Balancing a Brushless Birotor using a Visual Sensor

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Abstract

I. INTRODUCTION

A flying vehicle is not a novel engineering product. Yet, the rapid growth of unmanned aerial vehicles (UAVs) has made a research on the subject of flying vehicles a global hotspot today. One of the difficult difficulties has been reducing the number of rotors in a rotor-type UAV. One of the examples with only two rotors is the bicopter. As compared to other typical rotor-type UAVs with more rotors, it has a longer flight time. A reduction in the number of rotors can reduce unit time power demand and, as a result, improve flight time. However, because of the complexity of the mathematical dynamics model, controlling a bicopter system is not a simple process. To maintain the desired trajectory, the designed controller must be capable of stabilizing the bicopter with an acceptable response time while also overcoming the oscillation effect. To accurately stabilize the bicopter, a camera is used to find the angle of inclination of the birotor.

II. LITERATURE REVIEW

In this paper ([1]), the Ziegler-Nichols method was used to determine the control parameters based on tuning the PID components. It is powerful because it can easily calculate the P, PI, or PID gains by obtaining a few parameters before it. The PID controller was used to control the system dynamics. Since the bi-copter system has complex conjugate poles, the closed-loop approach (which consists of integrator or complex conjugate poles) was used. The closed loop structure contains the computation of the ultimate gain (Kcr) and the ultimate period (Pcr). Using root locus, the proportional gain (Kcr) was easily obtained, since it got information about a gain that is closest to the value of the proportional gain. The Pcr was obtained by calculating the period of the oscillation. After obtaining the Kcr and the Pcr, the Ziegler-Nichols table was ready for use. The results showed that the P-controller is not suitable for having a steady-state error, even though it reached stability. The PI-controller was better than the PID-controller in the overshoot, rising time, settling time, and other criteria. In conclusion, the PI-controller gave the best performance based on the Ziegler-Nichols tuning method.

In this paper ([2]), a bi-rotor using reaction wheels that control roll and yaw degrees of freedom was proposed, abbreviated as BiRW. Identical DC motors and RW were used, and their combinations were positioned at an angle concerning the roll axis equalizing the ratio of the maximum counter torque components to the ratio of the moment of inertia of the BiRW to attain similar control effectiveness. The translation and altitude are controlled using the translation controller to implement position control. PD controllers were designed based on the tuning parameters (kp and kd), obtained from the position control. The specifications desired were chosen to let the inner loop, the altitude subsystem, faster than the translation subsystem when compared to it. The PSO metaheuristic optimization technique was used to find the optimal values of kp and kd. The simulation results pointed out that the DC motors used gave more torque than the BLDC in controlling the altitude.

This paper ([3]) discusses the use of the bi-copter in flying a UAV. A comparison between the bi-copter and other UAV configurations was made. The bi-copter consumed less power than the Gemini UAV, which is the most efficient among single-propeller configurations. However, when compared with co-axial propellers, it consumes more power. The bi-copter has the advantage of making the UAV minimalist because it simplifies the mechanical design and increases maneuverability in small places. After various flight experiments, the bi-rotor platform proved stability in hover flight and also proved its capability of carrying significant payload.

In 2018, Mohammadreza Karami and Kourosh Sedghisigarchi published a paper in ”IEEE Transactions on Industrial Electronics” titled ”Generation and Control of Impulsive Forces by a Planar Bi-Rotor Aerial Vehicle through a Cable Suspended Mass” ([4]) that describes a brand-new technique for producing impulsive forces with a bi-rotor aerial vehicle. The importance of impulsive forces in a variety of applications, including aerospace, robotics, and transportation, is covered in the first section of the study. The authors then suggest a planar bi-rotor aerial craft that may produce impulsive forces by adjusting the rotors' rotational speeds, which in turn regulate the motion of a mass suspended by a cable. The work offers a thorough mathematical representation of the bi-rotor aircraft and derives the equations of motion for the mass hung by a cable. The authors then run simulation simulations to confirm that their methodology is effective at producing impulsive forces of different strengths and orientations. The authors constructed a prototype bi-rotor aerial vehicle and carried out experimental experiments to further evaluate their suggested strategy. The results of the experiments show that the bi-rotor vehicle is capable of producing impulsive forces with high accuracy and precision. The possible uses of the suggested bi-rotor vehicle in various industries, including search and rescue, inspection, and surveillance, are covered in the paper's conclusion. Overall, the research describes a unique method for producing impulsive forces with a planar bi-rotor aerial vehicle and offers thorough simulation and experimental findings to support the viability of their method. The suggested technique has the potential to develop aerial robots' state-of-the-art and open up new opportunities in a variety of industries.

A thorough investigation of the non-minimum phase dynamics of bi-copter unmanned aerial vehicles is presented in the paper by Yihang Li, Youming Qin, Wei Xu, and Fu Zhang titled "Modeling, Identification, and Control of Non-minimum Phase Dynamics of Bi-copter UAVs," ([5]) which was published in the journal "IEEE Transactions on Control Systems Technology" in 2020. (UAVs). The study starts by explaining the idea of non-minimum phase dynamics and how they affect the control of bi-copter unmanned aerial vehicles (UAVs). After that, the authors suggest a mathematical model for bi-copter unmanned aerial vehicles (UAVs) that incorporates dynamics with non-minimum phases as well as the interaction between the two rotors. The authors conduct identification experiments on a bi-copter UAV prototype to verify their suggested model. The identification experiments' findings demonstrate that the suggested model accurately depicts the bi-copter UAV's non-minimum phase dynamics. The authors create a control system that accounts for the bi-copter UAV's non-minimum phase dynamics using the described model. A feedforward controller and a feedback controller make up the proposed control system. The feedback controller ensures the system's stability and robustness while the feedforward controller corrects for non-minimum phase dynamics. The authors run simulation tests and experimental research on the bi-copter UAV prototype to confirm the efficacy of their suggested control system. The outcomes of the simulation and practical investigations show that the suggested control system can achieve precise control of the bi-copter UAV even in the presence of non-minimum phase dynamics. The potential uses of the suggested control system in various industries, including aerial photography, surveying, and inspection, are covered in the paper's conclusion. Overall, the paper offers a thorough analysis of the bi-copter UAVs' non-minimum phase dynamics and suggests a mathematical model and control scheme that considers these dynamics. The suggested strategy may open up new applications in several disciplines and advance the state-of-the-art in UAV control.

Halil Brahim Uurlu's 2020 Middle East Technical University thesis, "A Comparative Study of Learning-Based Control Policies and Conventional Controllers on 2D Bi-Rotor Platform with Tail Assistance," ([6]) provides a thorough analysis of the effectiveness of both types of controllers on a 2D bi-rotor platform with tail assistance. The thesis starts by outlining the idea of bi-rotor platforms and some of the potential uses they could have in different industries, including surveillance, inspection, and search and rescue. The difficulties regulating bi-rotor platforms, such as nonlinearity, coupling between the rotors, and instability, are then covered by the author. The author suggests a revolutionary tail help technique that gives the bi-rotor platform more control power to overcome these difficulties. The performance of learning-based control policies and traditional controllers on the bi-rotor platform with and without tail assistance is then compared by the author. On a prototype bi-rotor platform, the author performs simulation studies and experimental research to examine the effectiveness of different control policies, such as proportional-integral-derivative (PID), linear quadratic regulators (LQR), and deep reinforcement learning (DRL) controllers. These controllers' effectiveness is assessed based on their tracking performance, stability, and robustness. According to the modeling studies' and experimental studies' findings, the bi-rotor platform with tail aid achieves superior tracking performance, stability, and resilience than the platform without tail assistance. In terms of tracking performance, the results also demonstrate that the DRL controller works better than the PID and LQR controllers. The potential uses of the suggested tail support mechanism and the DRL controller in various industries, including precision farming, infrastructure inspection, and environmental monitoring, are covered in the thesis's conclusion. The performance of learning-based control strategies and traditional controllers on a 2D bi-rotor platform with tail help is thoroughly examined in this thesis. The proposed tail help system and DRL controller could enhance bi-rotor platform control and open up new opportunities in a variety of industries.

The paper titled "Robust Trajectory-Tracking for a Bi-Copter Drone Using INDI: A Gain Tuning Multi-Objective Approach" by Maryam Taherinezhad, Alejandro Ramirez-Serrano, and Arian Abedini, published in the journal "Sensors" in 2020 ([7]) presents a robust trajectory tracking approach for a bi-copter drone using the Integral Nonlinear Disturbance Observer (INDI) and a gain tuning multi-objective approach. The paper begins by outlining the difficulties in controlling bi-copter drones, such as rotor coupling, nonlinearity, and instability. The authors then suggest a control strategy to achieve reliable trajectory tracking for the bi-copter drone by fusing the INDI technique with a gain-tuning multi-objective optimization strategy. The mathematical model of the bi-copter drone is first derived by the authors, who then use experimental data to validate it. They then create a gain-tuning multi-objective optimization algorithm and an INDI controller to form a control system. The gain-tuning multi-objective optimization approach is used to tune the controller gains to obtain reliable trajectory tracking performance. The INDI controller is utilized to evaluate the disturbances and uncertainties in the system. The multi-objective optimization strategy takes into account a variety of performance goals, such as tracking accuracy, robustness, and stability, to create controllers that are effective in a variety of operating environments. The authors perform simulation studies and experimental investigations on a prototype bi-copter drone to gauge the viability of their suggested approach. The findings of the simulation studies and practical investigations show that the suggested approach outperforms more traditional control approaches, such as proportional-integral-derivative (PID) controllers and sliding mode controllers, in terms of trajectory tracking performance and robustness. The possible uses of the suggested approach in a variety of industries, including aerial photography, surveying, and inspection, are covered in the paper's conclusion. Overall, the research provides a gain-tuning multi-objective optimization method and an INDI technique for a robust trajectory-tracking approach for a bi-copter drone.

