

**AERIAL EYES - QUADCOPTER  
IMPLEMENTING PANORAMA AND 3D  
RECONSTRUCTION**

*by*

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**DEPARTMENT OF COMPUTER SCIENCE AND  
ENGINEERING**

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Certified that this project report titled **AERIAL EYES - QUAD-COPTER IMPLEMENTING PANORAMA AND 3D RE-CONSTRUCTION** is the *bonafide* work of **AVINASH RAMESH (2012103009)**, **MITHUL MATHIVANAN (2012103037)** and **SHRIYA SASANK (2012103069)** who carried out the project work under my supervision, for the fulfillment of the requirements for the award of the degree of Bachelor of Engineering in Computer Science and Engineering. Certified further that to the best of my knowledge, the work reported herein does not form part of any other thesis or dissertation on the basis of which a degree or an award was conferred on an earlier occasion on these or any other candidates.

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**Avinash Ramesh**

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**Shriya Sasank**

## **ABSTRACT**

Quadcopters are one of the most popular technologies of the 21st century. They have multifarious uses ranging from aerial photogrammetry(photography and 3d positioning of objects), military surveillance, taking panorama shots, movie-making, infrastructure inspection and delivery of products. It is also an extensive area of research, an example of which would be swarm robotics. Flight stability of drones is an ongoing area of research with algorithms such as PID and Fuzzy Logic under continuous development and refinement.

Our project delves into aerial photogrammetry i.e. taking pictures of objects/topography and reconstructing 3D representations of it. Since it is extremely difficult to take pictures or videos of places inaccessible to humans, such as caverns, waterfalls, ancient ruins, caves, etc, we can use drones to capture their images.

Our drone uses the Raspberry Pi 2 microcomputer to perform all on-board operations including flight control and image-processing. It carries an IMU sensor that detects the orientation of the quadcopter and feeds it to the PID controller. The PID controller uses this data as input to automatically stabilize the quadcopter.

The drone is controlled via WiFi using an Android App with a virtual joystick interface. It is also equipped with a camera module which allows it to take pictures of objects and terrain and perform panorama stitching and 3D reconstruction.

## **ABSTRACT**

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## LIST OF ABBREVIATIONS

<b>RPi</b>	Raspberry Pi
<b>IDE</b>	Interactive Desktop Environment
<b>UAV</b>	Unmanned Aerial Vehicle
<b>PWM</b>	Pulse Width Modulation
<b>IMU</b>	Inertial Measurement Unit
<b>PID</b>	Proportional-Integral-Derivative
<b>GUI</b>	Graphical User Interface
<b>GPS</b>	Global Positioning System
<b>JSON</b>	JavaScript Object Notation
<b>WiFi</b>	Wireless Fidelity
<b>SfM</b>	Structure from Motion
<b>DOF</b>	Degrees Of Freedom
<b>BLDC</b>	BrushLess Direct Current
<b>ESC</b>	Electronic Speed Controller
<b>SD</b>	Secure Digital
<b>LiPo</b>	Lithium Polonium
<b>RC</b>	Radio Control
<b>UI</b>	User Interface

# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 GENERAL OVERVIEW**

The Quadcopter UAV is one of the fastest growing technologies of the 21st century. It has a myriad of uses and is a field of intensive research and continuous development. A quadcopter, also called a quadrotor helicopter or quadrotor, is a multirotor helicopter that is lifted and propelled by four rotors. Quadcopters differ from conventional helicopters which use rotors which are able to vary the pitch of their blades dynamically as they move around the rotor hub. In the early days of flight, quadcopters (then referred to as 'quadrotors') were seen as possible solutions to some of the persistent problems in vertical flight; torque-induced control issues (as well as efficiency issues originating from the tail rotor, which generates no useful lift) can be eliminated by counter-rotation and the relatively short blades are much easier to construct.

It is a highly useful technology that can be used in aerial photogrammetry, reconstructing topographical landscapes for archaeological excavations, reconstruction of buildings and taking panorama shots for movie-making etc. Drones are actively used in real-estate photography where they provide "virtual walkthroughs" to allow buyers to see the elements of the home vividly without actually entering the site.

Drones play a major role in all categories of surveillance from border

patrol, building security and road-traffic monitoring. The advantage of using drones is that they're small, highly mobile, quiet and easy to camouflage.

Another innovative and popular use for drones is in the product/food delivery sector. There are several security and reliability concerns that challenge their feasibility but new technologies are being developed to combat these issues.

Ultimately, drone technology is advancing in leaps and bounds with every day and it is inevitable that it would soon be a part of our lives, solving many of our problems.

## 1.2 ABOUT THE PROJECT

The project is divided into three main modules. The first module is the quadcopter itself. The quadcopter runs on the Raspberry Pi 2 microcomputer which hosts a Debian-based OS (Raspbian Jessie) which allows the use of OpenCV and Python. It has four motors whose speeds are controlled using Pulse Width Modulation(PWM) technique. PWM signals are used to communicate with the ESC which controls the voltage given to the BLDC motors and thus control the speed. The RPi uses pigpio library to issue PWM signals to the ESC.

The flight dynamics including stability and orientation are detected using the IMU(Inertial Measurement Unit) Sensor which consists of an accelerometer, gyroscope and magnetometer. The IMU sensor has 9 degrees of freedom since the accelerometer, gyroscope and magnetometer have 3 axes each. The accelerometer measures the acceleration and tilt while the gyroscope measures the angular velocity. The sensor data are fed to the RPi controller which calculates the current orientation and automatically computes the required orientation of the quadcopter

using a PID algorithm. The RPi runs a Python server which receives JSON-encoded altitude, motor speed and trim values which are decoded and used as input by the Quadcopter program. The quadcopter is further equipped with a camera module which takes pictures and feeds them to the RPi's image-processing program which then performs Panorama stitching and 3D Reconstruction of the captured images.

The second module performs image processing on the images captured by the RPi camera. It is divided into two parts Panorama Stitching and 3D Model Reconstruction. The module has been implemented using OpenCV 3.1.0 with Python support. The quadcopter takes pictures using the camera module which are fed to the RPi. OpenCV is used to stitch the images together to create a panorama or a 360 degree view of the environment. Panorama stitching allows one to take individual images of a wide physical space which cannot be covered in a single shot, finds overlapping features, matches them and stitches them into one large, combined shot. This can be used in various applications such as movie-making, aerial photogrammetry and terrain localization and mapping.

The second part of the module deals with 3D reconstruction. The reconstruction algorithm also called Structure from Motion(SfM) algorithm is used to recreate 3D point clouds of buildings or topographies whose pictures are taken by the quadcopter. The point clouds are then visualized on a laptop using a browser. The advantage of using a quadcopter for this purpose is that it can fly to inaccessible locations and take shots which would otherwise be very difficult to capture. It can therefore be used for archaeological surveys, security and dynamic reconstruction of terrain.

The third module is the Android App which is used to control the quadcopter. Usually quadcopters are controlled using Radio Controllers but this project makes use of an Android app which will have other functions apart from simply controlling the flight of the drone viz. sending JSON-encoded signals using WiFi to the Python server running on the RPi. The app allows the user to manually control the altitude of the quadcopter, change trim values(which are special values used for stabilizing the quadcopter) and additionally control the speed of individual motors. The app has a virtual joystick interface for simple user-interaction and control.

### 1.3 ORGANIZATION OF THE THESIS

Chapter 1 deals with the general overview and an introduction to the project. Chapter 2 discusses the related work that has been accomplished in the field of drone technology and integration of image-processing with UAVs. Chapter 3 gives a detailed description of the requirements of the project. Chapter 4 describes the System Design. Chapter 5 talks about the System Development process. Chapter 6 deals with the test cases, results and evaluation. Chapter 7 marks the end of the thesis with the project's contributions and future work.

## **CHAPTER 2**

### **RELATED WORK**

A significant amount of research and work has gone into the quadcopter. There have been several algorithms for controlling the stability of the quadcopter such as PID(Proportional-Integral-Derivative) and Fuzzy Logic. With improvements to open source image processing libraries like OpenCV and the development of RaspberryPi microcomputer, the capability and use of drones for various activities have increased.

Alex G. Kendall, Nishaad N. Salvapantula and Karl A. Stol developed an on-board object-tracking control of a quadcopter with monocular vision [3]. This project used a Raspberry Pi for processing along with a camera module and sensors as input to the OpenCV library for object tracking based on the color of the objects.

