the laser.

f. Laser turret CAD The laser turret was designed in CAD using Autodesk Fusion 360. The laser turret was designed to be mounted on the bracket shown in Figure 10. The main component and subcomponents of the laser turret can be seen in Figure 17 and Figure 18 respectively.

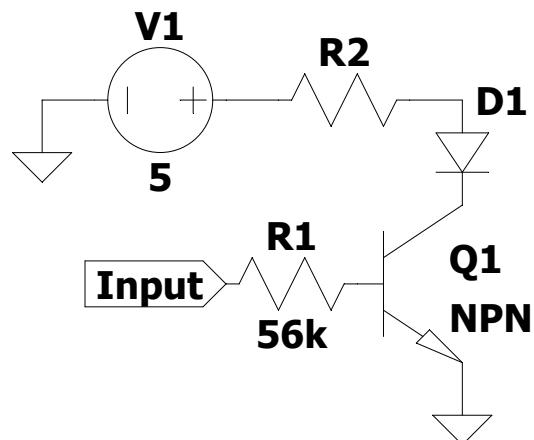


Figure 16.
Switching transistor circuit.

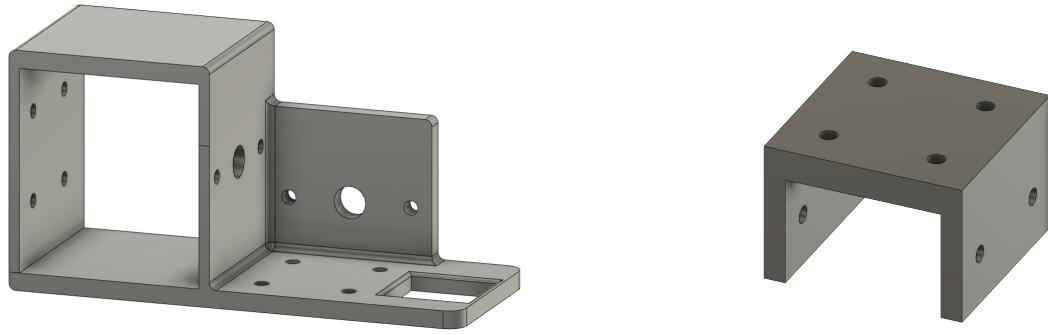


Figure 17.
Laser turret main components.

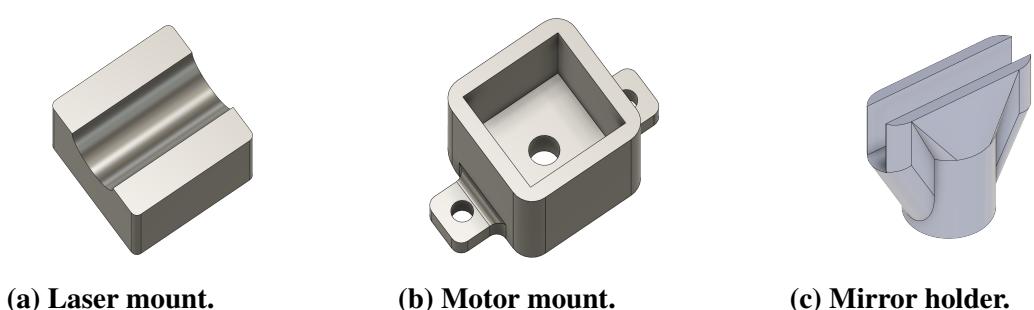


Figure 18.
Laser turret subcomponents.

3.4.5 Final system assembly

The final assembly of the full system can be seen in Figure 19. The laser turret and camera configuration can be seen up close in Figure 20.



Figure 19.
The full system assembly.

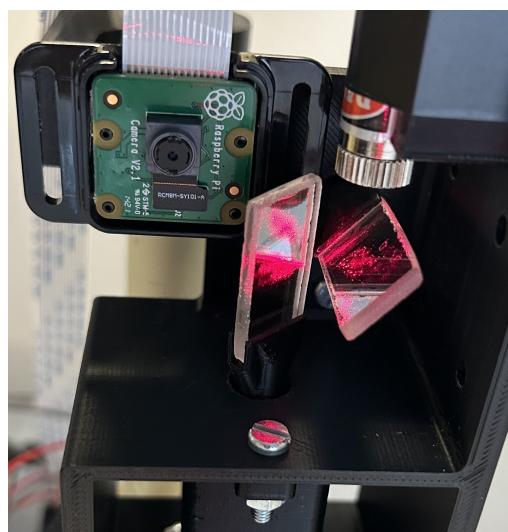


Figure 20.
The laser turret and camera configuration.

3.5 Software design

3.5.1 Mosquito and laser detection

It was assumed that the mosquitoes would be the only dark blobs in the enclosure and that the laser's reflections would be the only bright blobs in the enclosure. The video frame will be cropped such that only the white back surface of the enclosure is visible. To reduce the computational complexity of the image processing only the red channel of the RGB frame will be used, hence, the necessity of the red laser.

The mosquito detection was designed to detect dark blobs in the enclosure and would not be able to distinguish between mosquitoes and other dark blobs. The laser detection was designed to detect bright blobs in the enclosure and would not be able to distinguish between the laser's reflections and other bright blobs. The mosquito and laser detection processes are similar in nature. The basic detection process flow is shown in Figure 21. The red channel of

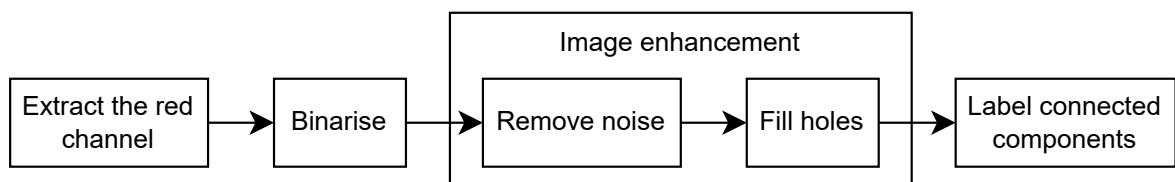


Figure 21.
Detection process flow.

the RGB frame will be extracted, which will be referred to as the frame for the rest of this discussion. The difference between the mosquito and laser detection processes occur in the binarisation step. A copy of the frame is made before binarising so that both the mosquito and laser detection can be performed since the frame will be overwritten in the image processing steps in pursuit of efficiency.

a. Binarisation

The frame will be binarised using a threshold value. The exposure of the camera will be fixed and the lighting in the mosquito enclosure will be controlled, thus the threshold value will be fixed. To detect mosquitoes the frame will be binarised with a less than threshold since the mosquitoes will be darker than the white background. To detect the laser's reflections the frame will be binarised with a greater than threshold since the laser and its reflections will be brighter than the white background. The ideal result of the binarisation is an image where the mosquitoes and the laser's reflections are the only foreground pixels in their respective copies of the frame. This will not be the case since the mosquitoes and the laser's reflections can not be perfectly isolated using a threshold value since the frame will contain noise from the camera sensor.

b. Image enhancement

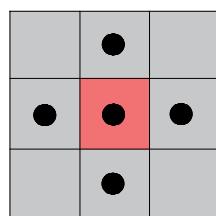
The binarised frames are subject to noise, holes, and erroneously joint or disjointed sections. This can be resolved using morphological operations. The goal of the morphological operations is to ensure that all the foreground pixels that correspond to a detection are connected, that there are no foreground pixels that do not correspond to a detection, and that there are no erroneously joint or disjoint foreground pixels. There must be a one to one correspondence between the groups of connected foreground pixels and the objects that must be detected. The connectivity of pixels will be explained in paragraph c. Morphological operations work by passing a structuring element over the pixels in an image and performing a logical operation on the pixels in the image that are covered by the structuring element.

The noise and erroneously joint sections are removed using the morphological opening operation. Opening has been formally defined in subsubsection 3.2.2. The opening of A by B is the union of all translations of B that are completely contained in A as illustrated in Figure 5a. The holes and erroneously disjointed sections are removed using the morphological closing operation. Closing has been formally defined subsubsection 3.2.2. The closing of A by B is the complement of the union of all translations of B that do not overlap A as illustrated in Figure 5b.

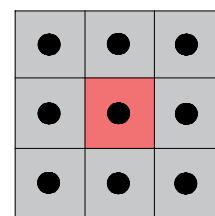
The structuring element must be identical, independent of orientation, in a 2D image since the orientation of the mosquitoes will be unknown. The structuring element will therefore be a disc. The size of the disc will be adjusted independently for the opening and closing operations for both the mosquito and laser detection. The structuring elements' size will be adjustable at runtime such that they can be tuned to provide optimal performance.

c. Connected components labelling

From the enhanced binary frames the co-ordinates of the connected foreground pixels must be obtained. This is done using connected components labelling (CCL). CCL is the process of assigning a label to each foreground pixel in a binary image such that connected pixels have the same label. The connectivity of pixels are defined using either four or eight connectivity. Four connectivity defines the neighbourhood of a pixel as the pixels to the left, right, top, and bottom of the pixel. Eight connectivity defines the neighbourhood of a pixel as the pixels to the left, right, top, bottom, top left, top right, bottom left, and bottom right of the pixel. The CCL connectivity is shown in Figure 22.



(a) Four connectivity.



(b) Eight connectivity.

Figure 22.
Connected components labelling connectivity.

Various algorithms exist to perform CCL. Two of the most commonly used algorithms are the two-pass algorithm and the breadth-first single-pass algorithm. The two-pass algorithm is generally faster for images with large connected components and the breadth-first single-pass algorithm is generally faster for images with small connected components. The nature of the mosquito and laser detection is such that the connected components will be small, thus the breadth-first single-pass algorithm was chosen. The breadth-first single-pass algorithm is presented in Algorithm 1.

Algorithm 1 Breadth-First Single-Pass Connected Component Labelling

```

1: procedure SINGLEPASSCCL(image)
2:   rows, cols  $\leftarrow$  dimensions of image
3:   label  $\leftarrow$  1
4:   labels  $\leftarrow$  2D array of zeros of size rows  $\times$  cols
5:   for y  $\leftarrow$  0 to rows - 1 do
6:     for x  $\leftarrow$  0 to cols - 1 do
7:       if image[y][x] = 1 and labels[y][x] = 0 then
8:         ExploreBlob(image, labels, x, y, label)
9:         label  $\leftarrow$  label + 1
10:      end if
11:    end for
12:  end for
13: end procedure
14:
15: procedure EXPLOREBLOB(image, labels, x, y, label)
16:   queue  $\leftarrow$  empty queue
17:   Enqueue(queue, (x, y))
18:   while not empty(queue) do
19:     (x, y)  $\leftarrow$  Dequeue(queue)
20:     if x < 0 or x  $\geq$  cols or y < 0 or y  $\geq$  rows or image[y][x] = 0 or labels[y][x] > 0
        then
21:       continue
22:     end if
23:     labels[y][x]  $\leftarrow$  label
24:     for each neighbour (nx, ny) of (x, y) do
25:       Enqueue(queue, (nx, ny))
26:     end for
27:   end while
28: end procedure
  
```

3.5.2 Distinguishing between the laser's reflections

The laser must shine through the front glass of the mosquito enclosure. This results in various reflections of the laser beam. There are three predominate reflections that can not be distinguished using a brightness threshold. These reflections are:

- The reflection of the laser beam off the front glass at the origin of the laser turret, resulting from scattered light off the turret mirrors.
- The reflection of the laser beam incident on the front glass.
- The reflection of interest, which is the reflection of the laser beam incident on a mosquito or the back surface of the enclosure.