The suggested method may enhance bi-copter drone control and open up new opportunities in a variety of industries.

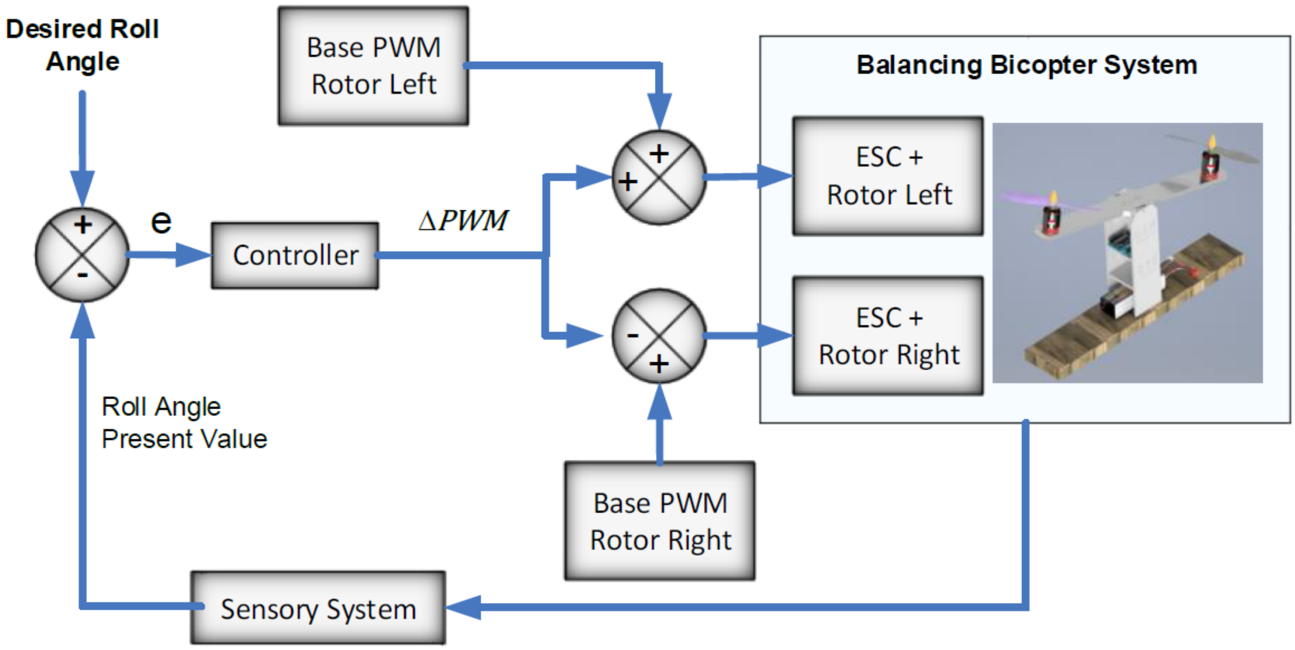

Fig. 1. The flow diagram of the system

III. Methodology

A. Workflow

To control the birotor, a desired angle is inputted, and according to this angle, the speed of both motors is adjusted as they rotate in directions opposite to each other. Below each propeller, a colored circle is attached to track the error between the pitch and the desired angle using a visual sensor, the camera. The circles will be of the color blue and a threshold will be applied to grab only the color needed. Then segmentation and edge detection will be applied to track the circle and draw a line connecting both and measuring the angle. This measured error angle is then fed from the camera into the control loop as feedback and the correct speed is sent to the ESC by the computer of the two brush-less motors to achieve the required angle desired. Figure 1 shows the flow diagram of the birotor system. The sensory system is the Logitech C270 Widescreen HD 720p webcam.

B. Components

TABLE I
List Of Components

Component	Number	Purchase Location	Price
Arduino Uno	1	Future Electronics	370E£
Electronic Speed Controllers	2	Future Electronics	205E£
Brushless Motor	2	Amazon Eg	388E£
Propeller	2	Future Electronics	150E£
12V 20A Power Source	1	Amazon Eg	220E£
Logitech C270 Webcam	1	Amazon Eg	599E£

C. Programming Language

The programming language used will be Python.

D. Hardware

Figures 2 and 3 shows the mechanical components of the birotor system. Figures 4 and 5 are for the Camera Set-up.

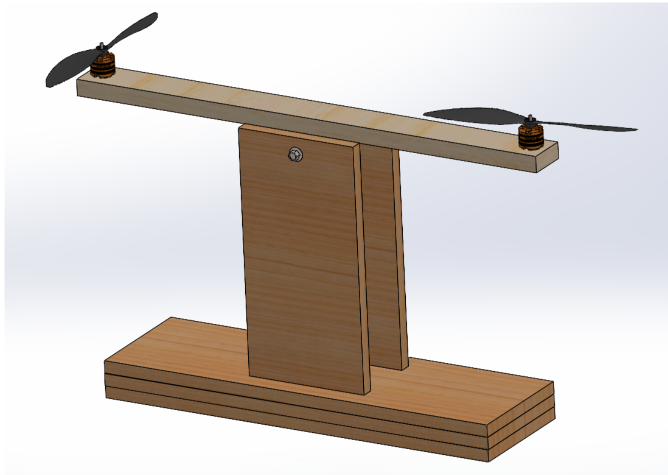

Fig. 2.   Solidworks Assembly 1

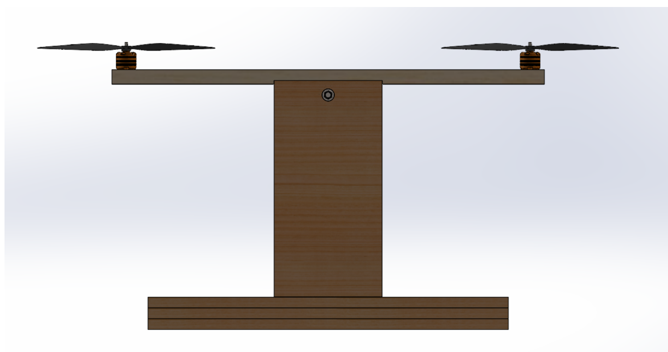

Fig. 3.   Solidworks Assembly 1

Fig. 4.   Camera

Fig. 5. Camera Holder

E. Circuit Design

The schematic circuit diagram of the birotor system is shown in Figure 6 which consists of the two brushless motors, the two ESCs, the Arduino, and the power source. The camera is the feedback element and is connected to the computer directly. The flow of data, Figure 7 is first from the camera to the computer which applies the image processing algorithm which calculates the angle of the bicopter which is then sent to the Arduino using a USB connection and into the control loop. The Arduino then calculates the required speed of the motors.