While our project also makes use of the RPi and OpenCV for image processing, it does not perform object tracking. Our project does not deal with tracking and we have focused largely on the flight stability and image processing modules.

Quadcopters are predominantly controlled using Radio Control joysticks. Since Android phones are ubiquitous now, we developed a virtual joystick interface to control the flight of the quadcopter as an Android app. The app is also used for directing image-processing functions of the drone.

Since our quadcopter's functions are panorama stitching and 3D reconstruction, we needed to develop an interface for rendering the results. A. Zul Azfar and Hazry Desa [2] had developed a Graphical User Interface for monitoring the flight dynamics and orientation of a remotely-operated quadcopter using LABView software. The motion of the quadcopter could be captured on the GUI using LabVIEW software.

The quadcopters processing was done on-board using Arduino microcontroller and the balancing and stability were managed using an IMU sensor. This was a path-breaking paper as it demonstrated how an unmanned aerial vehicle could be controlled from a remote station. The project did not concern itself with the stability of the drone or perform any specialized functions.

Priyanga M. And Raja Ramanan [5] developed a UAV for Video Surveillance to prevent unauthorized soil-mining operations. It used a RPi for on-board processing of live feeds from a webcam. The videos could be viewed on a webpage in real-time using WiFi. The drone used a GPS to calculate position and follow the target. The project demonstrated how a drone could be used for practical and real-time applications such as surveillance and tracking with high accuracy.

In our project, signals from the app are sent as JSON-encoded data using WiFi to the Python server running on the quadcopter. The quadcopter itself is controlled remotely via WiFi using the Android App.

Image processing on-board the quadcopter has been implemented by K.S. Shilpasree, Lokesha H and Hadimani Shivkumar [4] in their paper, Implementation of Image Processing on Raspberry Pi. They have described the purpose of image-enhancing algorithms to improve the quality of the images taken by the drone due to compromised image quality from unstable flight. Image-enhancing algorithms such as Rudin-Osher-Fatemi de-noising model (ROF) have been implemented.

Shawn McCann's thesis on 3D Reconstruction from Multiple Images [6] has tried to identify various techniques for dense and sparse reconstructions using Structure from Motion(SfM) algorithms. He has demonstrated and implemented the complete flow of 3D Reconstruction using the open source Bundler software. Our project makes use of VLFeat which has SfM support and OpenCV which offers a variety of useful libraries for feature detection and matching.

In both projects, Bundle Adjustment module was used to minimize re-projection errors and generate sparse point clouds. While [6] rendered the point clouds using third-party tools(MeshLab), our project uses an interactive JS library called, threeJS which renders the point cloud on a browser.

Argentim, Lucas M and Rezende, Willian C and Santos, Paulo E and Aguiar, Renato A's paper on PID, LQR and LQR-PID on a quadcopter platform [1] compared the stability of the use of a PID, LQR or a PID tuned with a LQR loop. Our project uses the PID controller loop as the LQR loop, though robust and produce a very low steady state error, have a big transition delay due to using six feedback gains, which may cause lag in the time taken between sensing the angle and computing the output due to the limited computing capacity of the Raspberry Pi used in our project.

Drone technology has advanced enormously along the lines of photography, surveillance, exploration and mapping of terrains and delivery. We were inspired by the mobility combined with the computational power of the RPi from these projects and hence, decided to build one.

The next chapter describes the requirements analysis of the project.

# **CHAPTER 3**

## **REQUIREMENTS ANALYSIS**

### **3.1 REQUIREMENTS**

#### **3.1.1 Quadcopter**

##### **Hardware Requirements for the Quadcopter**

- 1) Raspberry Pi 2 microcomputer
- 2) 9DOF IMU Sensor
- 3) 4 BLDC Motors
- 4) Raspberry Pi Camera Module
- 5) 4 Carbon Fibre Propellers
- 6) Battery
- 7) Quadcopter Frame
- 8) ESC
- 9) Male-Female Connecting Wires
- 10) 4 Propeller Guards
- 11) Breadboard
- 12) Resistors
- 13) Portable Charger

##### **Software Requirements for the Quadcopter**

- 1) Raspbian OS Jessie
- 2) OpenCV 3.1.0 and OpenCV 3.1.0
- 3) Python
- 4) Android Studio

## **Functional Requirements for the Quadcopter**

- 1) Quadcopter should be connected to the WiFi network
- 2) LiPo batteries should be charged
- 3) The SD Card should be securely connected
- 4) The SD Card should have enough space
- 5) Quadcopter should move according to the processed flight control signals

### **3.1.2 Image Processing**

#### **Hardware Requirements for the Image processing module**

- 1) Raspberry Pi Camera
- 2) Raspberry Pi microcomputer (Processing unit)

#### **Software Requirements for the Image processing module**

- 1) Python 2.7.6
- 2) OpenCV 3.1.0

### **Functional Requirements for Image processing module**

- 1) The Raspberry Pi should be connected to the WiFi network
- 2) The Raspberry Pi Camera should be mounted securely on the quadcopter
- 3) The quadcopter must be stable enough to take fairly clear pictures
- 4) The camera signal from the Android app should be received by the quadcopter
- 5) The SD Card must have enough space to store the images taken
- 6) The Raspberry Pi must execute the Python program without system failure

### **3.1.3 Android App Module**

#### **Software Requirements for the Android App module**

- 1) Android Studio IDE
- 2) Terminal emulator for android

## **Hardware Requirements for the Android App module**

- 3) Android phone supporting minimum API 18

## **Functional Requirements for the Android App module**

- 1) Create the Mobile Hotspot
- 2) Send motion, orientation and camera signals from the app to the Raspberry Pi

### **3.1.4 Analysis**

The quadcopter is built using the Raspberry Pi. The Raspberry Pi was used because of its computational power, portability and immense open-source support. The quadcopter is built with 4 motors, propellers, an IMU sensor, ESC and a Raspberry Pi native camera that is interfaced with the Raspberry Pi. The Android app sends JSON-encoded signals to the Pi. The Raspberry Pi hosts a Python server which decodes the signals received and triggers the appropriate Python program to fly the quadcopter and take pictures. The IMU sensor detects the orientation of the quadcopter and feeds that data to the quadcopter balancing program. The program can then use the roll, pitch and yaw data to compute the required orientation of the quadcopter. The Pi Camera takes images which are processed using OpenCV image processing library on the Pi and saved on the SD Card.

The next chapter describes the System Design.

## **CHAPTER 4**

### **SYSTEM DESIGN**

#### **4.1 COMPONENTS IN THE PROJECT**

##### **4.1.1 Hardware Components**

1. Raspberry Pi 2 microcomputer
2. 9DOF IMU Sensor
3. 4 BLDC Motors
4. Raspberry Pi Camera Module
5. 4 Carbon Fibre Propellers
6. Battery
7. Quadcopter Frame
8. ESC
9. Male-Female Connecting Wires
- 10.4 Propeller Guards
11. Breadboard
12. Resistors
13. Portable Charger

##### **4.1.2 Software Components**

1. Raspbian OS Jessie
2. OpenCV 3.1.0
3. Python 2.7.6
4. Android Studio IDE

#### **4.1.3 Programs**

- a) Python programs to control the quadcopter:
  - 1. PID Controller
  - 2. Kalman Filter
  - 3. Quadcopter Control
  - 4. Python Server
- b) Python programs for Panorama Stitching:
  - 1. Camera Calibration
  - 2. Panorama Stitching
- c) Python Programs for 3D Reconstruction:
  - 1. Extract Metadata
  - 2. Detect Features
  - 3. Match Features
  - 4. Create Tracks
  - 5. Reconstruct
  - 6. Mesh
- d) HTML Code for Visualizing Sparse Reconstruction
- e) Android App providing virtual joystick interface

## **4.2 TECHNOLOGY USED**

### **4.2.1 Raspberry Pi 2 Microcomputer**

The quadcopter is controlled using the Raspberry Pi 2. Raspberry pi (RPI) is a credit card sized microcomputer that runs on a Linux based operating system loaded on its SD card . It includes a 900MHz quad-core ARM Cortex-A7 CPU and 1GB RAM.