The reflection off the front glass at the origin of the laser turret remains stationary since the laser turret itself is stationary with only the angles of the mirrors changing. Thus, this reflection can be manually distinguished by drawing a bounding box around its position in the frame. The remaining two reflections are distinguished using the geometric properties of the system positioning. The yz -plane of the system is shown in Figure 23 showing the potential laser beam paths for various turret angles. The laser turret is slightly below the camera which is exaggerated in Figure 23 for illustration purposes. It can be seen in Figure 23 that if both detections are at or below the camera origin, the reflection of interest is closer to the camera origin. If both reflections are at or above the camera origin, then the reflection of interest is further from the camera origin. If the reflections are on either side of the camera origin, the reflection of interest is the reflection above the camera origin. This logic is easily extended to three dimensions by considering the yz -plane and xz -plane independently.

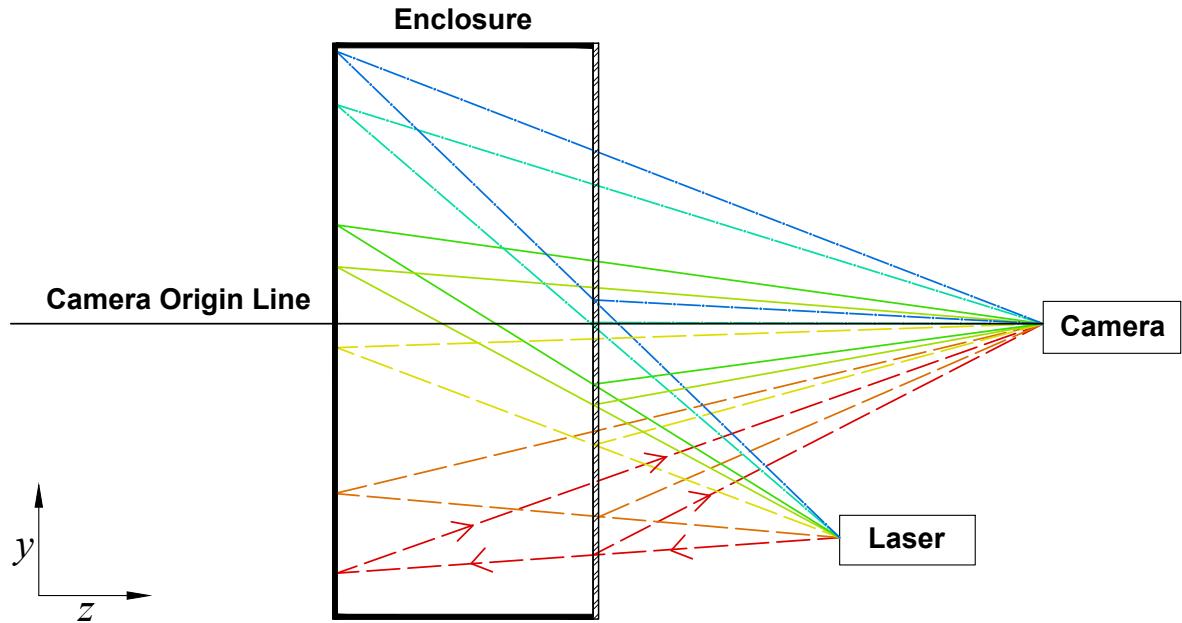


Figure 23.
Distinguishing between the laser's reflections.

3.5.3 Mosquito tracking

The mosquito tracking was performed using the SORT algorithm. The SORT algorithm is based on the tracking-by-detection paradigm, which means it relies on an external object detector. The object detector used was the mosquito detection algorithm described in subsection 3.5.1. The SORT algorithm associates the detections across frames to create

tracks.

a. Tracks

The mosquito tracks are created using the Kalman filter. The theoretical background of Kalman filter is discussed in subsubsection 3.2.3. The kinematic equation representing the flight of a mosquito must be defined to determine the state space of the Kalman filter. The kinematic equation used to model the flight of a mosquito is

$$\mathbf{x}_k = \mathbf{x}_{k-1} + \dot{\mathbf{x}}_{k-1}\Delta t + \frac{1}{2}\ddot{\mathbf{x}}_{k-1}\Delta t^2, \quad (28)$$

where \mathbf{x}_k is the position vector defined by the 2D pixel co-ordinate of a mosquito $[x \ y]^T$. A constant velocity model with acceleration as noise will be used since mosquitoes have an erratic flight pattern. Therefore, the set of differential equations describing the state space of the Kalman filter is

$$\begin{aligned} \mathbf{x}_k &= \mathbf{Ax}_{k-1} + \mathbf{Bu}_k + \mathbf{w}_k, \\ \begin{bmatrix} x_k \\ y_k \\ \dot{x}_k \\ \dot{y}_k \end{bmatrix} &= \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{k-1} \\ y_{k-1} \\ \dot{x}_{k-1} \\ \dot{y}_{k-1} \end{bmatrix}, \end{aligned} \quad (29)$$

where \mathbf{u}_k is the input vector, which is the acceleration of the mosquito according to its kinematic flight model defined in Equation 28. However, this acceleration is unknown and will be compensated for by the process noise \mathbf{w}_k , thus $\mathbf{u}_k = \mathbf{0}$. The process noise \mathbf{w}_k is assumed to be drawn from a zero mean multivariate normal distribution \mathcal{N} with covariance \mathbf{Q}_k . Hence, $\mathbf{w}_k \sim \mathcal{N}(0, \mathbf{Q}_k)$. Thus, $\mathbb{E}[\mathbf{w}_k] = \mathbf{0}$ and $\mathbb{E}[\mathbf{w}_k \mathbf{w}_k^T] = \mathbf{Q}_k$. The process noise covariance matrix \mathbf{Q} is given by

$$\mathbf{Q} = \begin{bmatrix} \sigma_x^2 & 0 & \sigma_x \sigma_{\dot{x}} & 0 \\ 0 & \sigma_y^2 & 0 & \sigma_y \sigma_{\dot{y}} \\ \sigma_{\dot{x}} \sigma_x & 0 & \sigma_{\dot{x}}^2 & 0 \\ 0 & \sigma_{\dot{y}} \sigma_y & 0 & \sigma_{\dot{y}}^2 \end{bmatrix}, \quad (30)$$

where σ_x and $\sigma_{\dot{x}}$ are the standard deviations of the position and velocity, respectively. The standard deviation of the position is defined as the standard deviation of the acceleration $\sigma_{\dot{x}}$ multiplied by $\frac{1}{2}\Delta t^2$, since this is the effect that the acceleration will have on the position as shown in Equation 28. Similarly, the standard deviation of the velocity is defined as $\Delta t \sigma_{\dot{x}}$. Therefore, the process noise covariance can be written as

$$\mathbf{Q} = \sigma_{\dot{x}}^2 \begin{bmatrix} \frac{\Delta t^4}{4} & 0 & \frac{\Delta t^3}{2} & 0 \\ 0 & \frac{\Delta t^4}{4} & 0 & \frac{\Delta t^3}{2} \\ \frac{\Delta t^3}{2} & 0 & \Delta t^2 & 0 \\ 0 & \frac{\Delta t^3}{2} & 0 & \Delta t^2 \end{bmatrix}. \quad (31)$$

The position of a mosquito is the only component of the state that is measured by the detection system. Thus, the observation matrix \mathbf{H} is

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \quad (32)$$

The measurement noise covariance matrix \mathbf{R} is

$$\mathbf{R} = \begin{bmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_y^2 \end{bmatrix}, \quad (33)$$

where σ_x^2 and σ_y^2 are the variances of the position detected. The initial state covariance matrix \mathbf{P} is given by

$$\mathbf{P} = \begin{bmatrix} \sigma_x^2 & 0 & 0 & 0 \\ 0 & \sigma_y^2 & 0 & 0 \\ 0 & 0 & \dot{x}_{max}^2 & 0 \\ 0 & 0 & 0 & \dot{y}_{max}^2 \end{bmatrix}. \quad (34)$$

The Kalman filter is initialised with the position of the mosquito as the initial state \mathbf{x}_0 . The position of the mosquito in the next frame $\hat{\mathbf{x}}_{k|k-1}$ is predicted using the adapted predict equation of the Kalman filter $\hat{\mathbf{x}}_{k|k-1} = \mathbf{A}_k \mathbf{x}_{k-1|k-1}$. This prediction will be used in the association step before the update step. The update step of the Kalman filter is performed using the update equation of the Kalman filter $\mathbf{x}_{k|k} = \mathbf{x}_{k|k-1} + \mathbf{K}_k (\mathbf{z}_k - \mathbf{H}_k \mathbf{x}_{k|k-1})$, where \mathbf{K}_k is the Kalman gain and \mathbf{z}_k is the measurement vector. The measurement vector \mathbf{z}_k is the position of the mosquito detected in the current frame.

b. Association

The association of tracks and detections will be done using the Hungarian algorithm, which is an optimised optimal assignment algorithm. The Hungarian algorithm has a time complexity of $O(n!)$ compared to the time complexity naïve approach $O(n^3)$. The Hungarian algorithm works as follows:

Generate a cost matrix.

Represent the problem with a square $n \times n$ matrix \mathbf{C} where the element $\mathbf{C}_{i,j}$ represents the cost of assigning track i to detection j . The cost function is the Euclidean distance between the predicted location and the detected location of the mosquito.

Row and column reduction.

Subtract the minimum value in each row from each element in the row. Perform the same operation for each column. This will produce a matrix with at least one zero in each row and column.

Cover zeros and check for optimality.

Cover all the zeros in the matrix using the minimum number of horizontal and vertical lines. If the minimum number of covering lines is n , an optimal assignment exists among the zeros, and the algorithm can proceed to the assignment phase. If not, you need to adjust the matrix and repeat from this step.

Adjust the matrix.

Find the smallest element that is not covered by any line. Subtract this element from all uncovered elements, and add it to all elements at the intersections of the covering lines. Return to *cover zeros and check for optimality*.

Assignment.

Once an optimal assignment is found, read the assignment from the zeros in the matrix.

3.5.4 Laser turret control system

The laser turret control system is a closed-loop PID controller. A PID controller is represented by the following equation

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}, \quad (35)$$

where $u(t)$ is the control signal, $e(t)$ is the error signal, K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain. The goal of the laser turret control system is to position the laser beam at the target co-ordinates. The target co-ordinates is defined by the mosquito detection and tracking system in pixels. The stepper motors are controlled in steps, thus the target pixels must be mapped to the number of steps required to move the laser beam to the target co-ordinates. The steps are defined in reference to the origin of the laser defined in subsubsection 3.4.4, which is the position when the laser beam is perpendicular to the xy -plane of the mosquito enclosure. The block diagram of the laser turret control system can be seen in Figure 24. The two axes of the laser turret are controlled independently, each having their own PID controller. The PID controller is implemented in software and the control signal is sent to the stepper motor drivers using GPIO.