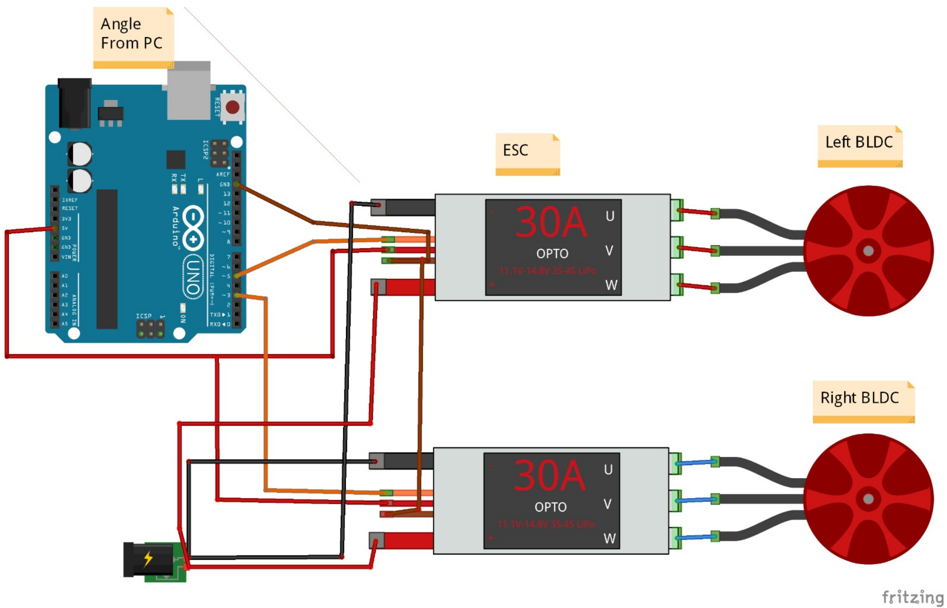

Fig. 6. Circuit diagram of the birotor system

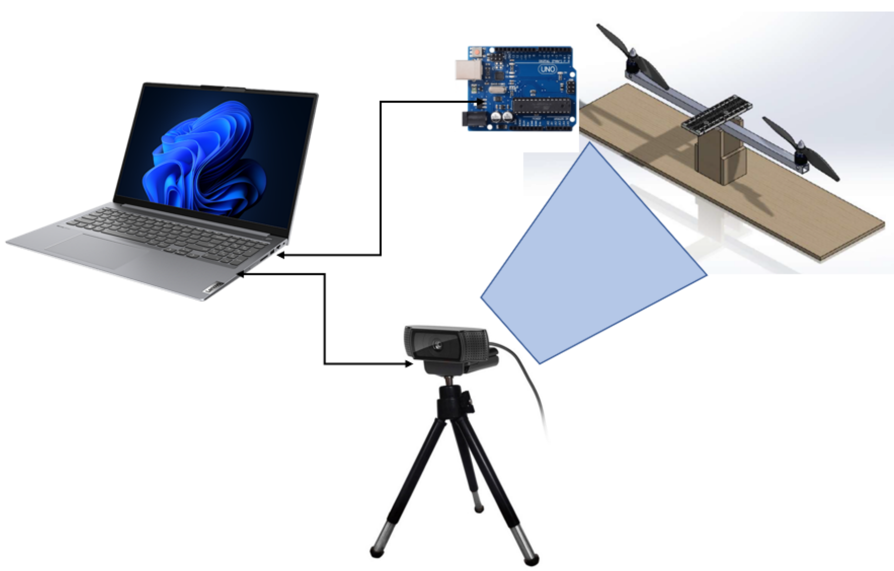

Fig. 7. Flow Schematic of the image to the computer

F. *Image Processing*

Image processing is the process of converting an image to a digital format and then executing various operations on it to extract valuable information. When specific specified signal processing methods are used, the image processing system typically interprets all images as 2D signals. The figure below 8 depicts the original photo taken by the camera prior to any image processing. Image processing tasks performed were translation and scaling, then converting the normal RBG image to LAB and HSV color spaces then grayscale where contrast enhancement and darkening were applied.

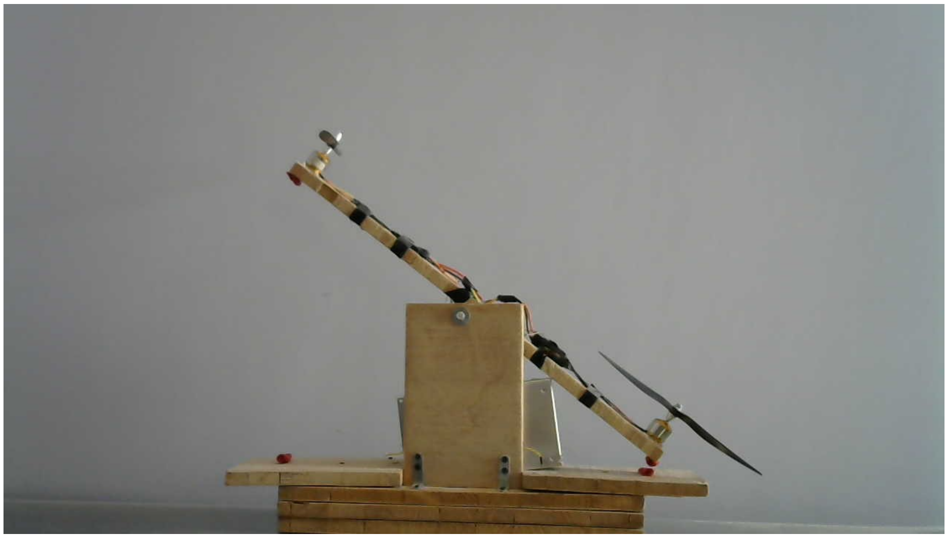

Fig. 8. Orignal Image before any transformations

The process done on the image is classified into:

1) Geometric Transformation

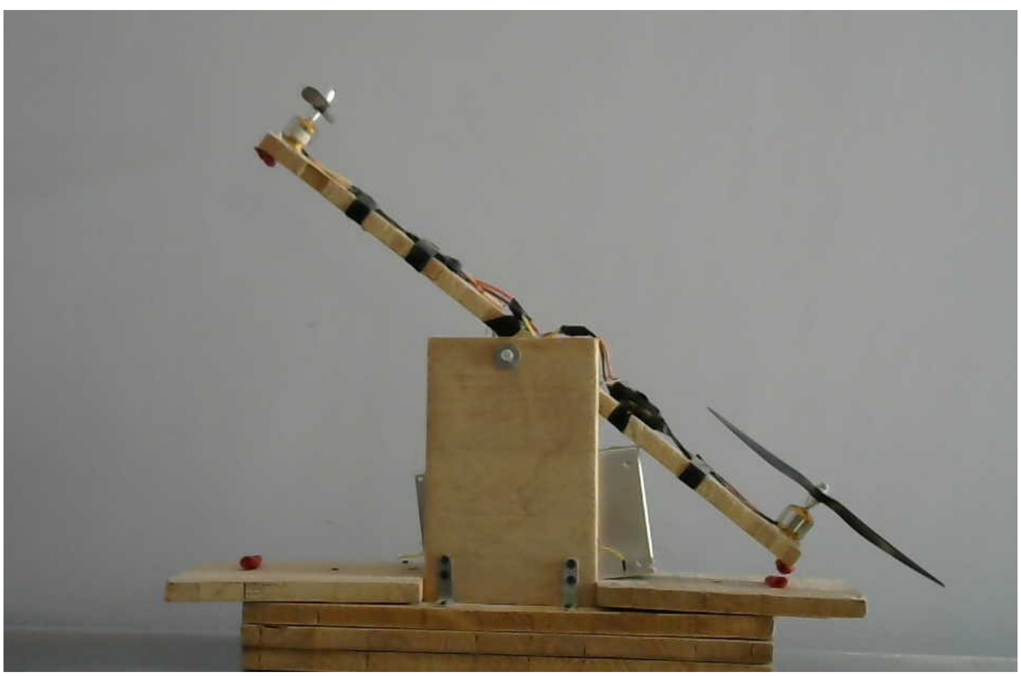

Fig. 9. The Image After Applying Cropping On The Original Image

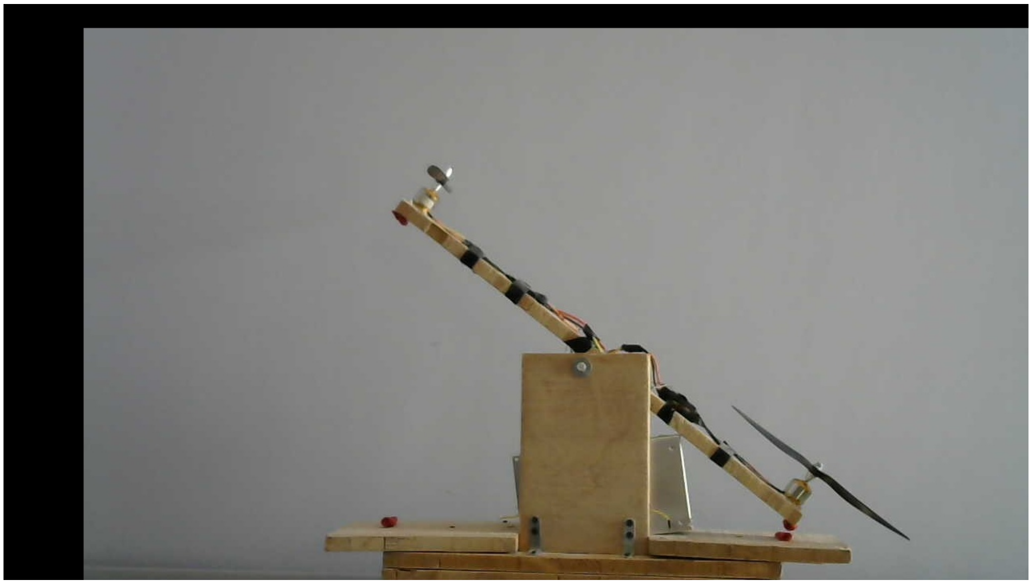

Fig. 10. The Image After Applying Vertical And Horizontal Translation On The Original Image