It can connect to a network by using an external user-supplied USB Ethernet or WiFi adapter. Furthermore, the RPi has four USB ports, a full HDMI port, 40 GPIO pins and an Ethernet port. Apart from

this, the Raspberry Pi has a camera interface which allows a native Pi Camera to be configured and used. It also has a Micro SD Card slot. The advantage of using a RPi over traditional Arduino boards is that the Pi has much greater computational power and thus, more complicated and better stabilization algorithms can be run on it.

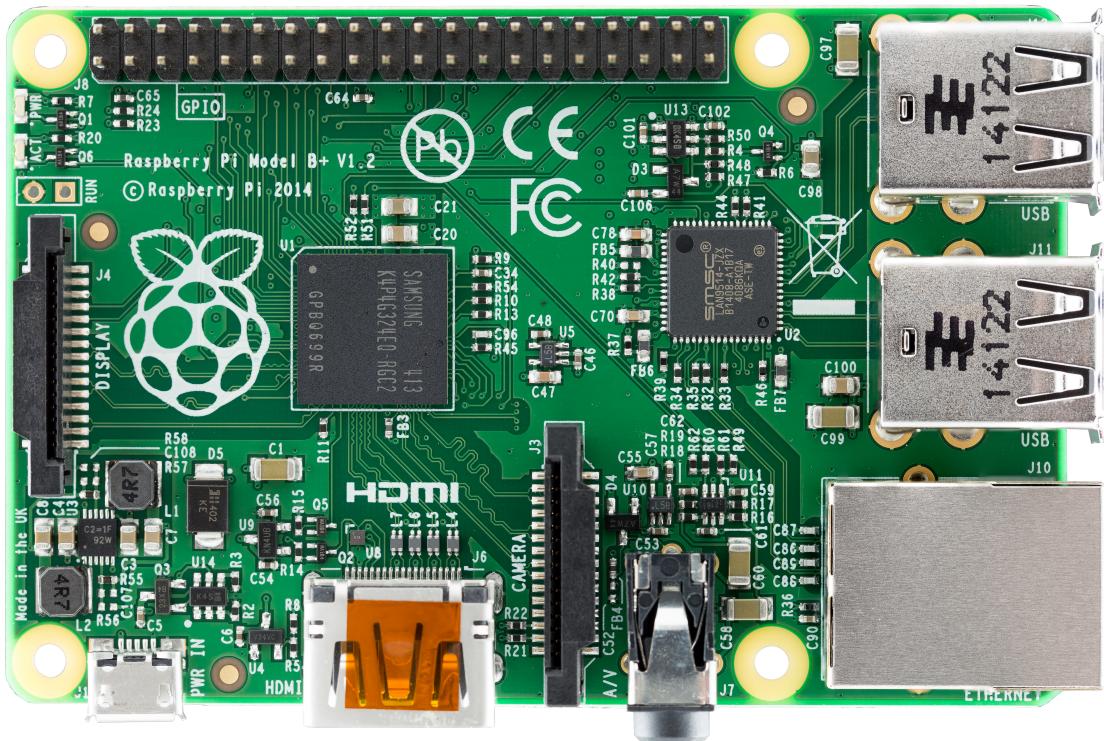


Figure 4.1: Raspberry Pi

Raspberry Pi2 GPIO Header		
Pin#	NAME	Pin#
01	3.3v DC Power	02
03	GPIO02 (SDA1 , I <sup>2</sup> C)	04
05	GPIO03 (SCL1 , I <sup>2</sup> C)	06
07	GPIO04 (GPIO_GCLK)	(TXD0) GPIO14
09	Ground	(RXD0) GPIO15
11	GPIO17 (GPIO_GEN0)	(GPIO_GEN1) GPIO18
13	GPIO27 (GPIO_GEN2)	Ground
15	GPIO22 (GPIO_GEN3)	(GPIO_GEN4) GPIO23
17	3.3v DC Power	(GPIO_GEN5) GPIO24
19	GPIO10 (SPI_MOSI)	Ground
21	GPIO09 (SPI_MISO)	(GPIO_GEN6) GPIO25
23	GPIO11 (SPI_CLK)	(SPI_CE0_N) GPIO08
25	Ground	(SPI_CE1_N) GPIO07
27	ID_SD (I <sup>2</sup> C ID EEPROM)	(I <sup>2</sup> C ID EEPROM) ID_SC
29	GPIO05	Ground
31	GPIO06	GPIO12
33	GPIO13	Ground
35	GPIO19	GPIO16
37	GPIO26	GPIO20
39	Ground	GPIO21

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26/01/2014

<http://www.element14.com>

Figure 4.2: Raspberry Pi 2 GPIO Header

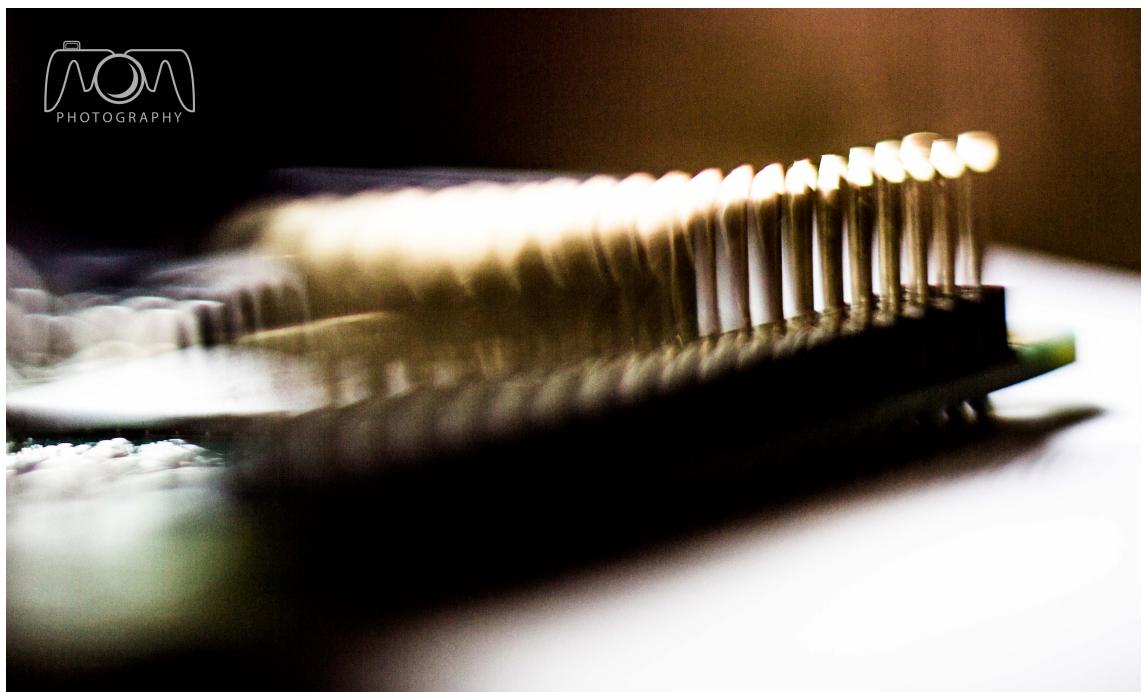


Figure 4.3: Raspberry Pi 2 GPIO Pins

#### 4.2.2 Electronic Speed Controller (ESC)

The Electronic Speed Controller is a circuit which varies the motor's speed, direction and acts like a dynamic brake. ESCs are most often used with BLDC motors necessary for translating digital signals to electric current. ESCs are an essential component of modern multirotor crafts that offer high power, high frequency, high resolution 3-phase AC power to the motors in an extremely compact miniature package. These crafts depend entirely on the variable speed of the motors driving the propellers.

The large variation and fine RPM control in motor/propeller speed gives all of the control necessary for a quadcopter (and all multirotors) to fly. On a quadcopter, each motor gets its own ESC, each of which connects to the controller. After computing the inputs(the amount of current and direction to be given to each motor), the controller directs each ESC to adjust its speed according to the PWM signal provided. This quadcopter uses a 40A, 3s ESC.



Figure 4.4: 40A 3s ESC

#### 4.2.3 IMU Sensor

An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes and magnetometers. IMUs are typically used to maneuver aircraft, including UAVs. This project uses a 9DOF IMU sensor with a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer. The accelerometer measures acceleration and has high accuracy. The gyroscope measures the angular velocity and is used to stabilize flight. It is less accurate than the accelerometer and is prone to drift errors.