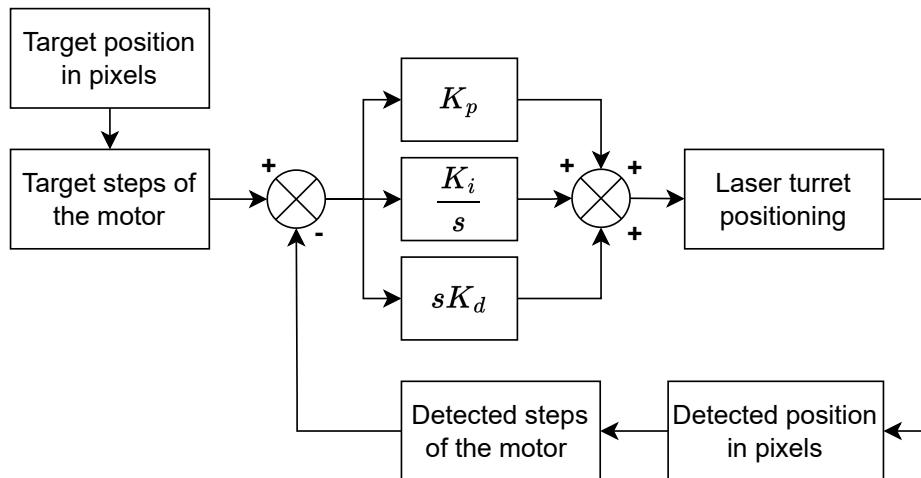


Figure 24.
Laser turret control system.

3.6 Software implementation and optimisation

3.6.1 Detection and tracking

The resolution of the camera was set to 1280×720 and was cropped such that only the back wall of the mosquito enclosure is visible. This low resolution was selected to reduce the computational complexity of the image processing. The binarisation and image enhancement

processes described in subsubsection 3.5.1 are suitable for parallelisation. Therefore, custom CUDA kernels were written to perform these operations on the Nvidia Jetson Nano GPU. The kernel for the morphological erosion operation is shown in Listing 1 to demonstrate the structure of a CUDA kernel. Utilising the GPU with kernels such as Listing 1 significantly improves the performance of the image processing system since the processing is performed concurrently across the 128 CUDA cores of the Nvidia Jetson Nano GPU. The image processing is optimised using three CUDA kernels, one for binarisation, one for morphological erosion, and one for morphological dilation. These kernels are used 10 times per frame to perform the mosquito and laser detection. Thus, this optimisation has a significant impact on the performance of the system.

```

1 __global__ void erosion(uint8_t* input,
2                         uint8_t* output,
3                         uint8_t* struct_elem,
4                         int struct_elem_radius) {
5     int x = blockIdx.x * blockDim.x + threadIdx.x;
6     int y = blockIdx.y * blockDim.y + threadIdx.y;
7
8     if (x < d_COLS && y < d_ROWS) {
9         int min_val = 255;
10        for (int i = -struct_elem_radius; i <= struct_elem_radius; i++) {
11            for (int j = -struct_elem_radius; j <= struct_elem_radius; j++) {
12                if (y + i >= 0 && y + i < d_ROWS && x + j >= 0 && x + j < d_COLS)
13                {
14                    if (struct_elem[(i + struct_elem_radius) *
15                                (2 * struct_elem_radius + 1) +
16                                j + struct_elem_radius] == 1)
17                    {
18                        int idx = (y + i) * d_COLS + (x + j);
19                        min_val = min(min_val, (int)input[idx]);
20                    }
21                }
22            }
23        }
24        output[y * d_COLS + x] = min_val;
25    }
26 }
```

Listing 1.
Erosion GPU kernel.

The Kalman filter was implemented as designed in subsubsection 3.5.3. The matrix operations for the Kalman filter were implemented from first principles. Loops were used to perform the elementary operations on the individual elements of the matrices.

3.6.2 Laser turret control

The control of the laser turret required the following fundamental processes to be implemented:

- Interfacing with stepper motor drivers.
- Converting pixels to steps.

The stepper motors drivers were connected to the Nvidia Jetson Nano GPIO according to the diagram in Figure 25. The motors are enabled by setting the "enable pin" to a logical high.

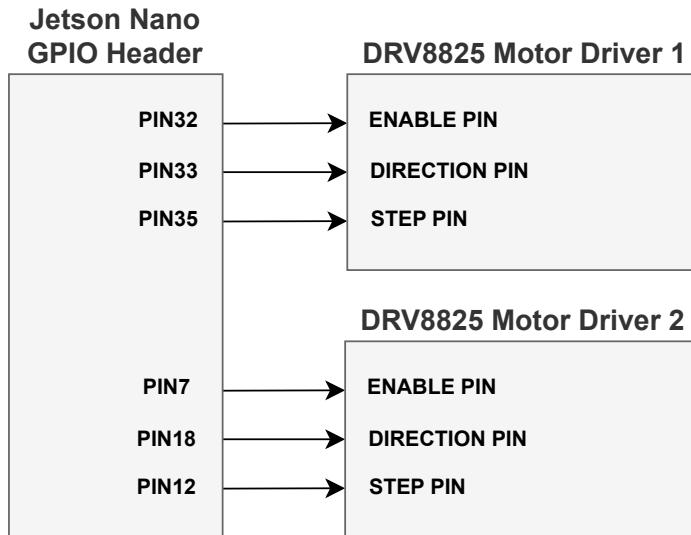


Figure 25.
Stepper motor driver connections.

The direction of rotation is determined by the logic level of the "direction pin". The stepper motors are driven by pulsing the "step pin" at the desired frequency for the required number of steps. This is shown in Algorithm 2.

Algorithm 2 Stepper Motor Control

- 1: *ENABLE PIN* \leftarrow logical high
 - 2: *DIRECTION PIN* \leftarrow *direction*
 - 3: **for** *step* $\leftarrow 0$ to *steps* – 1 **do**
 - 4: *STEP PIN* \leftarrow logical high
 - 5: delay(*period*)
 - 6: *STEP PIN* \leftarrow logical low
 - 7: delay(*period*)
 - 8: **end for**
-

The target position in pixels must be converted to the number of steps required to move the laser beam to the target position. This conversion is done using Equation 1, with the laser origin as the reference pixels. Hence, the motors steps are calculated in respect to the 45° origin position of the laser turret.

The major challenge in the implementation of the laser turret control system was the complete system integration required to achieve a functional discrete PID controller.

3.7 Final system integration

The system was programmed in C++ and integrated into a single executable system. The system is required to operate in real-time. Therefore, the mosquito tracking and control of the laser turret must occur simultaneously. To achieve this, multi-threading was required. The multi-threaded implementation can be seen in the software flow diagram shown in Figure 26. Thread 1 performs the laser detection, mosquito detection, and mosquito tracking. Threads 2 and 3 are used to control each axis of the laser turret. The communication between threads is performed using atomic variables. This system enables the laser turret to continue adjusting the position of each axis to reach the target position while the video frames are processed to provide feedback for the laser turret control system and the updated position of the mosquito being targeted.

The laser turret control system in threads 2 and 3 continuously poll flags that indicate whether there is new feedback available for laser position, and whether there is a new target position available. If either is available the control system breaks out of the loop that provides the pulses to drive the stepper motors. The new data is used to update required control action determined by the PID controller. The system then resumes to drive the stepper motors until the control action is completed, or new data is available.

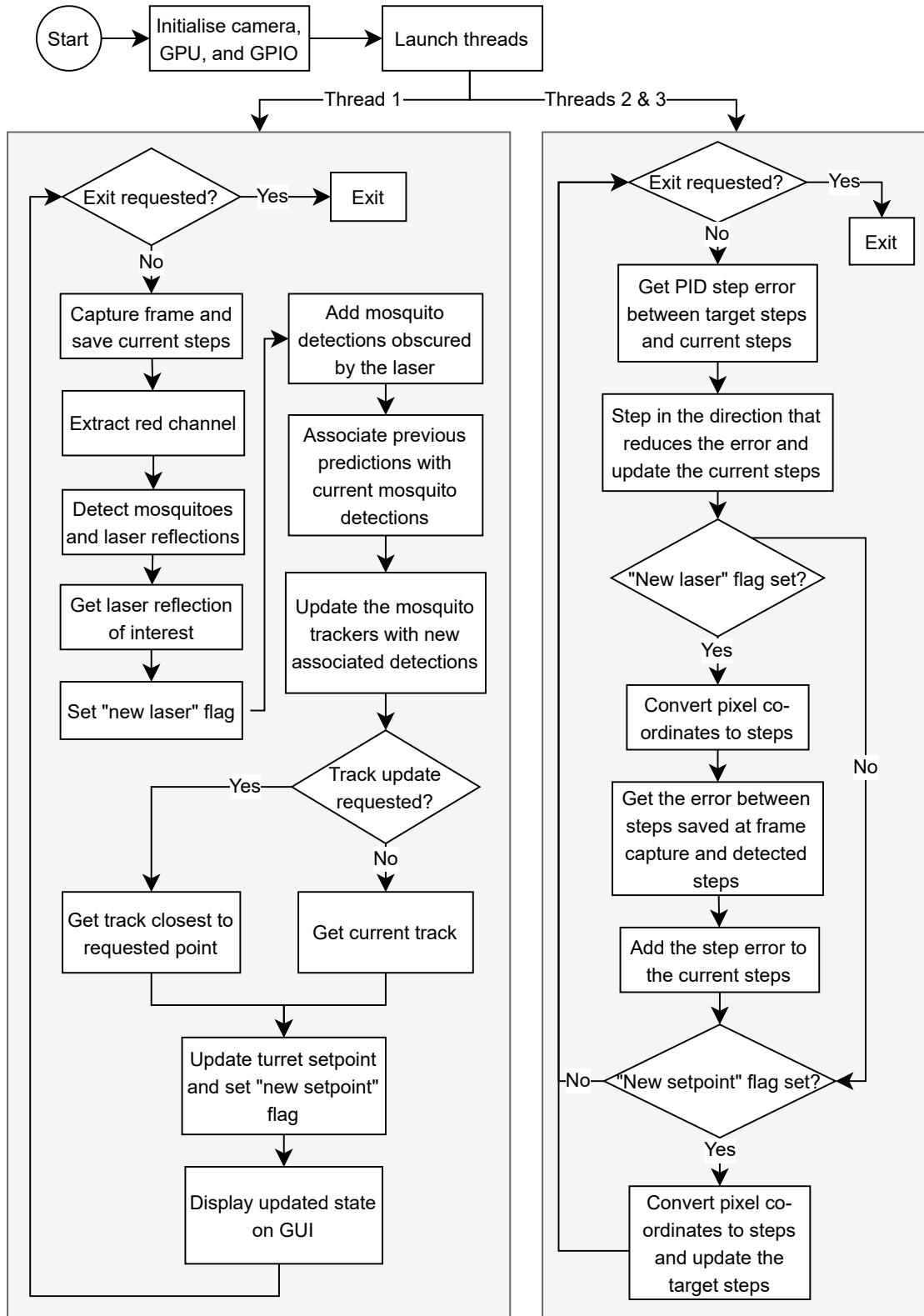


Figure 26.
Software flow diagram.