2) Intensity Level Transformation

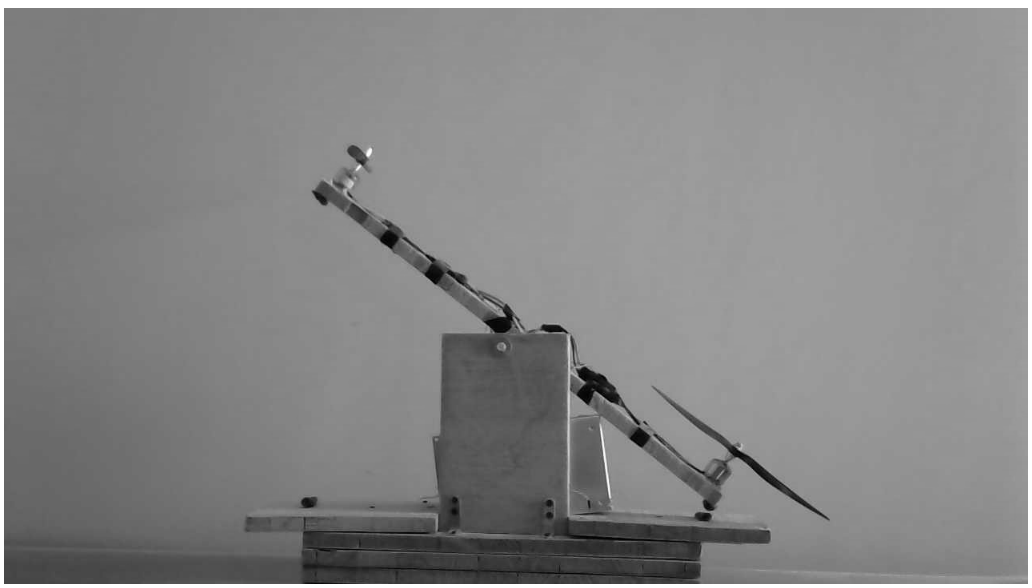

Fig. 11. The Image After Applying Gray Scale Transformation

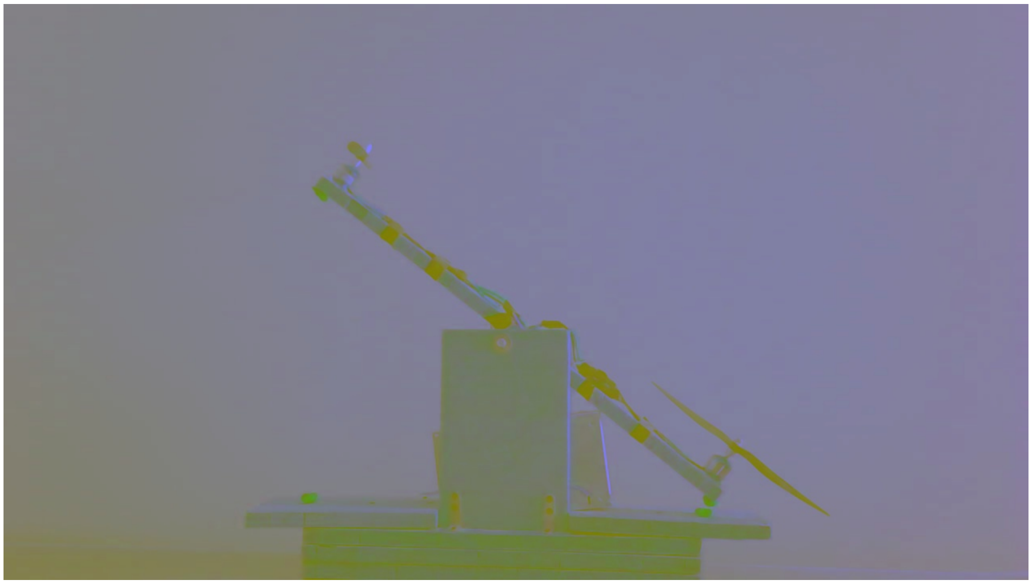

Fig. 12. The Image After Applying LAB Color Space

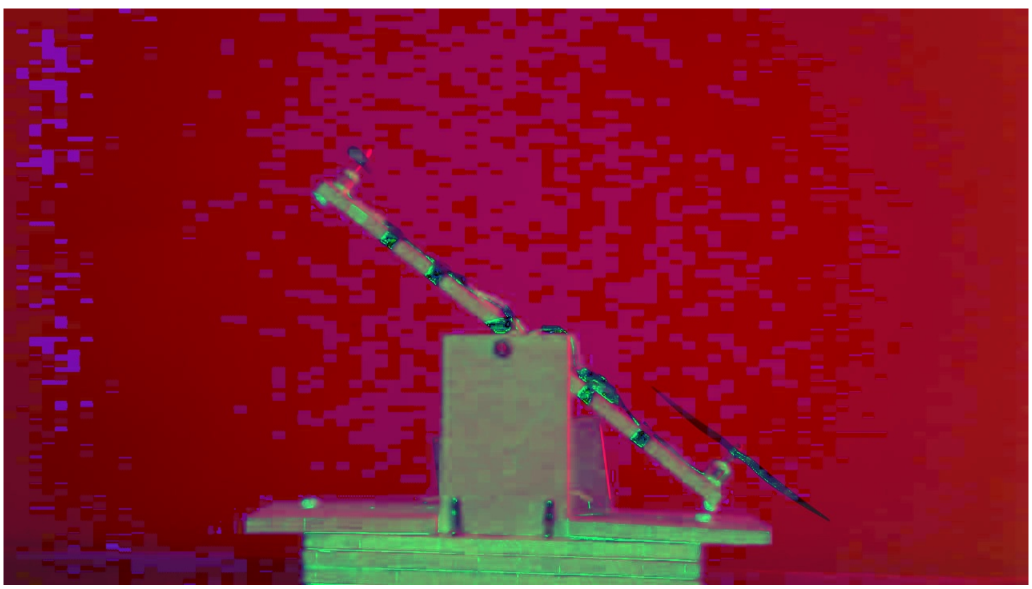

Fig. 13. The Image After Applying HSV Color Space

Fig. 14. The Image After Applying Darkening On The Image

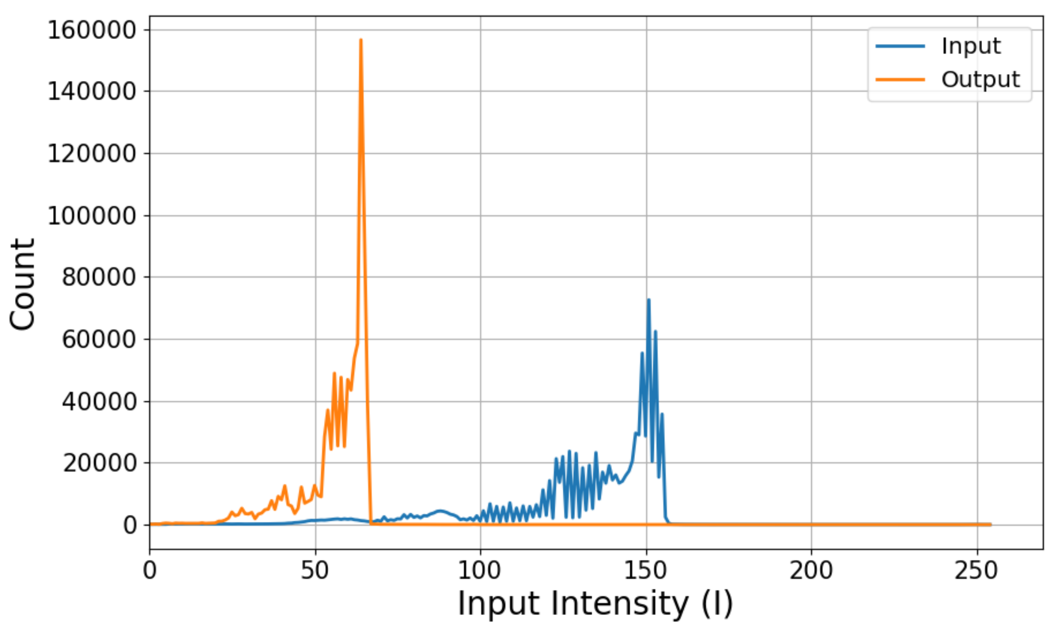

Fig. 15. Histogram Of The Image After Applying Darkening, the values are shifted more to the left.