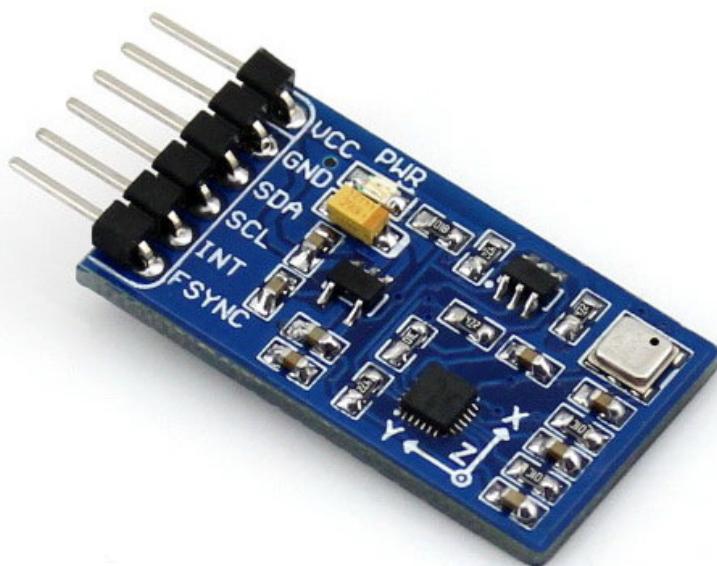


Figure 4.5: IMU Sensor

#### 4.2.4 Raspberry Pi Camera

The Raspberry Pi camera module can be used to take high-definition video, as well as photographs. The camera has a five megapixel fixed-focus camera that supports 1080p30, 720p60 and VGA90 video modes, as well as stills capture. It attaches via a 15cm ribbon cable to the CSI port on the Raspberry Pi. It can be configured using the Python Picamera library. The project uses the Pi Camera to capture images for panorama stitching and 3D reconstruction.