4. Results

4.1 Summary of results achieved

Intended outcome	Actual outcome	Location in report
Core mission requirements and specifications		
The system must track mosquitoes in a mosquito enclosure and illuminate a mosquito every 5 seconds.	The system tracks mosquitoes in the enclosure and illuminates a mosquito under certain conditions	Section 4.2.1
The laser must be able to illuminate a setpoint within 2 seconds accurate to within 1 millimetre.	The laser is able to illuminate setpoint within 2 seconds accurate to within 1 millimetre.	Section 4.2.2
The system must be able to detect mosquitoes with a 90% accuracy and 5% false positive rate. The detection must be updated at least every 500 milliseconds.	The system is able to detect mosquitoes with 90% accuracy. The detection is updated every 500 milliseconds.	Section 4.2.3
The system must be able to track mosquitoes with 90% accuracy of correct association between frames after 5 seconds.	The system is able to track mosquitoes with 90% accuracy or correct association between frames.	Section 4.2.4
Field condition requirements and specifications		
Mosquitoes should be in an enclosure with controlled lighting and white lining on all the sides except the front facing side. The enclosure should be at least 1 metre wide.	The enclosure has LEDs to control the lighting and white lining on all the sides except the front facing side. The enclosure is approximately 1 metre wide.	Sections 4.2.1 to 4.2.4
If mosquitoes cannot be obtained a suitable substitute will be used. The substitute will be a similar flying insect.	Mosquitoes and similar flying insects were obtained. Dead mosquitoes were also used.	Sections 4.2.1 to 4.2.4

Table 4.
Summary of results achieved.

4.2 Qualification tests

Qualification test 1: Test of tracking and illuminating a mosquito

Objectives of the test or experiment

The objective of this experiment is to determine whether the system can track and illuminate a mosquito in the mosquito enclosure. The requirement states that the system must track mosquitoes in the enclosure and illuminate a mosquito every 5 seconds.

Equipment used

The Nvidia Jetson Nano was used as the embedded platform to control the system. The Raspberry Pi Camera Module V2 was used to capture the video feed. The laser turret developed for this project was used to position the laser. The mosquito enclosure, laser turret, and camera was positioned as described in subsubsection 3.4.2. The Nvidia Jetson Nano was connected to user peripherals for user input and output. C++ code was developed specifically to capture the results for qualification test 1.

Test setup and experimental parameters

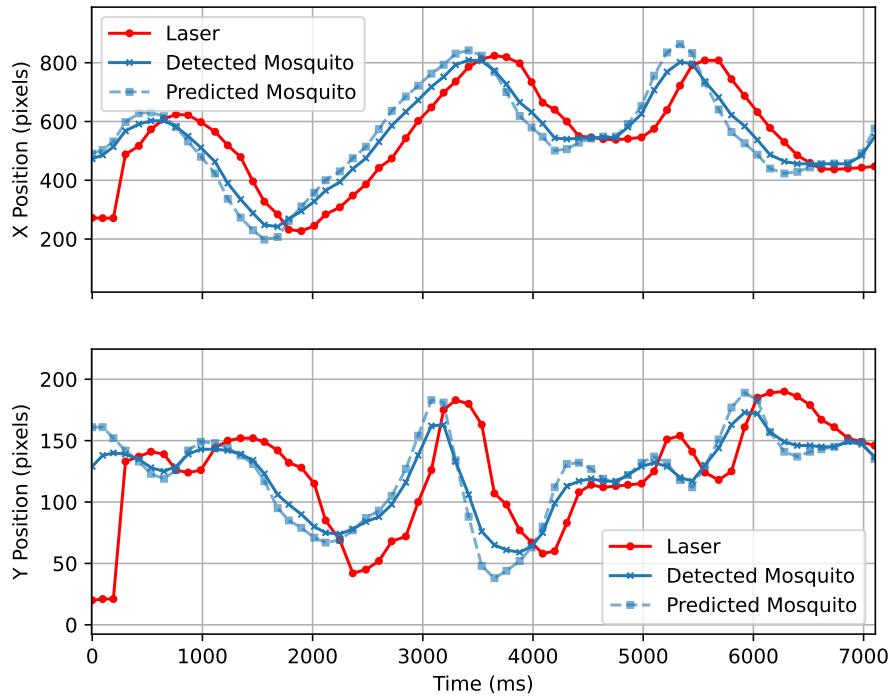
Mosquitoes were simulated with a small black dot attached to a white shafts. The shafts were inserted into the enclosure and moved by hand to mimic the motion of mosquitoes.

Results or measurements

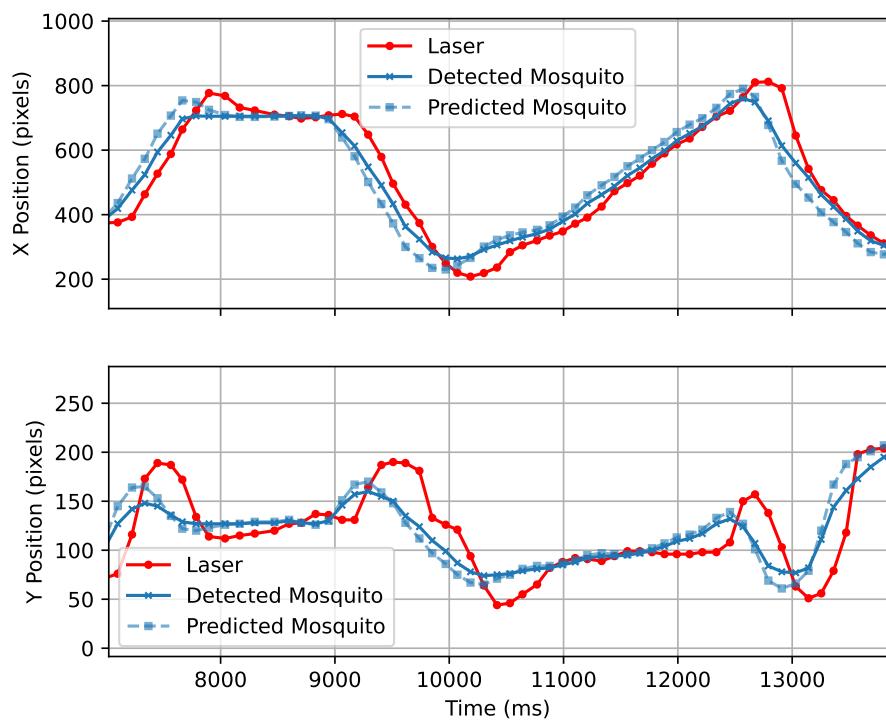
The results from three different scenarios are presented in Figures 27 to 29. The first scenario is where the laser is set to target the detected location of the mosquito. The second scenario is where the laser is set to target the predicted location of the mosquito. In the third scenario two mosquitoes were inserted into the enclosure and the laser was set to target the predicted locations of the mosquitoes.

Observations

In Figures 27 to 29, it can be seen that the system is actively adjusting the position of the laser to track the mosquitoes. In Figure 27, the system was set to target the detected position of the mosquito. With this targeting technique it can be seen that the laser is trailing behind the actual position of the mosquito unless the mosquito is stationary. In Figure 28, the system was set to target the predicted position of the mosquito. With this targeting technique it can be seen that the laser reaches the actual position of the mosquito if the mosquito moves linearly for a sufficient amount of time. However, this targeting technique also results in significant overshoot when the mosquito changes direction. Figure 29 shows the system tracking two mosquitoes in the enclosure. It can be seen that the system is able to track both mosquitoes simultaneously. The system selects one of the mosquitoes to target with the laser and the other mosquito is ignored by the laser. The same tracking behaviour is observed as in Figure 28, where the laser is set to target the predicted location of the mosquito.

**Figure 27.**

The position of the laser, detected mosquito, and predicted mosquito over time. The laser was set to target the detected location of the mosquito in this test.

**Figure 28.**

The position of the laser, detected mosquito, and predicted mosquito over time. The laser was set to target the predicted location of the mosquito in this test.

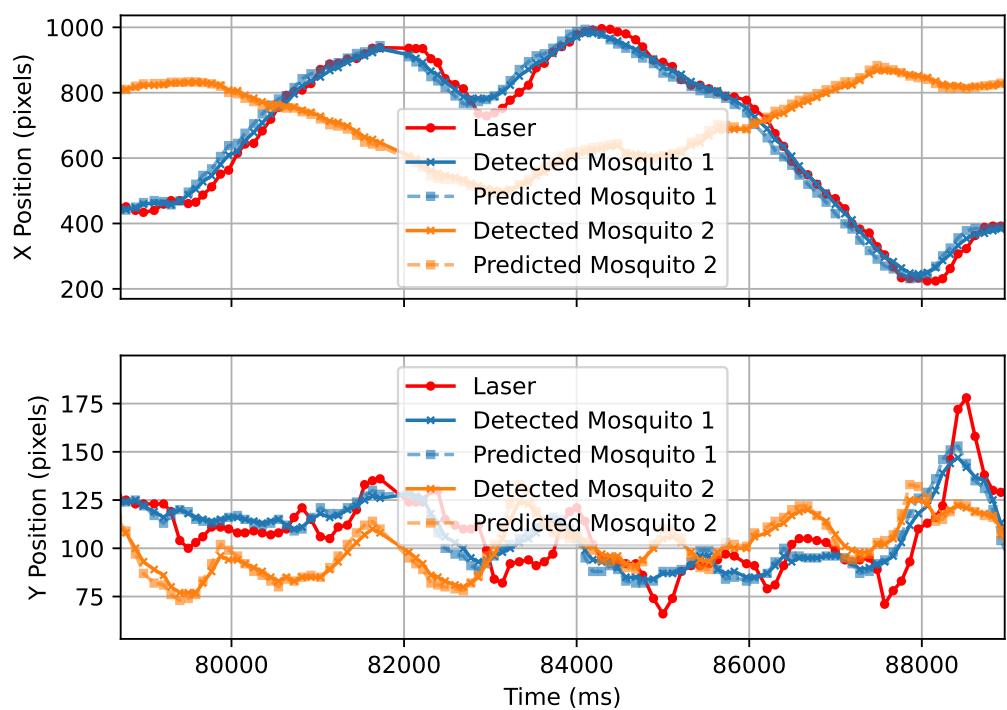


Figure 29.

The position of the laser, detected mosquitoes, and predicted mosquitoes with two mosquitoes in the enclosure over time. The laser was set to target the predicted location of the mosquito in this test.

Qualification test 2: Measurement of the time taken for the laser to reach a setpoint

Objectives of the test or experiment

The objective of this experiment is to measure the time it takes for the laser to reach a setpoint. The requirement states that the laser must be able to illuminate a setpoint within 2 seconds accurate to within 1 millimetre.

Equipment used

The Nvidia Jetson Nano was used as the embedded platform to control the system. The Raspberry Pi Camera Module V2 was used to capture the video feed. The laser turret developed for this project was used to position the laser. The mosquito enclosure, laser turret, and camera was positioned as described in subsubsection 3.4.2. The Nvidia Jetson Nano was connected to user peripherals for user input and output. C++ code was developed specifically to capture the results for qualification test 2.