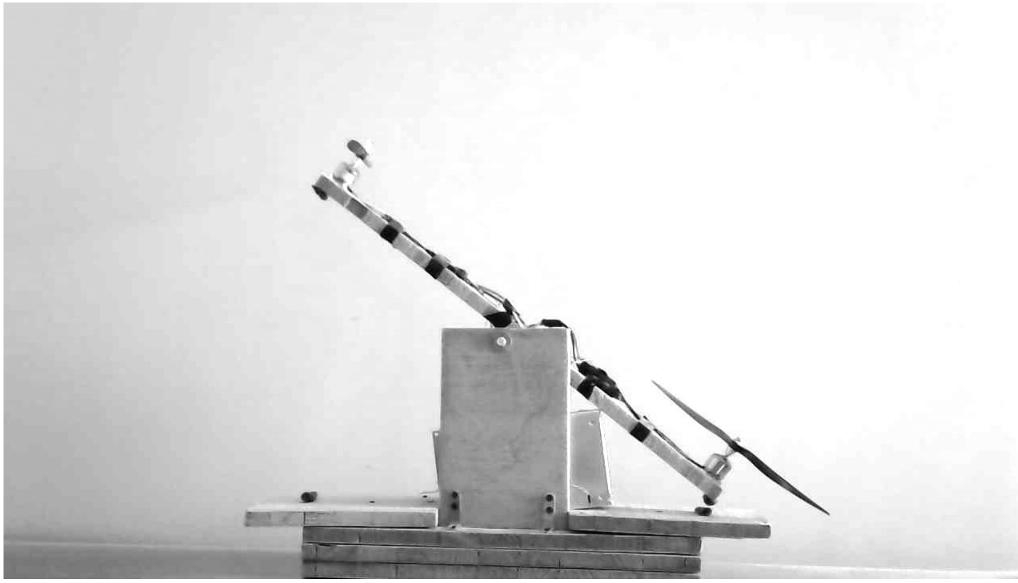

Fig. 16. The Image After Changing It To High Contrast

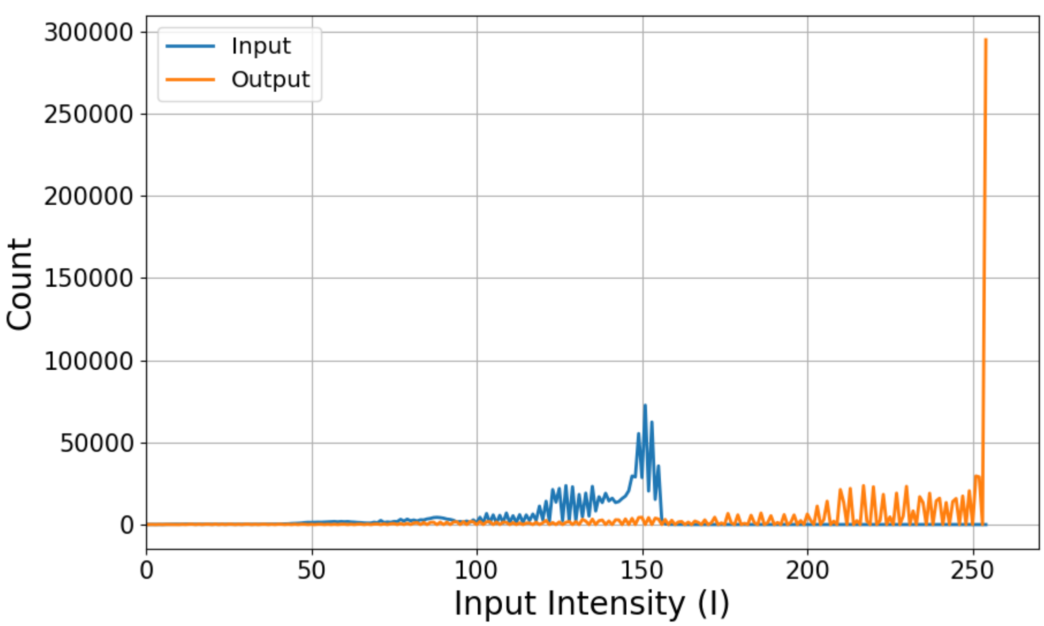

Fig. 17. Histogram Of The High Contrast

3) Morphological Operations
Morphological operations are a set of operations that process images based on shapes. They apply a structuring element to an input image and generate an output image.

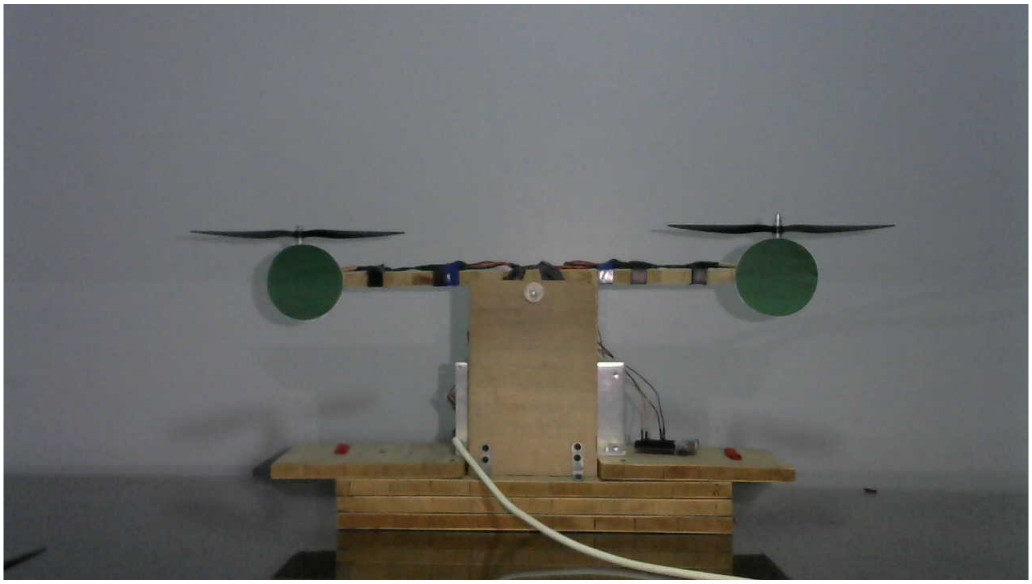

Fig. 18. The original image after adding colored figures, circles, under each motor

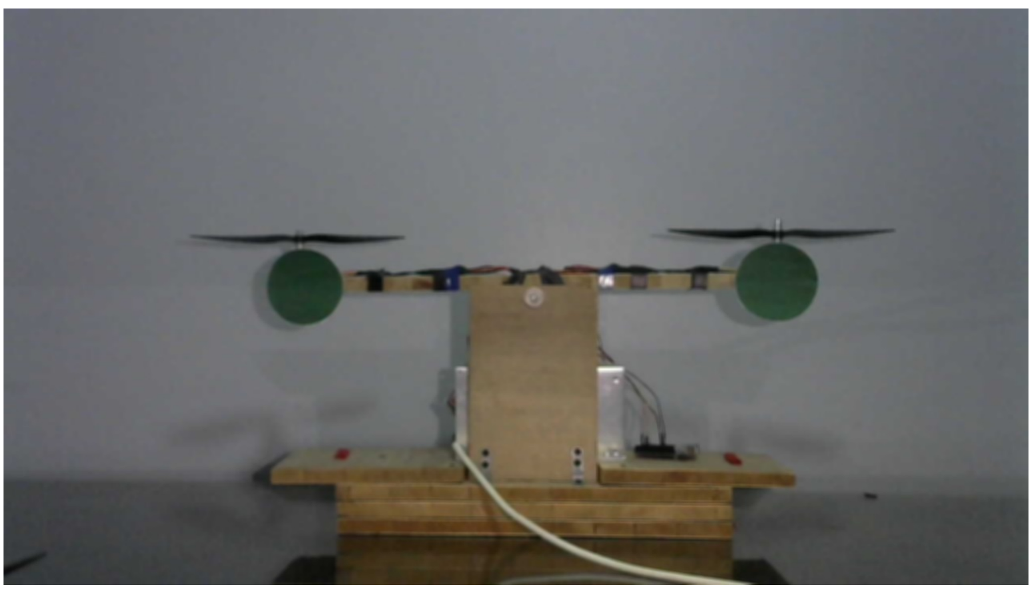

Fig. 19. The image after applying an averaging filter

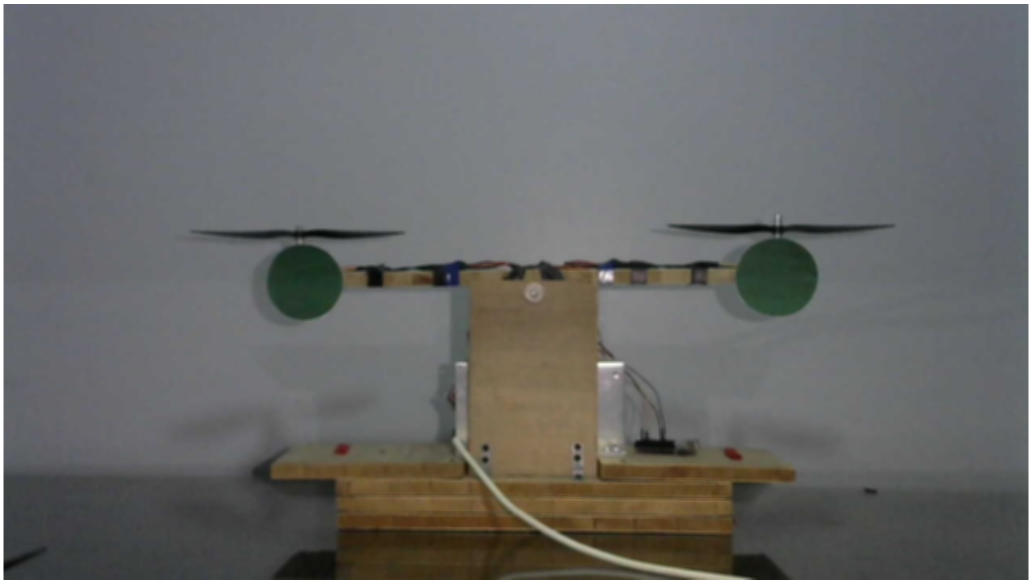

Fig. 20. The image after applying a guassian filter

Next, erosion and dilation are applied. Basics of Erosion: Erodes away the boundaries of the foreground object, Used to diminish the features of an image. Basics of dilation: Increases the object area, Used to accentuate features. Both are applied using a 5 x 5 kernel.