Figure 4.6: Raspberry Pi camera

### 4.3 BLOCK DIAGRAM

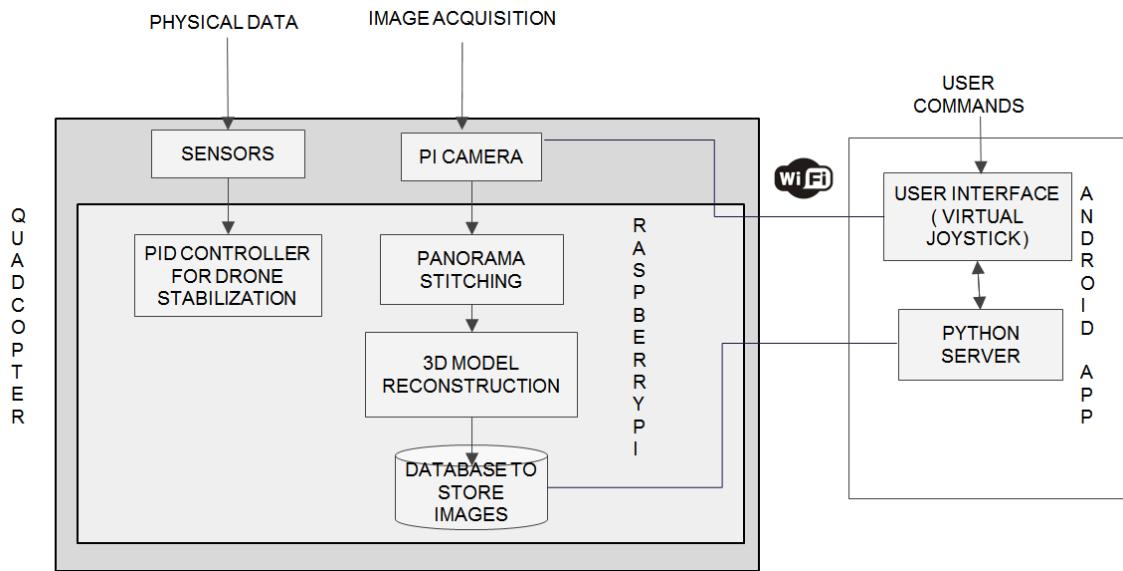


Figure 4.7: Block Diagram

### 4.4 CIRCUIT DIAGRAM

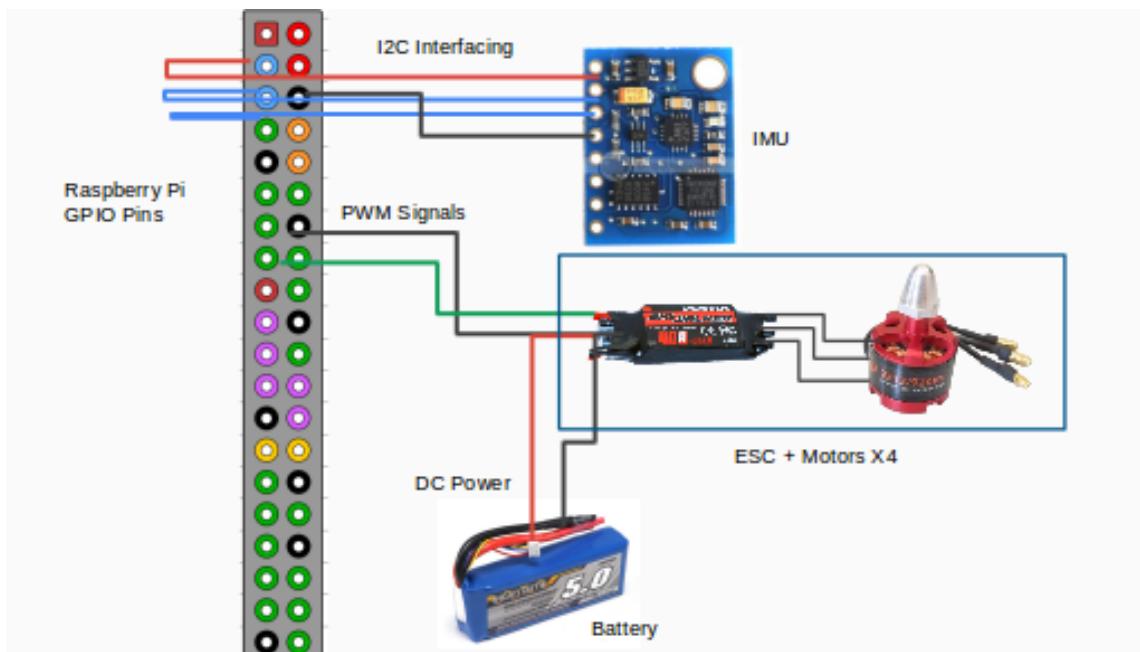


Figure 4.8: Circuit Diagram

## 4.5 FLOW DIAGRAM

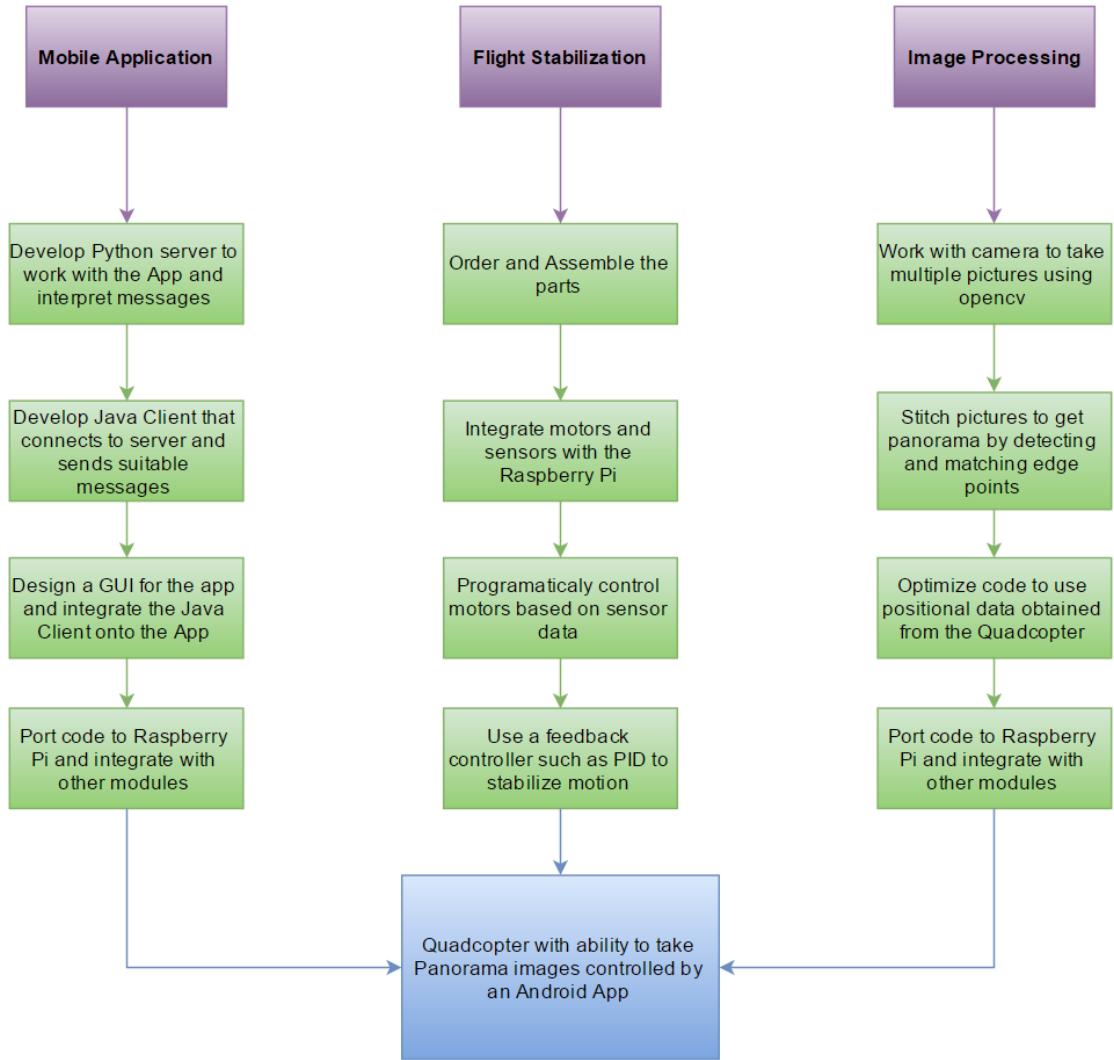


Figure 4.9: Flow Diagram from Input to Output

### Description of Flow Diagram

The user begins the quadcopter program by clicking a button on the Android App which is sent as input to the Python server on the Raspberry Pi. These signals are sent over a WiFi network using an Android phone as a mobile hotspot. The user can control the altitude of the drone and the individual motors using the virtual Joystick on the app. Signals are sent as JSON-encoded data to the quadcopter. The orientation data i.e. the roll, pitch and yaw values are detected by the

IMU sensor on the quadcopter and are fed as input to the balancing algorithm. This data is processed by the python program and the orientation of the quadcopter is automatically corrected using the PID algorithm.

When the camera signal is triggered, the Pi Camera begins taking pictures at an interval of 1 second and saves them on the SD Card. Once the camera is disabled, the image-processing program is executed on the captured images. The final results i.e. the Panorama image and the reconstructed 3D Point Cloud are separately rendered on a web browser using a remote laptop on the ground. Thus, the quadcopter is semi-autonomous as its flight is controlled by the user but its stability is automatically corrected. It is remotely controlled using an Android app. The next chapter discusses the System Development of the project.

# **CHAPTER 5**

## **SYSTEM DEVELOPMENT**

### **5.1 INPUT AND OUTPUT TO SYSTEM**

#### **5.1.1 Input**

Input to the system consists of sensor data by the IMU, JSON-encoded orientation data from the app and images taken by the RPi camera to the quadcopter.

#### **5.1.2 Output**

The output of the system consists of automatic stabilization of the quadcopter's flight, change in orientation of the quadcopter and image processing functions respectively.

- 1) An upward swipe on the left joystick results in increase in altitude of the quadcopter
- 2) A downward swipe on the left joystick results in decrease in altitude of the quadcopter
- 3) An upward swipe on the right joystick results in the quadcopter pitching forward i.e. increase in the back motors
- 4) A downward swipe on the right joystick results in the quadcopter pitching backward i.e. increase in the front motors
- 5) An swipe right on the right joystick results in the quadcopter pitching right i.e. increase in the left motors
- 6) An swipe left on the right joystick results in the quadcopter pitching left i.e. increase in the right motors

## 5.2 INPUT AND OUTPUT FOR EACH MODULE

### 5.2.1 Raspberry Pi-controlled quadcopter

#### Input

The input to Raspberry Pi is the gesture packets from the internet.

1. IMU sensor-data from the accelerometer and gyroscope regarding acceleration and angular velocity.
2. JSON-encoded orientation data from the Android app.
3. JSON-encoded image-acquisition signal data from the Android App.

#### Output

There are 3 kinds of outputs based on the input to the quadcopter.

1. IMU sensor data is used by the PID algorithm to calculate the required orientation and stabilize the quad automatically.
2. Orientation (x,y, z) data is sent to the quad to make it move to the left/right or increase/decrease in altitude.
3. Image acquisition signals allow the RPi camera to click pictures and store them.

#### Process

##### Code for Python Server

---

```
s = socket.socket()
host = '0.0.0.0'
port = 12345
s.bind((host, port))
s.listen(5)
c, addr = s.accept()
print 'Got connection from', addr
```

```
bus = smbus.SMBus(1)

while True:
    try:
        msg=c.recv(1024)
        data = json.loads(msg)
        if 'reset' in data:
            quadcopter.set_zero_angle()
            continue
        p = int(data['P'])
        i = int(data['I'])
        d = int(data['D'])
        height = int(data['pitch'])
        quadcopter.set_height(height)
        quadcopter.set_PID(p,i,d)
    except Exception as e:
        print e
quadcopter.stop()
c.close()
```

# **Code for Balancing the Quad using PID**

```

[axis_output['z'], i_z]=self.compute_PID_output(self.kp_z,
    self.ki_z, self.kd_x, yaw-self.offset_z, i_z,
    old_yaw)

self.motor_bl.setW(int(self.height+axis_output['x']/2
    +axis_output['y']/2))
self.motor_br.setW(int(self.height+axis_output['x']/2
    -axis_output['y']/2))
self.motor_fl.setW(int(self.height-axis_output['x']/2
    +axis_output['y']/2))
self.motor_fr.setW(int(self.height-axis_output['x']/2
    -axis_output['y']/2))

end_time = time.time()
print end_time-start_time
while(end_time-start_time <= 0.02):
    end_time = time.time()
    time.sleep(0.0001)

i=i+1

```

---

### 5.2.2 Image-Processing Module

This module is split into two parts:

1. Panorama stitching
2. 3D Model Reconstruction

#### **Input - Panorama Stitching**

The input consists of images taken by the RPi camera.

#### **Output**

The input images are stitched together forming a 360 degree equirectangular panorama image.

## Process

---

```

image_1 = imread(path_to_image_1)
image_2 = imread(path_to_image_2)

(keypoints1, descriptors1) = detect_and_compute(image_1)
(keypoints2, descriptors2) = detect_and_compute(image_2)
matches = knn(descriptors1,descriptors2)
points1 = new Array(keypoints1[i] for (i,j) in matches)
points2 = new Array(keypoints2[j] for (i,j) in matches)
homography = find_homography(points1,points2)
(size, offset) = calculate_size(image_1, image_2, homography)
warped_image = warp_perspective(image_2,homography)
panorama = warped_image
panorama[offset_x:offset_x+image_1_width,offset_y:offset_y+image_1_height]
= image_1

```

---

## Input - 3D Reconstruction

The input consists of images taken by the RPi camera.

## Output

Sparse point-cloud representing 3D model of the images taken by the quadcopter rendered on a browser.

## Process

---

```

images = read_images(image_path)
for each image in images:
    features = detect_features(image)
    save_features(features)
matches = {}
for each image1 in images:
    for each image2 in images:
        if image1 not equal to image2:
            count = match_features(image1.features,image1.features)

```

```

if count > threshold:
    matches[image1] = image2
for each image1 in matches:
    for match in matches[image1]:
        track = add_track(image1,image2)
        create_track_graph(track)
        im1, im2 = find_images_with_largest_matches(images)
        pts3d = bootstrap_reconstruction(im1,im2)
    for each image in images:
        if image not equal to im1 and if image not equal to
            im2:
            pts2d = get_keypoints(im2)
            pts3d = incremental_reconstruction(pts3d,pts2d)
            pts3d = bundle_adjustment(pts3d)

```

---

### 5.2.3 Android App Module

#### Input

Touch and click (Haptic) controlled movements on the virtual joystick interface of the app.