Test setup and experimental parameters

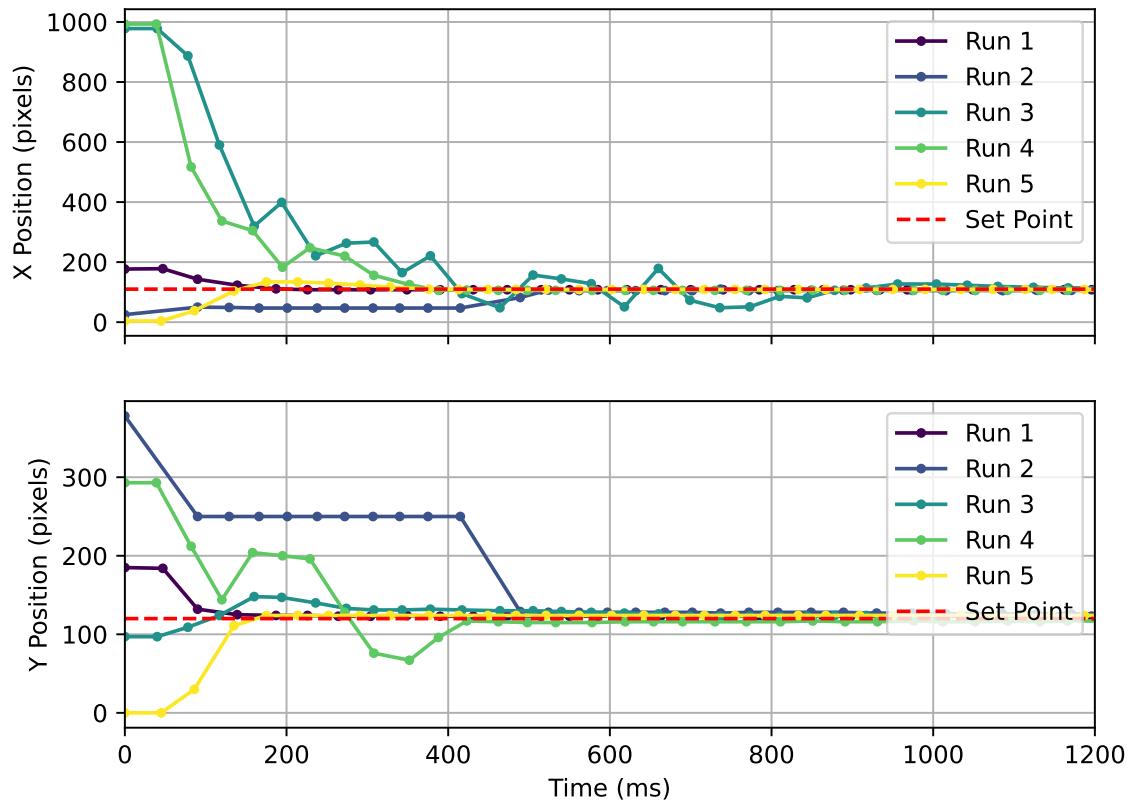
1. The setpoint was set to an arbitrary location in the mosquito enclosure.
2. The laser was manually positioned to an arbitrary location in the mosquito enclosure.
3. The laser turret control system was activated.
4. The time and position of the laser was recorded for each frame captured by the system until the laser reached a settling point.
5. Steps 1 to 4 were repeated.

Results or measurements

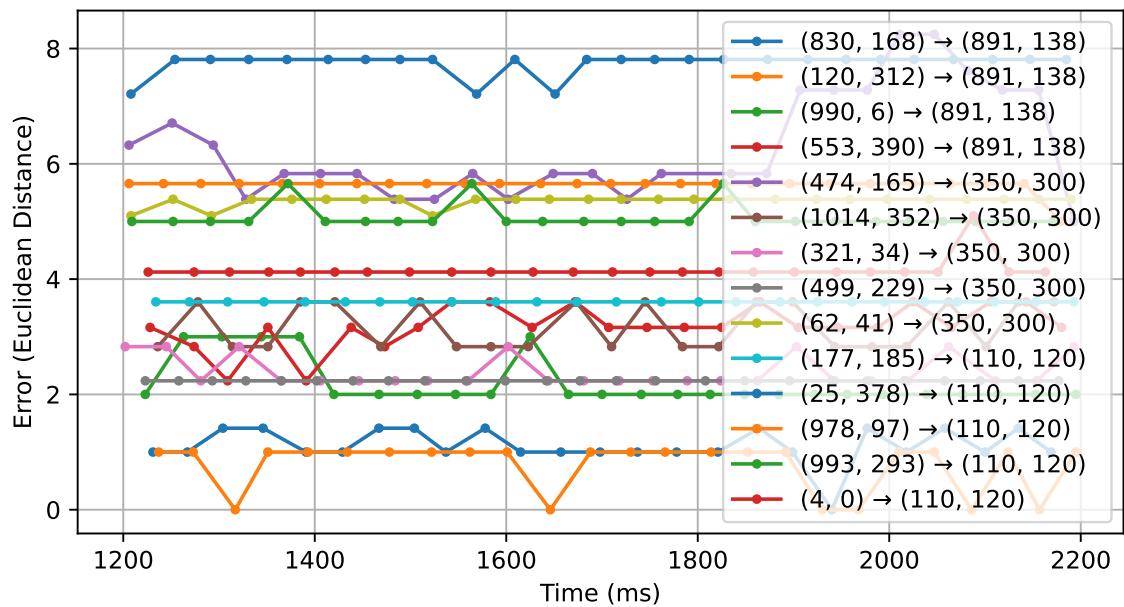
Figure 30 shows the position of the laser over time for multiple runs with different starting points with a constant setpoint. Figure 31 shows the Euclidean distance between the laser and the setpoint in pixels for multiple runs with different starting points and setpoints. Figure 31 has been restricted to the time range of 1200 to 2200 milliseconds such that the exact error between laser and setpoint can be observed. The radius of the laser was measured to a minimum of 5 pixels. The radius of a 2 millimetre disc was measured to be an average 2 pixels.

Observations

Figure 30 shows the position of the laser over time for multiple runs with different starting points with a constant setpoint. It can be seen that general behaviour of the control system adjusts the position of the laser to move towards the setpoint. Figure 31 shows the Euclidean distance between the laser and the setpoint in pixels for multiple runs with different starting points and setpoints. The graph is restricted to the time range of 1200 to 2200 milliseconds which is after the position of the laser has stabilised. It can be seen from the various tests that the maximum Euclidean distance between the laser and the setpoint is less than 8 pixels.

**Figure 30.**

The position of the laser over time for multiple runs with different starting points with a constant setpoint.

**Figure 31.**

The Euclidean distance between the laser and the setpoint in pixels for multiple runs with different starting points and setpoints.

Qualification test 3: Test of mosquito detection

Objectives of the test or experiment

The objective of this experiment is to determine whether the system can detect mosquitoes in the mosquito enclosure. The requirement states that the system must be able to detect mosquitoes with a 90% accuracy and 5% false positive rate. The detection must be updated at least every 500 milliseconds.

Equipment used

The Nvidia Jetson Nano was used as the embedded platform to control the system. The Raspberry Pi Camera Module V2 was used to capture the video feed. The laser turret developed for this project was used to position the laser. The mosquito enclosure, laser turret, and camera was positioned as described in subsubsection 3.4.2. The Nvidia Jetson Nano was connected to user peripherals for user input and output. C++ code was developed specifically to capture the results for qualification test 3.

Test setup and experimental parameters

Mosquitoes and similar flying insect specimens were glued to white shafts as shown in Figure 32.



Figure 32.
Dead mosquitoes glued to white shafts.

The test procedure was as follows:

1. A known number of mosquitoes were inserted into the enclosure.
2. The detection system was activated for 100 frames.
3. The number of mosquitoes detected in each frame was recorded as well as the time between each frame.
4. The experiment was repeated for different amounts of mosquitoes in the enclosure.

Results or measurements

The detection accuracy and false positive rate was determined using

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}}, \quad (36)$$

and

$$\text{False positive rate (FPR)} = \frac{\text{FP}}{\text{FP} + \text{TN}}, \quad (37)$$

where TP is the number of true positives, TN is the number of true negatives, FP is the number of false positives, and FN is the number of false negatives. The detection time requirement was determined by calculating the time between each frame.

Four tests were conducted using the test procedure described above. The results were captured for 0, 1, 2, and 3 mosquitoes in the enclosure. The true positives, false positives, false negatives, and true negatives for the combined tests are shown in Figure 33. The detection update interval is shown in Figure 34. The detection results for qualification test 3 are

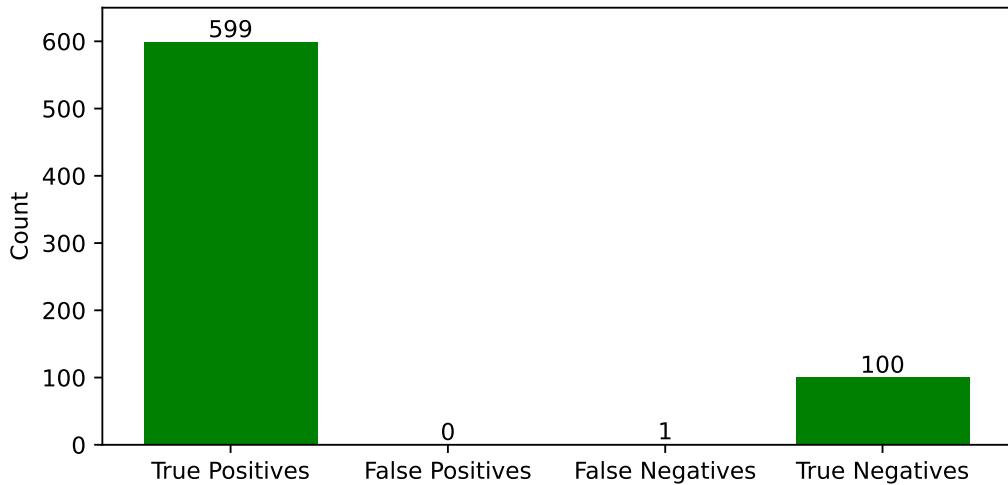


Figure 33.
Mosquito detections.

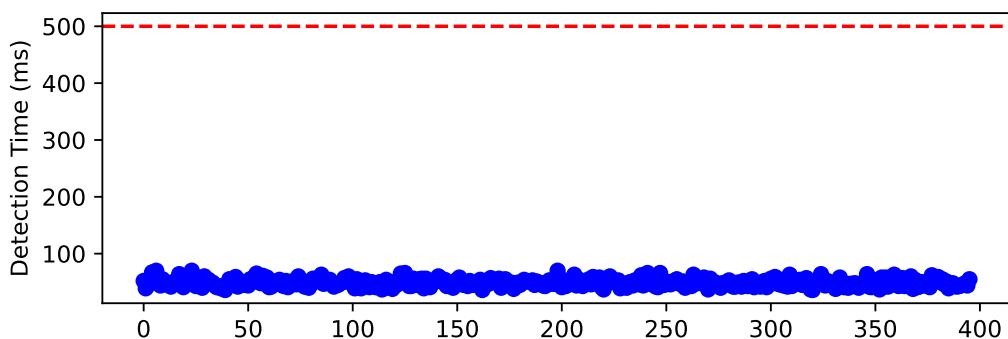


Figure 34.
Mosquito detection update interval.

summarised in Table 5

Observations

The system performs detections within 100 milliseconds which is well within the 500 milli-

Metric	Value
True Positives	599
False Positives	0
False Negatives	1
True Negatives	100
Accuracy	0.998571
False Positive Rate	0.0

Table 5.
A summary of the detection results.

second requirement. The system is able to detect mosquitoes with a 99% accuracy and 0% false positive rate.

Qualification test 4: Test of mosquito tracking

Objectives of the test or experiment

The objective of this experiment is to determine whether the system can track mosquitoes in the mosquito enclosure. The requirement states that the system must track mosquitoes in the enclosure with 90% correct association after 5 seconds.