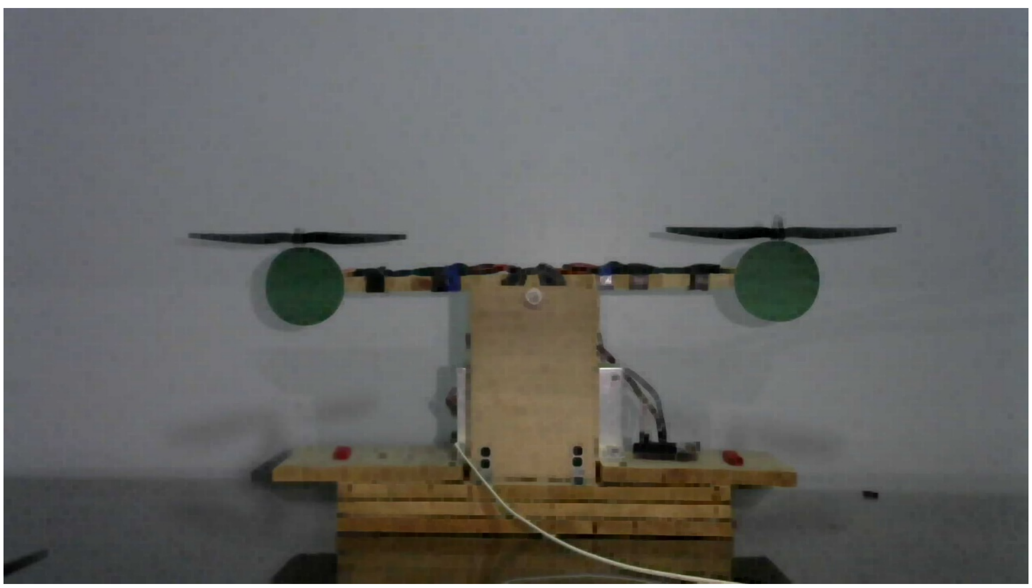

Fig. 21. The image after applying erosion using a 5 x 5 kernel

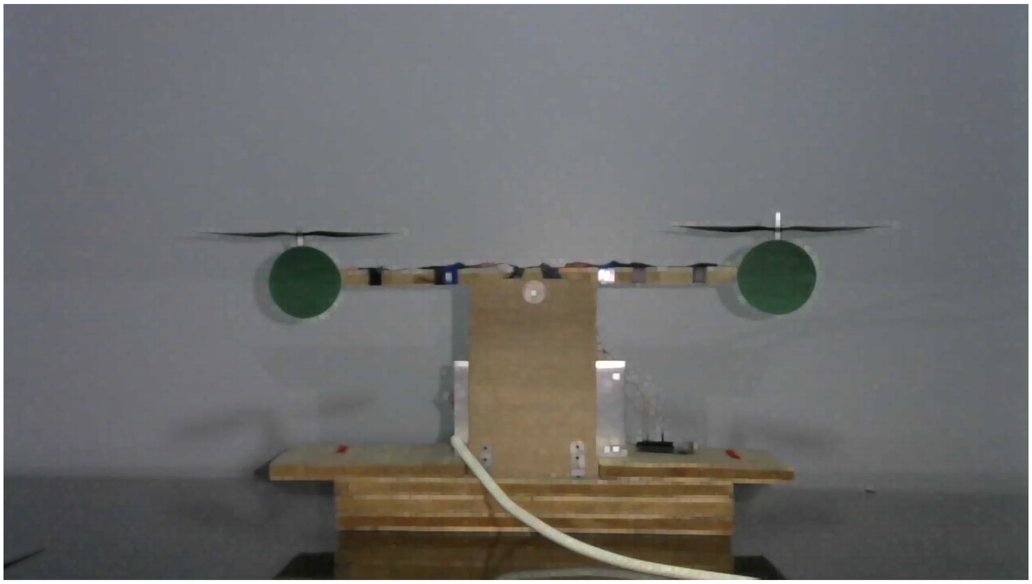

Fig. 22. The image after applying dilation using a 5 x 5 kernel

4) Edge Detection Edge detection is an image processing technique for finding the boundaries of objects within images. It works by detecting discontinuities in brightness. In this paper, edge detection is implemented using 3 different methods applied on the, 5 x 5 Gaussian blurred image:
   a) Canny Edge Detection

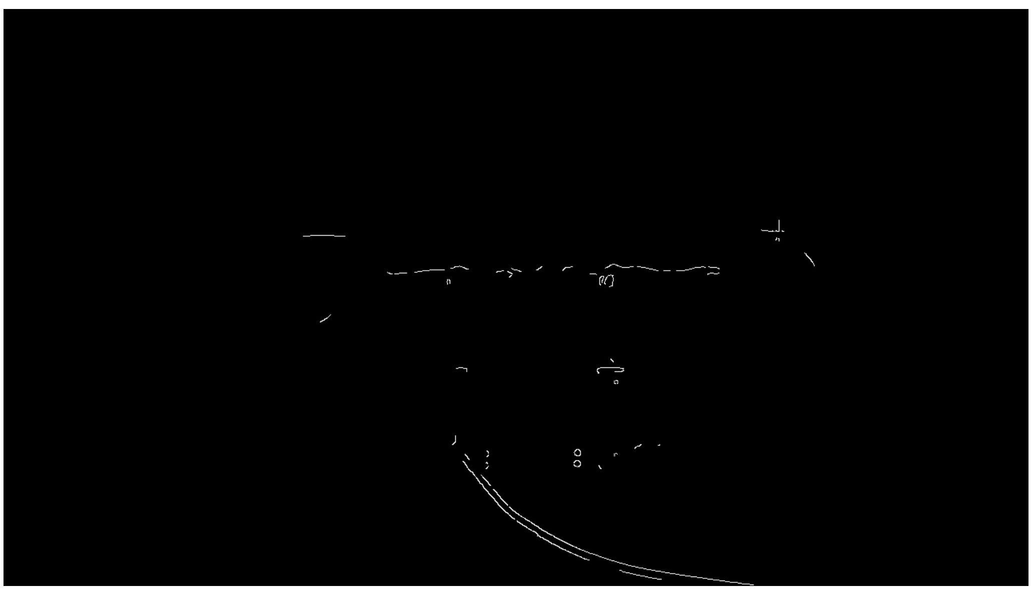

Fig. 23. The image after Canny edge detection using a threshold range 210 to 250

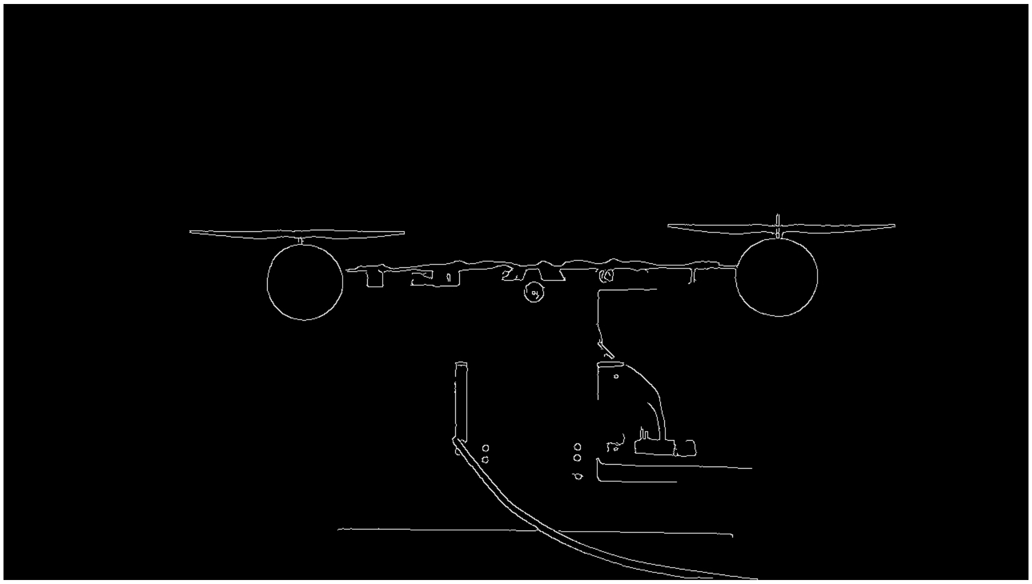

Fig. 24. The image after Canny edge detection using a threshold range 50 to 200

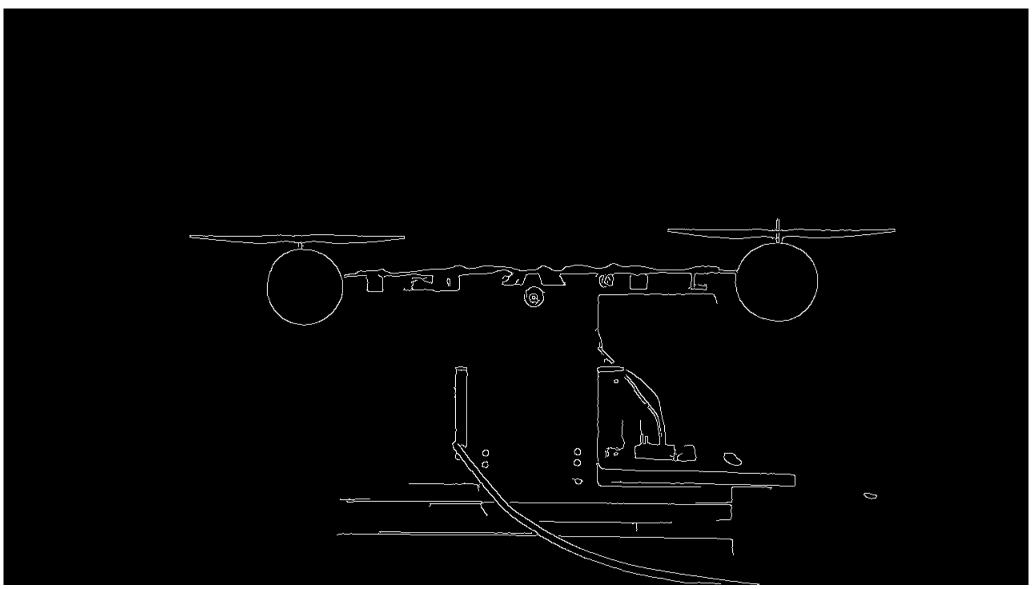

Fig. 25. The image after Canny edge detection using a threshold range 30 to 150

As shown in Figures 23, 24, and 25, the results keep on improving as the threshold is adjusted by trial and error until reaching the best values in Figure 26