#### Output

Touch movement on the circular joystick results in change in orientation of the quad. Clicking the camera button send a signal to the RPi Camera to take pictures.

#### Process

---

```

joystick_left = new Joystick()
joystick_right = new Joystick()
joystick_left.setTouchListener()
joystick_right.setTouchListener()
camera_button.setOnClickListener()

```

```
camera_button.click(){
    camera.shoot()
    camera.enable()
}

while(app_running)
{
    action_left = joystick_left.touch()
    action_right = joystick_right.touch()
    distance_left = joystick_left.getDistance()
    distance_right = joystick_right.getDistance()
    switch(action_left)
    {
        case 'up': increase_height(distance_left)
                    break
        case 'down': decrease_height(distance_left)
                    break
        default: print 'Invalid action'
    }
    switch(action_right)
    {
        case 'up': pitch_forward(distance_right)
                    break
        case 'down': pitch_backward(distance_right)
                    break
        case 'left': pitch_left(distance_right)
                    break
        case 'right': pitch_right(distance_right)
                    break
        case 'upleft': pitch_upleft(distance_right)
                    break
        case 'upright': pitch_upright(distance_right)
                    break
        case 'downleft': pitch_downleft(distance_right)
                    break
    }
}
```

```

        case 'downright': pitch_downright(distance_right)
                            break
            default: print 'Invalid action'
        }
    }

```

---

## 5.3 MODULES

### 5.3.1 Raspberry Pi 2-controlled quadcopter

The objective of the project was to build a semi-autonomous quadcopter capable of self-controlled, stable flight guided via wireless communication through an Android app. A quadcopter, also called a quadrotor helicopter or quadrotor, is a multirotor helicopter that is lifted and propelled by four rotors. Quadcopters differ from conventional helicopters as they use rotors which vary the pitch of their blades dynamically as they move around the rotor hub.

In the early days of flight, quadcopters were seen as possible solutions to some of the persistent problems in vertical flight; torque-induced control issues as well as efficiency issues originating from the tail rotor could be eliminated by counter-rotation of the relatively short blades which were also much easier to construct.

The quadcopter utilizes a Raspberry Pi microcomputer that runs a Python server and takes care of all the on-board computation. It also holds an ESC, IMU sensor and a Raspberry Pi native camera.

The Raspberry Pi interfaces with the IMU using an I2C interface that allows it to communicate with the accelerometers, gyroscopes and magnetometers independently using only 2 pins(viz. SCL and

SDA pins) by using separate addresses for each. The Pi gets the accelerometer and gyroscope angles separately for each axis and computes on them to find out the overall orientation of the quadcopter.

The Raspberry Pi can only supply digital signals that is 0 or 1 i.e. on or off. This does not allow us to directly control the motors to vary their speed. The Electronic Speed Controller (ESC) allows such digital signals to be converted to variable voltage and allow speed regulation of motors by supplying a PWM signal to them. PWM signals are achieved by sending pulses at a certain frequency while controlling the amount of time the pulse is on in a cycle. The longer the pulse is high during a cycle, the higher the voltage supplied to the motor.

The ESC also allows an external power source such as a battery to be used for powering the motors. Our drone uses a 10V LiPo battery. LiPo batteries are commonly used for powering drones because they have high discharge rates required to power the four motors functioning at high speed and requiring order of 20A of current.

The quadcopter's flight is controlled using a PID controller. The PID algorithm is a closed-loop feedback mechanism that is used in control systems. The controller attempts to minimize the error by adjusting control inputs(P,I,D values). In the quadcopter, the PID controller will be taking data measured by the IMU sensor and comparing that against expected values to alter the speed of the motors to compensate for any differences and maintain balance. It involves three separate constant parameters viz. the proportional(P), the integral(I) and derivative(D) values. Heuristically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors and D is a prediction of future errors, based

on current rate of change.

The Proportional Gain Coefficient(P) is the most important value. This coefficient determines which value is more important - those measured by the gyroscopes or those defined by human control. The higher the coefficient, the more sensitive the quadcopter becomes to angular change. If 'P' is too high, the quadcopter will start to oscillate.

The Integral Gain Coefficient(I) is used to increase precision of angular position. This term is extremely useful for combating turbulence due to wind and motors. If this value becomes too high, the reaction speed of the drone will decrease.

The Derivative Gain Coefficient(D) is used to allow the quadcopter to reach the desired altitude more quickly as it amplifies the user input. It is dangerous to increase this value as the quadcopter may become highly susceptible to small changes.

The quadcopter flight and on-board operations are controlled via WiFi using an Android app. It receives signals encoded as JSON objects as steady stream from the App. The signal carries altitude, trims, motor speeds and camera information to the RPi. The signal is received by a Python server running on the RPi which is decoded and fed as input to the Quadcopter program.

The quadcopter also houses a native Pi camera module which has the ability to take high quality photos and videos. It interfaces with the Raspberry Pi using a Camera Serial Interface.

The function of the quadcopter is to take pictures and perform two

major image-processing operations viz. Panorama Stitching and 3D-Model Reconstruction.

The quadcopter itself is small enough to control its flight and large enough to hold all the on-board equipment.

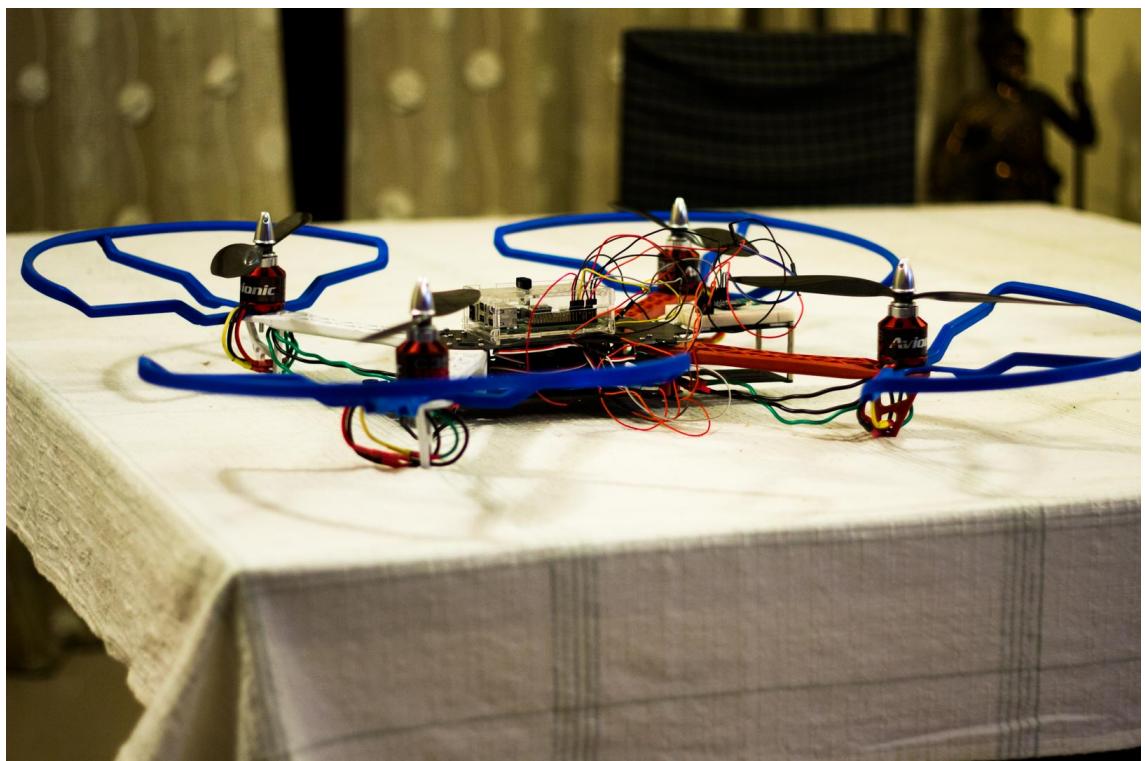


Figure 5.1: The Preliminary Quadcopter without the camera. It carries the ESC, IMU sensor and the RPi. It also has 4 propeller guards (blue) to protect the propellers from excessive damage.