Equipment used

The Nvidia Jetson Nano was used as the embedded platform to control the system. The Raspberry Pi Camera Module V2 was used to capture the video feed. The laser turret developed for this project was used to position the laser. The mosquito enclosure, laser turret, and camera was positioned as described in subsection 3.4.2. The Nvidia Jetson Nano was connected to user peripherals for user input and output. C++ code was developed specifically to capture the results for qualification test 4.

Test setup and experimental parameters

Mosquitoes were simulated with a small black dot attached to a white shafts.

1. The mosquito shafts were inserted into the enclosure.
2. The data capturing procedure was started.
3. The mosquito moved by hand to mimic the motion of mosquitoes.
4. The data capturing procedure automatically stops after 100 frames have been recorded.

Results or measurements

Figure 35 shows the detected and predicted position of the tracked mosquitoes in the camera pixel co-ordinate system.

Observations

In Figure 35, it can be seen that the system is able to correctly associate the mosquitoes between frames. The detected and predicted paths travelled by the mosquitoes are plotted. It can be seen that the predicted locations significantly deviates from the detected locations when there is a change in the direction of the path travelled by the mosquito. Three mosquitoes were tracked in this test.

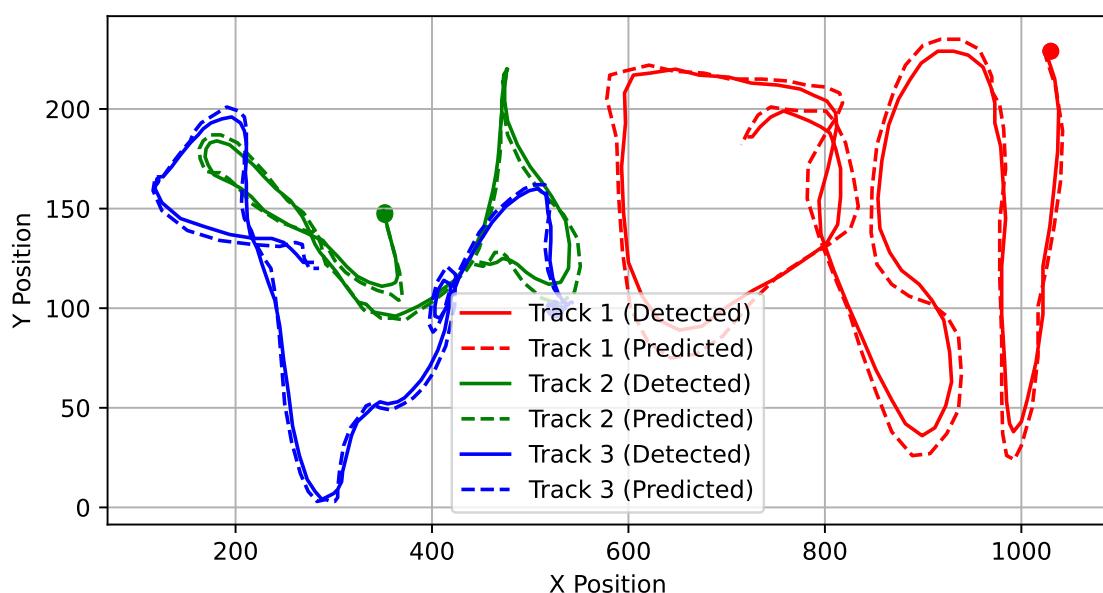


Figure 35.

The detected and predicted position of the tracked mosquitoes in the camera pixel co-ordinate system.

5. Discussion

5.1 Critical evaluation of the design

5.1.1 Interpretation of results

a. Laser turret

It can be seen in Figure 30 that laser turret responds rapidly to a step input. The laser turret reaches a settling point within 600 ms of the step input for all runs in Figure 30 other than run 3, which reached a settling point within 1200 ms. The system specification requires the laser turret to reach a settling point within 2 seconds. The response time of the laser turret is well within this specification.

In Figure 31, it can be seen that the laser turret reaches the setpoint accurate to within 6 pixels for all tests with one exception. The system specification requires the laser turret to reach the setpoint accurate to within 1 millimetre. To determine whether this accuracy has been met the following measurements were made: the radius of the laser beam was measured to be a minimum of 5 pixels and the radius of a known 2-millimetre disc was measured to be an average 2 pixels. These two measurements indicate that the laser can be a maximum of 6 pixels away from the setpoint and still be within 1 millimetre of the setpoint. This indicates that all the test runs in Figure 31, except for one which has an error of 8 pixels, reach the setpoint accurate to within 1 millimetre. However, the radius of the laser beam and the known 2-millimetre disc do vary. The laser beam radius varies with the specific lighting conditions and the incident angle with the mosquito enclosure. The radii of the laser beam and disc also vary depending on the location in the camera frame in terms of the depth which they are from the camera and the lateral position in the camera frame since the camera is subject to lens distortion. This means that pixel distance that equates to 1 millimetre accuracy is not constant. The measurements of laser beam and disc radii were made conservatively such that the accuracy of the laser turret is likely to be better than 1 millimetre if it is within 6 pixels of the setpoint.

In run 2 of Figure 30, it can be seen that the laser plateaus for about 300 ms before reaching the target position. This is likely due to a false negative laser detection. The laser position error is not updated for the period of false negative detections and thus no control action is taken since the control system is unaware of the error.

b. Mosquito detection

From the bar graph in Figure 33 it can be seen that the detection system produced 599 true positives, 0 false positives, 100 true negatives, and 1 false negative for the tests conducted. The system specification requires the detection system to have an accuracy of 90% and a false positive rate of less than 5%. The detection results indicate that the detection system has a 99% accuracy and 0% false positive rate. This is well within the system specification. However, the detection system was tested using a small set of specimens that were available.

The specimens were dead mosquitoes and other similar flying insects that were glued to white shafts. The white shafts were moved by hand to mimic live mosquitoes. This test setup does not accurately represent the true appearance of live mosquitoes. The white shafts form shadows and other artefacts that are not present when detecting live mosquitoes. This reduces the range of pixel intensity values that can be considered for a potential mosquito detection. Therefore, the detection system could perform better with the given test specimens if it was not necessary to attach them to the white shafts.

c. Mosquito tracking

In Figure 35, it can be seen that system is able to track multiple mosquitoes simultaneously. The tracking specification requires that mosquitoes are correctly associated between frames with 90% accuracy. It can be seen by inspecting the systems tracked paths of the mosquitoes in Figure 35 that the system has correctly associated the mosquitoes between frames with 100% accuracy. This was determined by analysing the different flight paths captured. It can be seen that there is no other logical association of the flight paths other than the one shown in Figure 35. This system is able to correctly associate mosquitoes between frames with flight paths that cross each other. These results indicate that the tracking system meets the system specification. However, the tracking results were obtained using a small set of specimens that were moved by hand to mimic the true flight of mosquitoes. This does not accurately represent the true flight and behaviour of mosquitoes. The true flight of mosquitoes is likely to be more erratic than the mimicked flight. Real mosquitoes are also capable of crossing paths with trajectories that can lead to ambiguous identities that can result in incorrect association. However, for the performance of the overall system this should not be a concern since the ultimate goal of the system would be to kill all mosquitoes in the enclosure.

The tracking system does predict the future position of the mosquitoes, however it can be seen in Figure 35 that when movement of the mosquitoes are highly non-linear this prediction is not accurate. This is because the system does not accurately model the movement of the mosquitoes. The acceleration of the mosquitoes are modelled as system noise since the acceleration of the mosquitoes cannot be accurately modelled due to their erratic movement.

d. Overall system performance

The graphs in Figures 27 to 29 illustrate the performance of the system as a whole. Figure 29 demonstrates the system's ability to track multiple mosquitoes simultaneously while targeting the mosquitoes with the laser. When multiple mosquitoes are tracked the system only targets the selected mosquito with the laser and ignores the other mosquitoes. The system can be seen to correctly target a single mosquito in the presence of other mosquitoes in Figure 29. The accuracy of the targeting system can be seen in Figure 28. In Figure 28, it can be seen that the laser is able to consistently remain near the position of the mosquito regardless of the movement of the mosquito. However, the laser is only able to illuminate the mosquito when it moves linearly for more or less 1 second. The primary requirement of the system is that the system must track mosquitoes in the mosquito enclosure and illuminate a mosquito every 5 seconds. The system is able to track mosquitoes in the mosquito enclosure, however, the system is only able to illuminate mosquitoes under certain conditions. The mosquito must move linearly or be stationary for a sufficient period of time, which is typically not more than 2 seconds. Therefore, if the mosquito does not exhibit this behaviour at least once every 5 seconds the system will fail to illuminate a mosquito according to the 5-second specification.

The typical behaviour of mosquitoes that were captured and placed inside the mosquito enclosure was found to be very erratic. The captured mosquitoes tended to move very erratically for short periods of time before coming to a complete rest. The system will only be able to illuminate the mosquitoes exhibiting this behaviour when they come to a rest. However, this is not the natural behaviour of mosquitoes since they have been captured and placed in a distressing environment. Mosquitoes may behave more predictably in host seeking scenarios. There are various studies on the behaviour of mosquitoes in different scenarios. Future work on the system could include research into the behaviour of mosquitoes to develop models that more accurately represent the flight behaviour of a mosquito. This would enable the system to more accurately predict the future position of the mosquitoes and thus enable the system to illuminate the mosquitoes more frequently.

5.1.2 Critical evaluation

The decision to use a segmentation approach rather than a deep learning approach for the mosquito and laser detection image processing proved to be a good decision. The image segmentation approach enabled the system to be optimised to perform most of the image processing operations on the Nvidia Jetson Nano GPU. The image segmentation approach was able to achieve a 99% accuracy in mosquito detection, while maintaining a low enough computational complexity to enable the system to operate in real-time near 10 frames per second.

The system was implemented to the capability to adjust many of the system's parameters at runtime. This enabled critical system parameters that determine the behaviour of the system to be tuned at runtime. The system also has multiple display options with different levels of granularity. The combination of the various display options and runtime adjustment of critical system parameters proved to be a powerful tool for debugging and optimising the system. This enabled individual parameters to be tuned while visualising the system at a level of granularity where its impact could be directly observed.

5.1.3 Unsolved problems

The system does not account for the slight difference in perspectives between the camera and the laser. This difference in perspective is inevitable due to the physical separation of the camera and the laser required to ensure that the laser and camera do not obstruct each other's point of view of the mosquito enclosure. The difference in perspective results two different physical locations of the laser beam corresponding to the same two-dimensional point in the camera's pixel co-ordinate frame. The two physical locations correspond to the point in the xy -plane in which the mosquito is and the point on the xy -plane of the back wall of the mosquito enclosure. The laser turret will always settle on the physical location that corresponds to the point on the back wall of the mosquito enclosure. This is not a problem when the difference in depth between the back wall of the enclosure and the mosquito is small. Through testing the maximum depth at which this difference is not problematic was found to be approximately half the depth of the mosquito enclosure. To resolve this problem it is necessary to determine the depth of the mosquito which is being tracked. This requires

additional hardware such as a depth camera or a second camera with a known separation from the first camera. The depth of the mosquito can then be determined using triangulation.