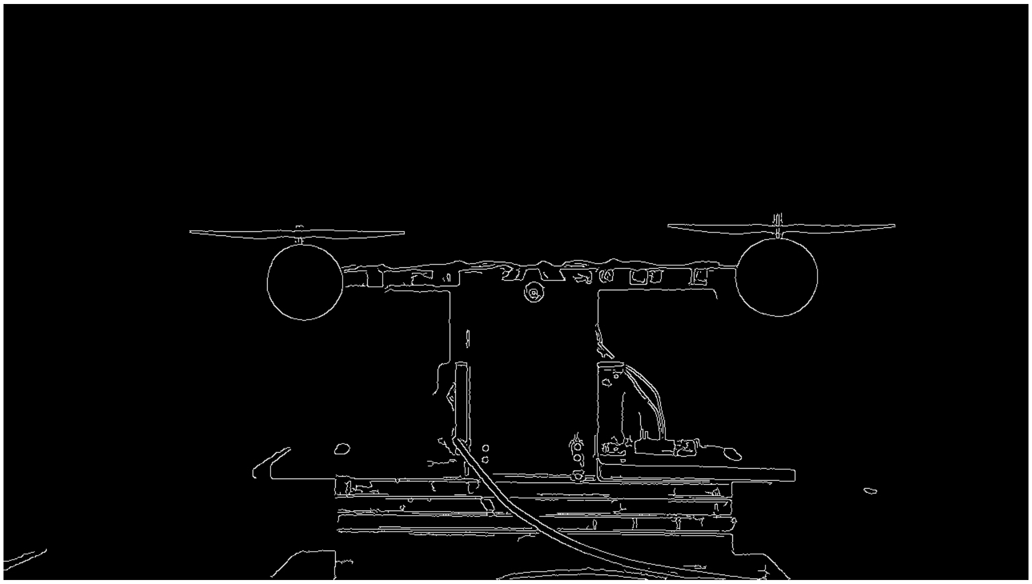

Fig. 26. The image after Canny edge detection using a threshold range 0 to 60

b) Laplacian Edge Detection

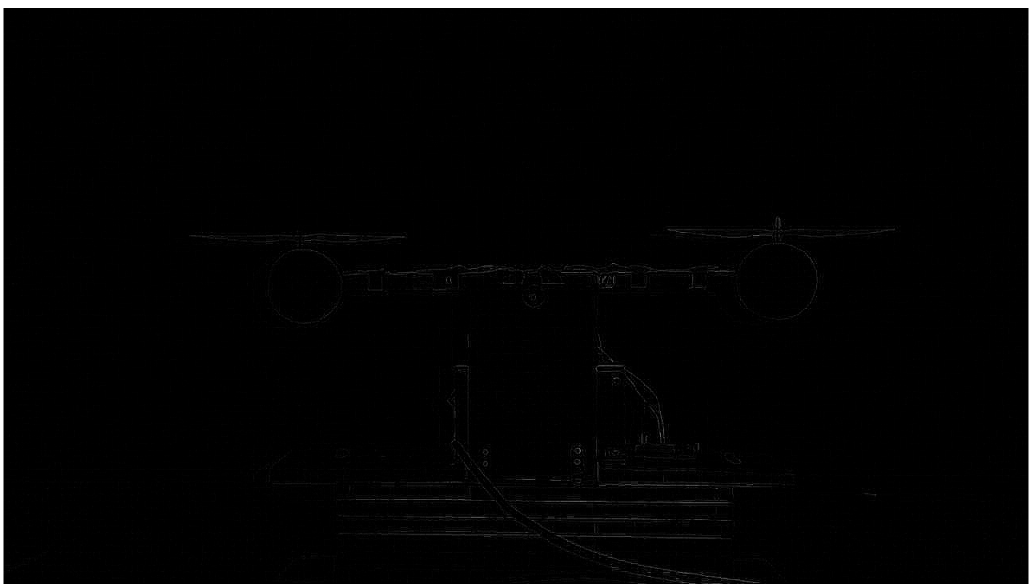

Fig. 27. The image after applying Laplacian edge detection, as shown the result is terrible based on trial and error