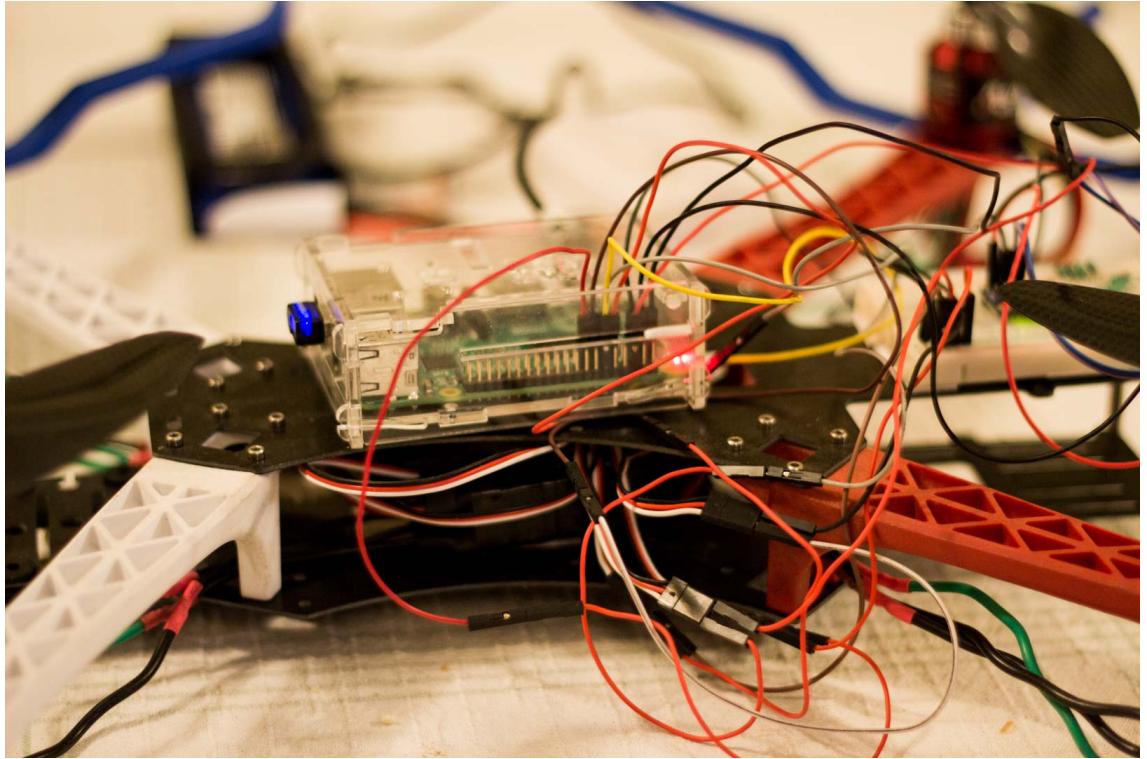


Figure 5.2: Closer look at the wiring of the quadcopter

### 5.3.2 Image-Processing Module

The objective of the project is to build a quadcopter that can perform Panorama Stitching and 3D Reconstruction of images taken during its flight. The reason we chose these functions is because the drone is mobile and can capture pictures of inaccessible locations like tall buildings and can perform mapping of wide-open spaces.

OpenCV is an open-source image processing library which has an enormous number of functionally-rich libraries and detailed online documentation. OpenCV Version 3.1.0 (the latest version) is used to provide image-processing support in this project.

The image-processing module is divided into two parts – Stitching and Reconstruction. The initial stages are the same for both the operations i.e. Acquisition of images, Detecting Features and Matching

Features. Feature detection is accomplished using SURF (Speeded Up Robust Features algorithm and Feature Matching is done by building Kd-Trees and using (K-Nearest Neighbours) Flann Algorithm. Feature detection yields keypoints and descriptors used for matching images.

In panorama stitching, RANSAC (Random Sample Consensus) is used to detect outliers and construct a homography matrix. This is essential as it relates pixel coordinates in each pair of images. It is then used to warp the images and construct the panorama by aligning them. A multi-threaded stitching algorithm has been implemented that stitches images in parallel, reducing the time while maintaining the quality of the constructed image. The quality of the panorama is improved if images are taken with large overlapping features.

3D-Reconstruction is implemented by using the Structure from Motion(SfM) algorithm. The preliminary stage is to calibrate the RPi Camera and calculate intrinsic and extrinsic camera parameters. Once camera calibration is complete, the images have to be preprocessed to collect metadata i.e. EXIF tags which hold important GPS, latitude, longitude and camera information.

The next stages are the feature detection and matching stages which have been described above. Matching features are then organized into tracks and a bipartite graph of these 'good tracks' is constructed. This is used to find common tracks and construct the 3D point cloud incrementally. Reconstruction begins with 'bootstrap reconstruction' using two images. The reconstruction consists of triangulating the 2D points to 3D points which is visualized as a point cloud. Consequently, the rest of the images' points are added incrementally to the point cloud.

After each addition, Bundle Adjustment is done to minimize the reprojection error. Once all the images have been added to the reconstruction, the final point cloud is generated and stored as a '.ply' file. The point cloud is visualized in an interactive browser environment using a Javascript Library called, 'threeJS'.



Figure 5.3: Incremental panorama stitching of test images

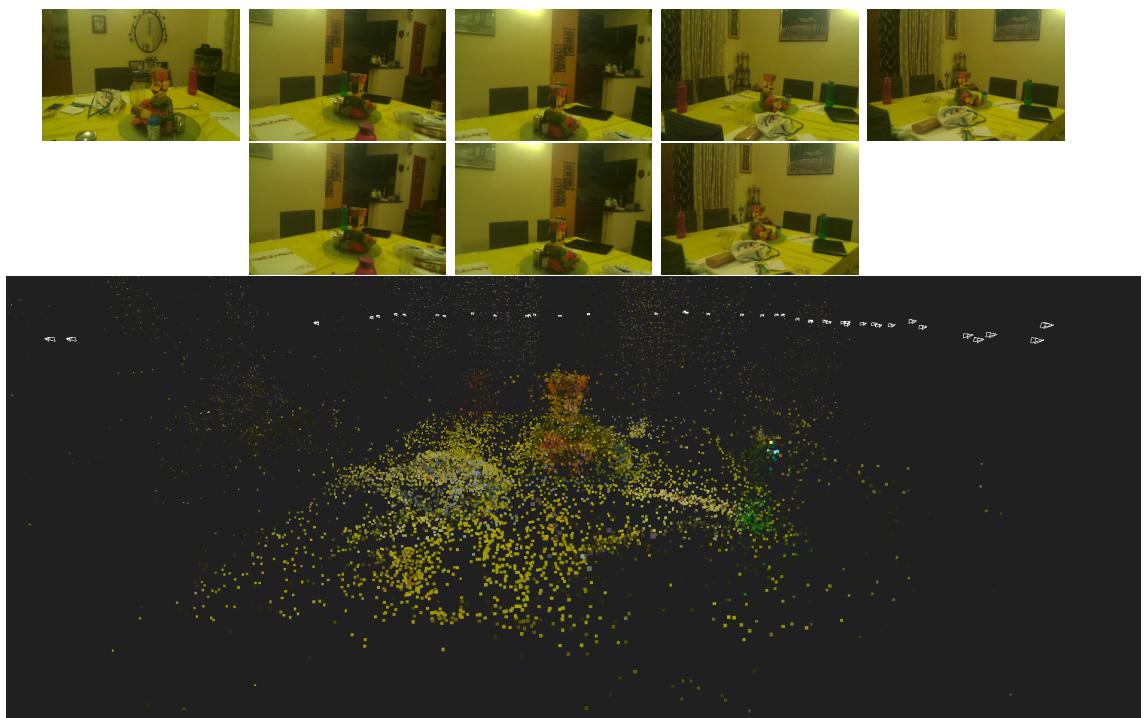


Figure 5.4: 3D Reconstruction of test images where colored point cloud is rendered on the browser which can be inspected closer.

### 5.3.3 Android App

The Android App is used to control all the operations on the quadcopter. It implements a virtual Joystick interface for easy user-interaction. The interface consists of two joysticks, buttons to start the quadcopter program, enable camera mode, dynamically alter x and y trim values and a text box for feeding in the IP address of the RPi.

The two joysticks - left and right are for altitude control and motor control respectively. The user can swipe upwards and downwards on the left joystick to increase and decrease the height of the quadcopter. Similarly, the user can swipe in all directions on the right joystick to control the speed of individual motors depending on the distance from the center of the joystick.