The feedback from the camera based laser detection system is the only mechanism that the system has to sense the position of the laser turret's motors. This means that if the laser beam is outside the video frame the system has no way of knowing the position of the laser turret. This is problematic when the target position of the laser turret is near the edge of the video frame. When the target position is near the edge of the video frame the laser beam is likely to go outside the video frame due to overshoot and system inaccuracies. When this happens the system is unable to determine the required control action to return the laser to within the video frame since the feedback required to determine this control action is unavailable. This problem can be resolved by adding position encoders to the motors of the laser turret. This will enable the system to determine the position of the laser turret even when the laser beam is outside the video frame, albeit with less accuracy.

5.1.4 Strong points of the design

The multi-threaded implementation of the system allowed the core system processes that perform the mosquito detection, laser detection, and mosquito tracking to operate in parallel with the two-axis PID control required to operate the laser turret. The lightweight and optimised implementation of the system's core processing functions enabled the real-time operation of the system between 5 and 30 frames per second depending on state of the system and the amount of mosquitoes in the enclosure.

The system's internal LED lighting is very effective at illuminating the mosquito enclosure. This makes the system fairly robust to varying ambient lighting conditions. The system positioning bracket adds a level of robustness against accidental shifts in the relative positions of the system's hardware components.

5.1.5 Expected failure conditions

The mosquito detection system relies on the difference in pixel intensity between the background of the mosquito enclosure and the mosquito. The system requires multiple pixels to be below a certain intensity threshold to detect a mosquito. This is to prevent false positives due to noise. This means that the system may fail to detect extremely small mosquitoes, as there may be an insufficient number of pixels below the intensity threshold required to detect a mosquito. A similar failure condition exists for the laser detection system. If the laser beam is too small or not bright enough the system will fail to detect it. The effective laser beam size and brightness from the perspective of the camera varies depending on the angle with which it is incident on the mosquito enclosure. If the mosquito enclosure lighting is too bright it also causes the laser detection system to fail. This can be resolved by using a brighter laser at the expense of safety.

5.2 Considerations in the design

5.2.1 Ergonomics

The system has been designed to be modular to facilitate easy transportation of the system. The system is easy to assemble with the correct placement of components with the use of the system positioning bracket that can be seen in Figure 10. The system has user-friendly graphical user interfaces (GUIs). The main GUI displays the mosquito tracking and laser targeting in real-time as well as critical system information. The system enables manual control of the laser turret via the terminal. The system has a host of parameters that can be adjusted at runtime to optimise the performance of the system for the field conditions. The system also has numerous display options with different levels of granularity to facilitate debugging and optimisation of the system. At any stage of operation the user can type ‘?’ into the terminal to view the current commands available.

5.2.2 Health and safety

Direct eye contact with the laser beam can be harmful to the user. A low-powered laser diode was used to minimise the risk of eye damage. A laser activation circuit was also designed to mitigate the risk of accidental laser eye contact. The laser is powered off by default and must be activated by the user through the terminal. The laser can easily be deactivated through the terminal with the single key command ‘1’. The presence of live mosquitoes in the mosquito enclosure poses a health risk to the user. The mosquito enclosure is designed with mesh openings that can easily be opened and closed to allow access to the enclosure with minimal risk of mosquitoes escaping.

5.2.3 Environmental impact

The system does not create any pollutants or harmful emissions. If the system reaches its end of life, the system can be disassembled and most of its components can be recycled. The embedded platform, the motors, and the laser can be repurposed for other applications.

5.2.4 Social and legal impact

The system is developed as first concept. To actually kill mosquitoes the system will need to be equipped with a laser that can burn mosquitoes. This type of system would likely not be approved for public use. A laser this powerful presents a potential fire hazard and a potential safety hazard in the case of accidental eye contact or prolonged skin exposure. However, a successful implementation of such a system could prevent the spread of malaria and other mosquito-borne diseases, which would have a major positive impact on society. In summary

there is much further research and development required before such a system could create an impact on society.

5.2.5 *Ethics clearance*

The system does not require ethics clearance.

6. Conclusion

6.1 Summary of the work completed

This report describes the work carried out on the design and implementation of a laser pointer turret based mosquito air defence system, with the objective of tracking and illuminating mosquitoes with a laser pointer.

A literature review was conducted on modern tracking systems. The hardware and software for a mosquito tracking and laser turret targeting system was then designed from first principles. At the core of the system is a single board computer, a camera, and a laser turret that was designed and implemented. A multi-threaded C++ application was developed to control the system. The system was implemented, and several tests were carried out. The main result is shown in the position tracking graph in Figure 29.

6.2 Summary of the observations and findings

The system can successfully track mosquitoes in real-time with high accuracy. The laser turret control system performs as expected reaching a setpoint within 2 seconds. The system is able to target a mosquito with the laser turret and illuminate it under certain conditions. Figure 28 shows the targeting performance is dependent on the mosquito's flight path.

It was discovered that the accuracy of the predicted position of a mosquito is highly dependent on linearity of the mosquito's flight. The accuracy of the predictions can be improved with a more accurate model of the mosquito's flight. A more accurate model should be developed by considering the specific environment in which the mosquito is flying. For example, a host seeking mosquito will fly differently compared to a mosquito flying in an enclosure.

6.3 Contribution

New software that the student had to master to complete this project was multi-threading in C++ and GPU programming with CUDA. Multi-threading was required to simultaneously track mosquitoes and control the laser turret to target a mosquito. CUDA was required to accelerate the image processing algorithms to achieve real-time performance. Multi-threading and GPU programming is not something that undergraduate students would typically have any knowledge of and is not covered in any undergraduate modules.

The student was required to learn how to create 3D models using CAD software to design the laser turret. The student did not have any prior experience with CAD and this was not covered in any of the student's undergraduate modules.

The student was required to map camera pixels to real-world co-ordinates. In order to do this, a thorough understanding of the camera's imaging model had to be developed. The student did not have any prior knowledge of camera imaging and this was not covered in any of the

student's undergraduate modules. The mathematics used to map camera pixels to real-world co-ordinates reflects the theory explained in the first principles of computer vision course presented by Nayar in [7].

The student was required to master embedded development on the Nvidia Jetson Nano. The software for this project was developed by the student without the reliance on existing libraries, with two exceptions. The student relied on existing libraries for hardware interfacing and the implementation of Hungarian algorithm was taken directly from an existing software module. The hardware for the laser turret was developed by the student.

Bi-monthly meetings were held with the student's study leader. The student's study leader provided guidance on the project concept development and the design aspects to focus on. The student's study leader did not provide any assistance with the design and implementation of the project.

6.4 Future work

The model used to represent the flight of a mosquito is a major area in which future work can be done. Future work should include the investigation into the different behaviour of mosquitoes based on their specific environment. This will improve the accuracy with which the position of a mosquito can be predicted.

An alternative design would include additional hardware that can be used to detect the depth of a mosquito. This would allow the system to target mosquitoes at any depth irrespective of the difference in perspective between the camera and the laser turret.

Finally, the system should be further optimised to increase the frame rate at which the system can operate. This will improve the accuracy with which the position of a mosquito can be predicted, since the predictions will be corrected more frequently. This will also improve the targeting performance of the laser turret, since feedback on the true laser position will be received more frequently.

7. References

- [1] W. H. Organisation. (2020, 12) The top 10 causes of death. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death>
- [2] P. Hurtik, D. Číž, O. Kaláb, D. Musiolek, P. Kočáek, and M. Tomis, “Software for visual insect tracking based on f-transform pattern matching,” in IEEE Second International Conference on Data Stream Mining & Processing, Lviv, Ukraine, 2018.
- [3] W. Liang, H. Wang, and H. Krim, “A behaviour-based evaluation of product quality,” in International Conference on Acoustics, Speech, and Signal Processing, 2016.
- [4] Y. Bao and H. Krim, “Video tracking of insect flight path: Towards behavioral assessment,” in IEEE, 2018.
- [5] Z. Khan, T. Balch, and F. Dellaert, “Efficient particle filter-based tracking of multiple interacting targets using an mrf-based motion model,” in Proceedings of the 2003 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems, Las Vegas, Nevada, USA, 2003.
- [6] A. Bewley, Z. Ge, L. Ott, F. Ramos, and B. Upcroft, “Simple online realtime tracking,” Queensland University of Technology, University of Sydney, Tech. Rep., 2017.
- [7] S. Nayar, “First principles of computer vision.” [Online]. Available: <https://fpcv.cs.columbia.edu/>
- [8] Renatokeshet, “Erosion (morphology).” [Online]. Available: [https://en.wikipedia.org/wiki/Erosion_\(morphology\)](https://en.wikipedia.org/wiki/Erosion_(morphology))
- [9] “Polarization effects of galvos in SLA 3D printing.” [Online]. Available: <https://henryquach.org/galvpolarization.html>

Part 4. Appendix: technical documentation

HARDWARE part of the project

Record 1. System block diagram

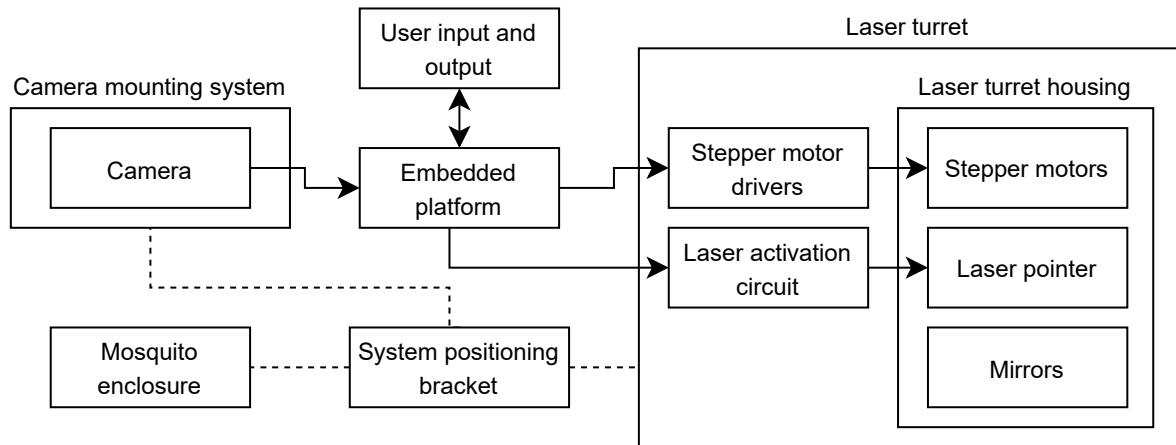


Figure 36.
System block diagram.

Record 2. Systems level description of the design

The processing for the entire system is done on the Nvidia Jetson Nano. The Jetson Nano reads a frame from the camera. The frame is then processed to detect the position of the mosquitoes and laser reflections. The system updates the mosquitoes tracks. The laser turret target position and the belief position of the laser turret is then updated. The system determines the control action required by the laser turret. The Jetson Nano sends the control signals to the stepper motor drivers. The Jetson Nano is connected to a display, keyboard, and mouse for user interaction. The laser pointer can be powered on and off by the user. The appropriate control signal is sent to the laser activation circuit by the Jetson Nano. The camera, laser pointer, and mosquito enclosure are kept in known positions relative to each other by the system position bracket.