c) Sobel Edge Detection

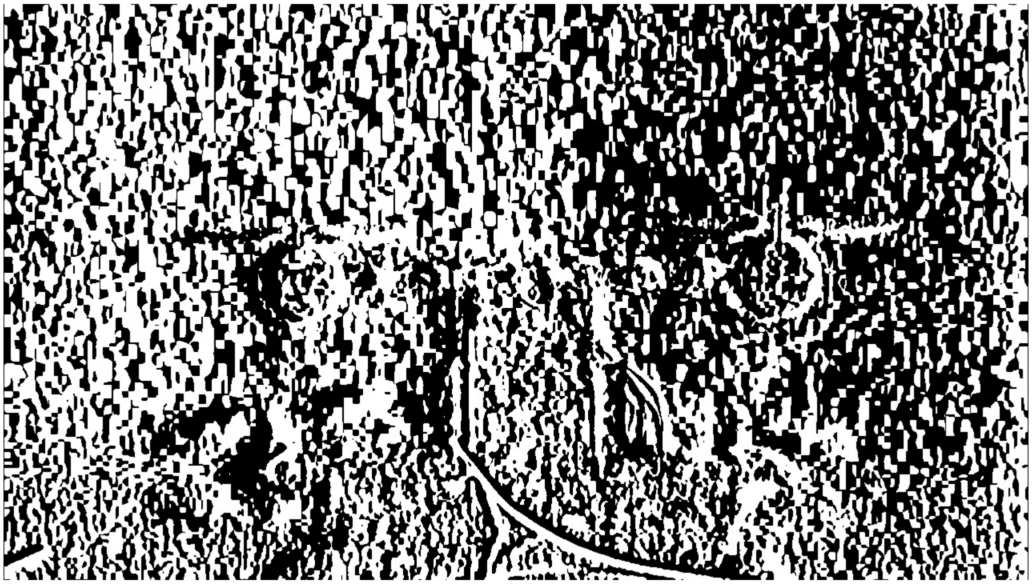

Fig. 28. The image after applying Sobel edge detection in x direction

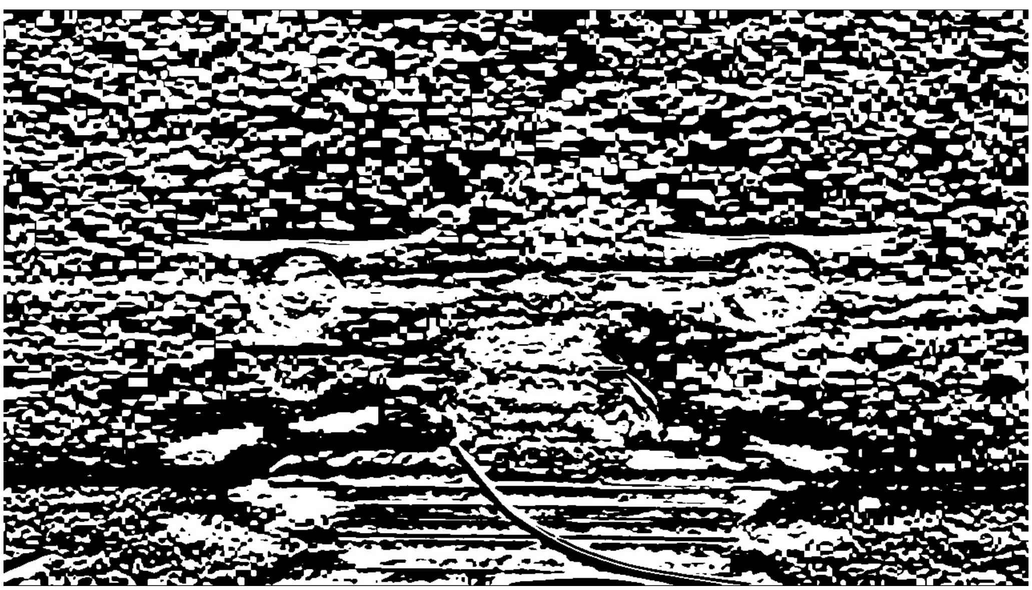

Fig. 29. The image after applying Sobel edge detection in y direction

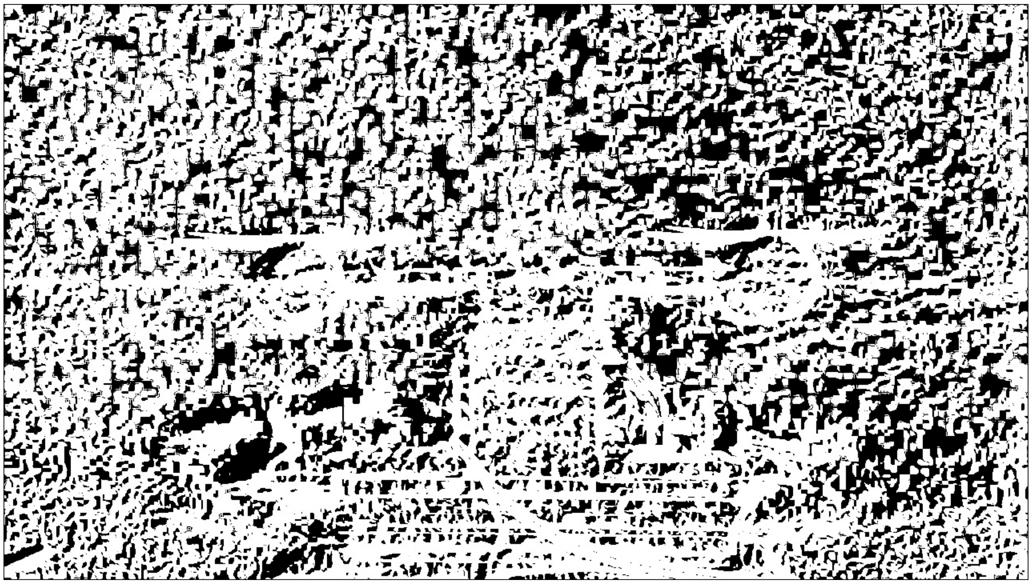

Fig. 30. The image after applying Sobel edge detection in both x and y directions

5) Segmentation

a) Color Segmentation The first type of segmentation applied was to color segment the green circle which will be used later for angle calculation.

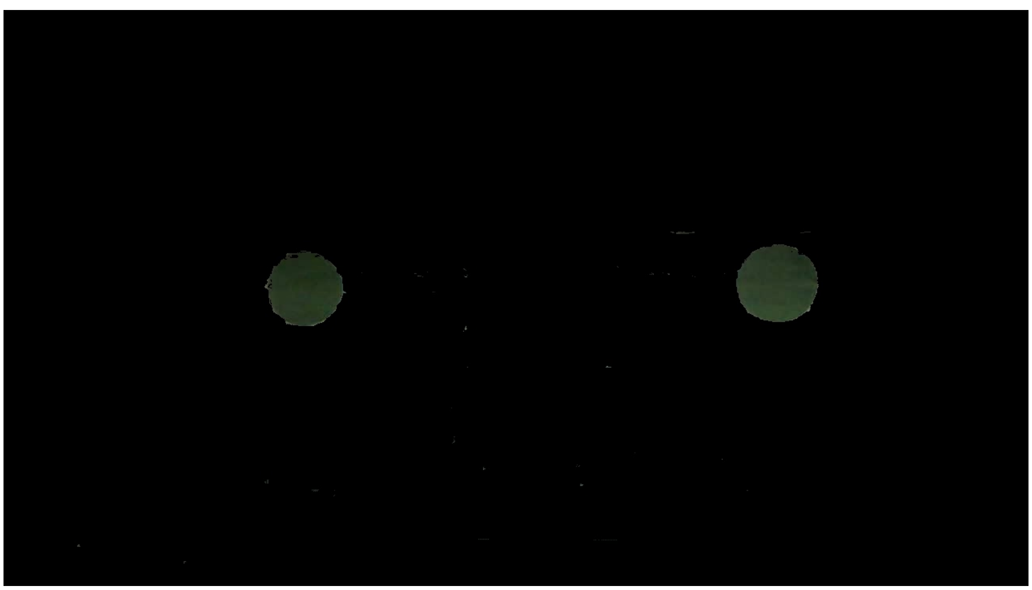

Fig. 31. The image after applying the green segmentation

b) Contour Detection

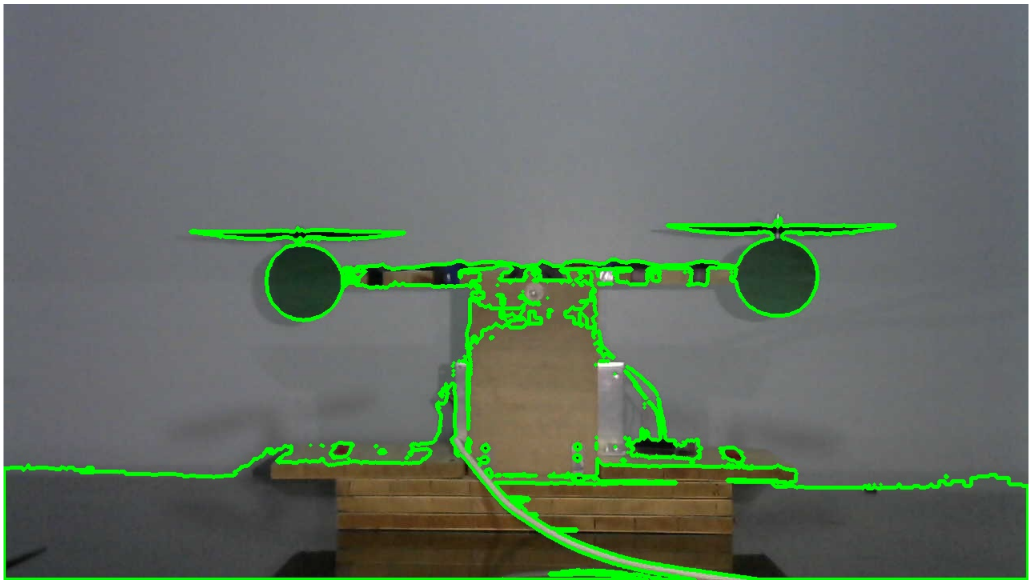

Fig. 32. The image after applying Contour Detection

c) Watershed Algorithm The watershed algorithm is used for segmentation in some complex images if we apply simple thresholding and contour detection then will not be able to give proper results. The watershed algorithm is based on extracting sure background and foreground and then using markers will make a watershed run and detect the exact boundaries. This algorithm generally helps in detecting touching and overlapping objects in the image. For markers, it can be user-defined like manually clicking and getting the coordinates and also using some defined algorithms such as thresholding or any morphological operations. Due to the presence of noise, we can't apply watershed algorithms directly.

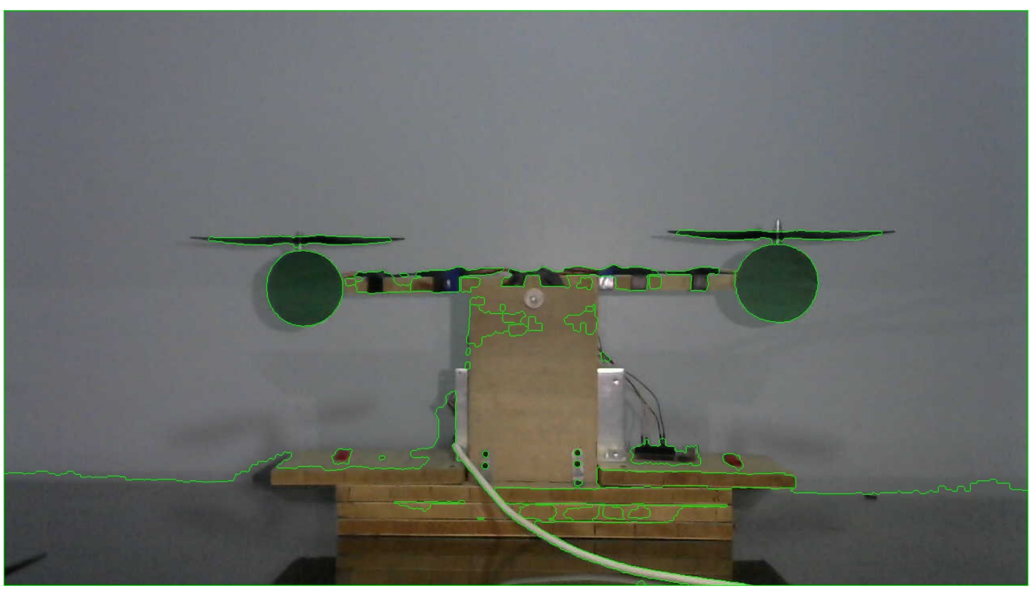

Fig. 33. The image after applying the watershed algorithm

G. Control

The transfer function is shown in Equation 1:

$$\ddot{\theta}_b = \frac{M_2 - M_1 * g * \frac{L}{2} - b\theta_b - a\theta_b(\omega_{m_2} + \omega_{m_1}) + 0.00125L * (\omega_{m_2} + \omega_{m_1})}{MomentofInertia} \tag{1}$$

a) Closed Loop Response In this section, a simple closed loop is tested. Python communicates with Arduino to send a control action to the 2 BLDC motors based on the image processing signal by establishing a serial communication. First in the image processing code in python, the frame captures from the external camera then converts the frame into gray-scale. After converting, numpy mean method is used to calculate the average of the intensity levels of the pixels in the image. If the pixels have a mean higher than 100, also called a bright frame, the left motor is actuated based on a signal given from python to the Arduino. If the mean is less than 50, dark frame, the right motor is actuated.

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