Record 3. Complete circuit diagrams and description

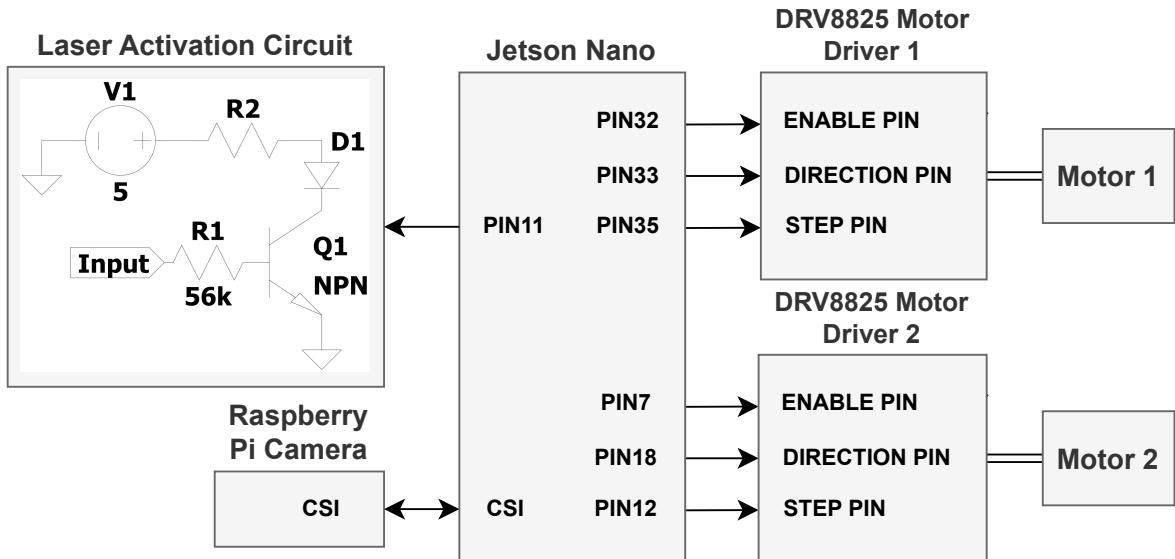


Figure 37.
All modules of the system.

Figure 37 shows a hardware diagram of all the system modules. The laser activation circuit is a switching transistor circuit. The design of the laser activation circuit can be seen in paragraph e of subsubsection 3.4.4. It was not required to develop circuits for any other modules of the system. The double line connecting the motors and motor drivers represent the connection of the four phases of a bipolar stepper motor.

Record 4. Hardware acceptance test procedure

The following procedure should be followed to ensure that system is powered and functioning correctly:

1. Confirm that all the hardware modules of the system are correctly connected as shown in Figure 37.
2. The system must be powered using an 8 to 28 V power supply that can provide at least 15 W of power.
3. After the system is powered, the power LED on the Jetson Nano should be on.
4. The Jetson Nano should be connected to a display, keyboard, and mouse.
5. Launch the system application as described in subsection 6.4. Manually moving the laser pointer with the `w`, `a`, `s`, `d`, keys should confirm that the system is functioning correctly.

Record 5. User guide

1. Confirm that all the hardware modules of the system are correctly connected as shown in Figure 37.
2. The system must be powered using an 8 to 28 V power supply that can provide at least 15 W of power.
3. After the system is powered, the power LED on the Jetson Nano should be on.
4. The Jetson Nano should be connected to a display, keyboard, and mouse.
5. The hardware setup is now complete. The system application can be launched as described in subsection 6.4.

SOFTWARE part of the project

Record 6. Software process flow diagrams

The software process flow diagram for the system can be seen in Figure 38.

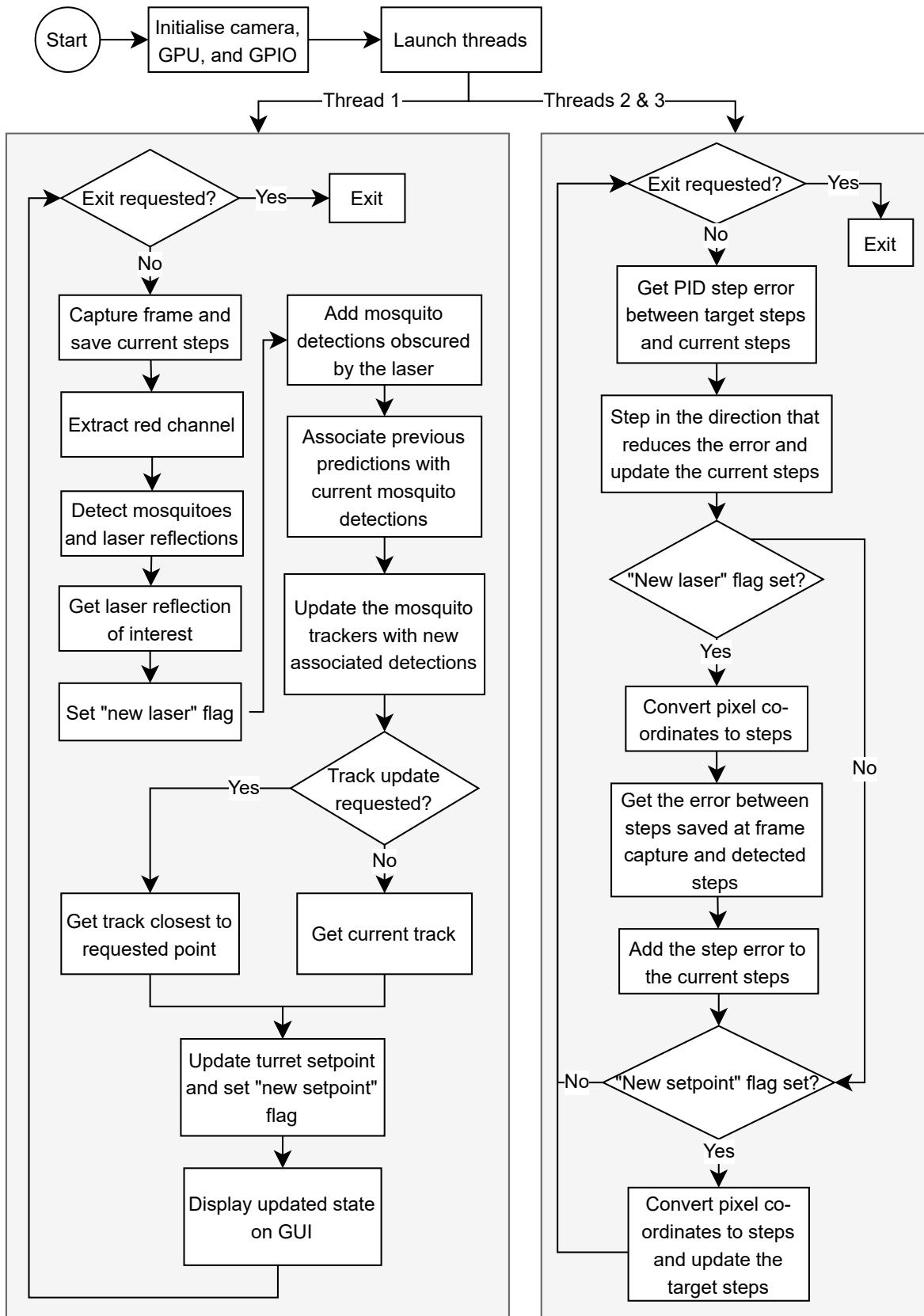


Figure 38.
Software flow diagram.

Record 7. Explanation of software modules

The software developed for this system is an integrated system. The software flow diagram for the system can be seen in Figure 38. The system starts by initialising the camera, the GPIO, and the GPU. The multiple threads of the system is then launched that are responsible for operating the entire system. Thread 1 is where the main processing of the system occurs and threads 2 and 3 are responsible for controlling the two axes of the laser turret. Communication across the threads is done using atomic variables. All the threads are contained within a loop that continues unless a system exit is requested. This is required to ensure a graceful exit of the system.

Thread 1 is used to interface with the camera. It performs the image processing required for the mosquito and laser detection on the GPU and the mosquito tracking. It then updates the detected laser position and target position and sets system flags to indicate this.

Threads 2 and 3 are identical and control the two axes of the laser turret independently. These threads determine the control action required to move the laser turret to the target position. They continuously loop to create the pulses required to move the steppers according to the control action. In this loop the system flags are polled in each iteration. If the system flags indicate that the target position has changed or that the detected laser position is updated, the control action is recalculated. The loop that sends the pulses to the stepper motor drivers is then resumed.

Record 8. Complete source code

Complete code has been submitted separately on the AMS.

Record 9. Software acceptance test procedure

After the software has been launched, the main system GUI should appear on the screen. The GUI should indicate that the laser pointer is powered off, and the system is in MANUAL MODE. After the laser pointer has been powered on and positioned to within the camera frame, the user should change the system to FULL AUTO MODE. The live tracking on the main system GUI and laser targeting of mosquitoes in the enclosure will indicate that the system is functioning correctly.

Record 10. Software user guide

1. Once the system is launched, use the main system GUI to confirm that the system is in MANUAL MODE.
2. Use the terminal interface to manually position the laser, with the `w`, `a`, `s`, `d`, keys, to within the camera frame. The laser pointer should be powered on at any time during this process as deemed appropriate by the user to ensure the safe operation of the system.
3. Switch the system to FULL AUTO MODE using the `k` command in the terminal interface. This will start the automated tracking and targeting of the mosquitoes in the enclosure.
4. The user can use the mouse to click on any location in the main system GUI, that will be displaying the live tracking and targeting of the mosquitoes. The system will target the mosquito that is closest to the clicked location.
5. The user can further interact with the system by using the `?` command to view all the available control and display commands.
6. The system can be exited at any point in its operation by using the `CTRL + c` command in the terminal interface.

The main system GUI can be seen in Figure 39.

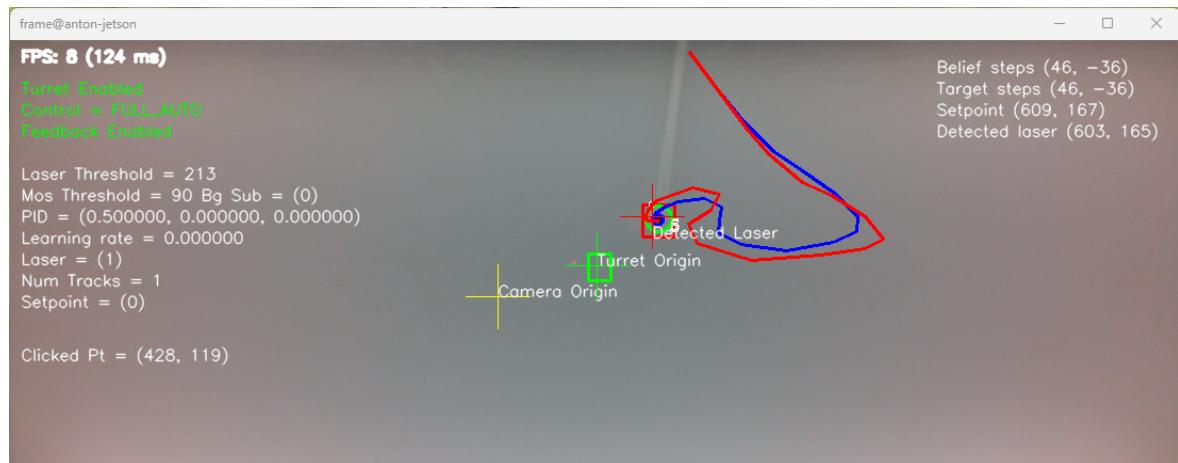


Figure 39.
Main system GUI.