The x and y trim values can be dynamically changed using the app. These values are used to add bias to the quadcopter and control its stability. The camera button can enable or disable camera mode on the quadcopter. Enabling it allows the RPi camera to begin shooting pictures with an interval of 1 second while disabling it stops the camera program.

Using an Android app to remotely control UAVs is a level up from traditional RC controllers as it allows users greater flexibility. Users can now control many more aspects of the quadcopter apart from height and orientation such as camera control and bias using a simple and attractive user interface.

The next chapter deals with the Results and Evaluation of test cases.

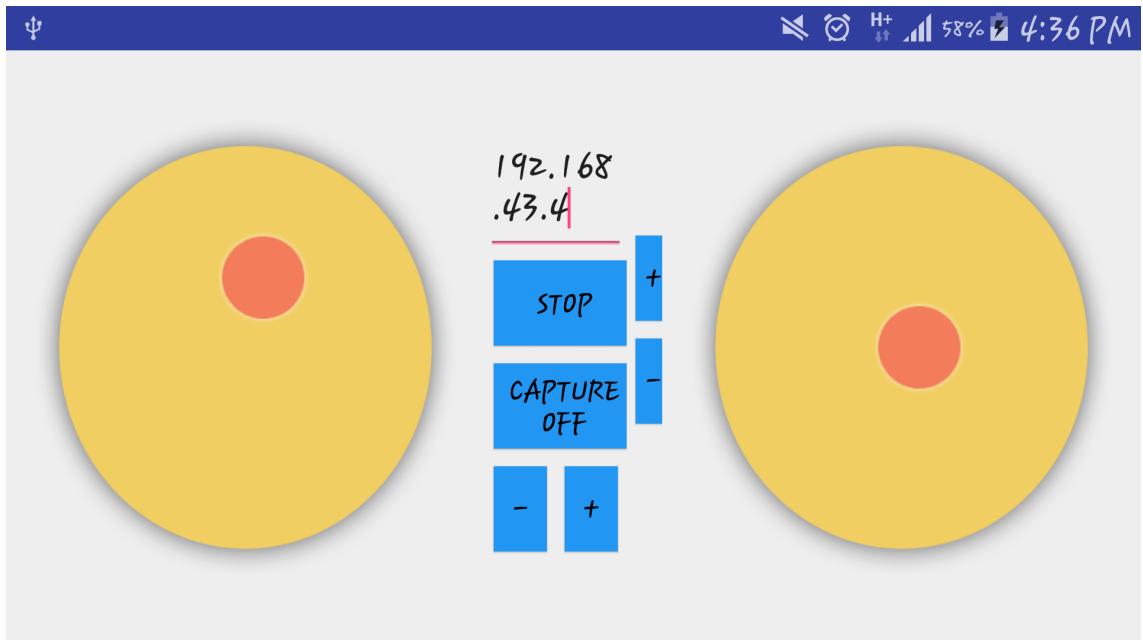


Figure 5.5: Android App Joystick Interface

#### 5.4 OVERALL COMPONENT DIAGRAM

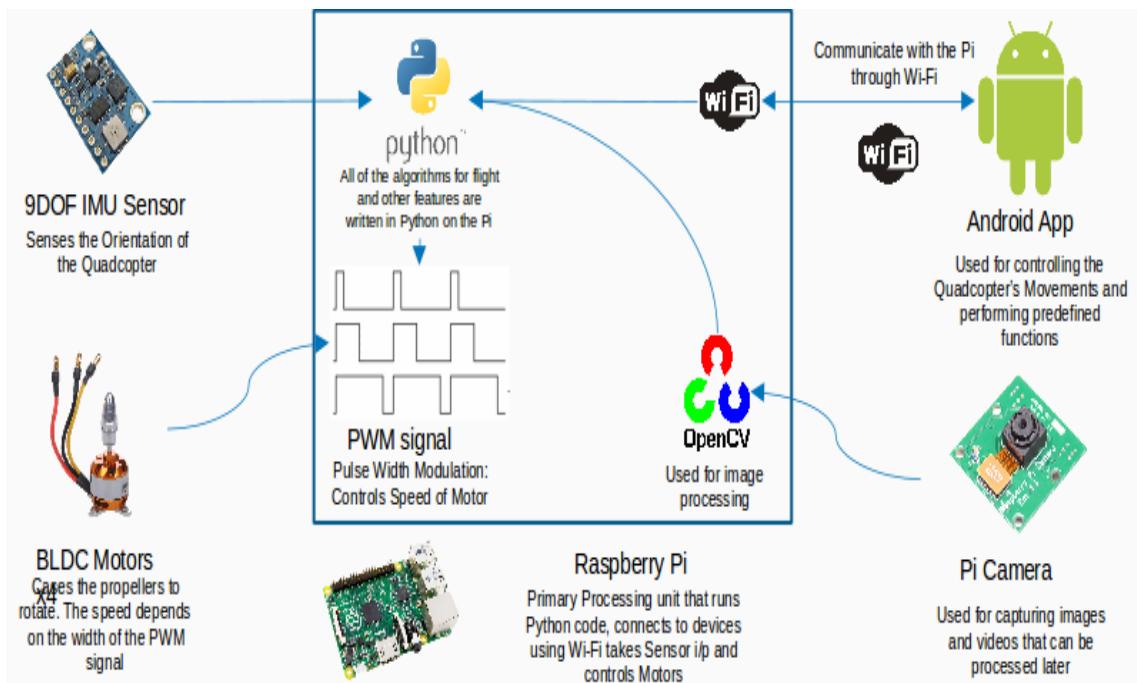


Figure 5.6: Overall Hardware and Software Component Diagram describing the flow of execution

# CHAPTER 6

## RESULTS AND DISCUSSION

### 6.1 RESULTS

#### 6.1.1 Assessment

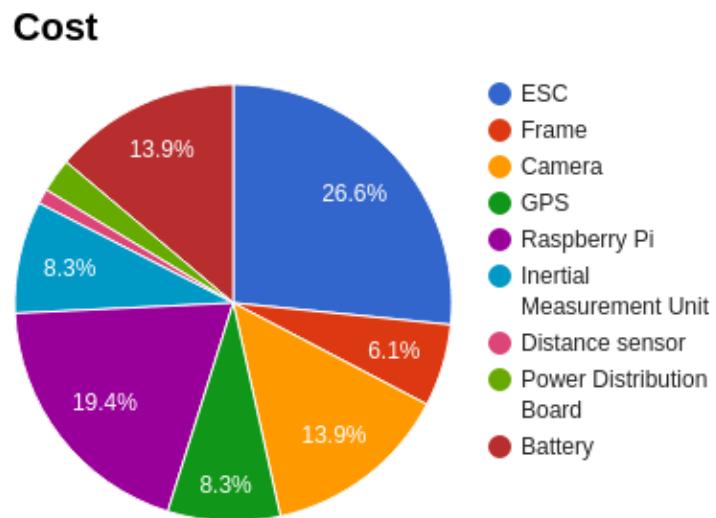


Figure 6.1: Project Cost for each Part

S.No	Signal	Result
1	Swipe left joystick up	Quadcopter flies upward
2	Swipe left joystick down	Quadcopter's height decreases
3	Swipe right joystick up	Quadcopter pitches forward
4	Swipe right joystick down	Quadcopter pitches backward
5	Swipe right joystick left	Quadcopter pitches left
6	Swipe right joystick right	Quadcopter pitches right
7	Click the 'start' camera button	Pi Camera starts shooting
8	Click the 'stop' camera button	Pi Camera stops shooting
9	Click the '+/-' button on the x-axis	Quadcopter's x-trim values change
10	Click the '+/-' button on the y-axis	Quadcopter's y-trim values change

Table 6.1: Test Cases and Results

### 6.1.2 Evaluation

There are several changes that have to be made when flying the quadcopter in varying environments. The PID values change according to the wind conditions and other disturbances. Although the SD Card is securely inserted into the RPi, due to a large amount of vibration caused in the course of the quadcopter's flight, it may loosen leading to connection loss between the RPi and the App.

The quadcopter is controlled by the App from a distance of about 10-15 metres since communication occurs via WiFi. Images are taken by a RPi native camera which is fixed securely on top. The quality of the images taken largely depend on the stability of the quadcopter which are subject to the vagaries of the environment. The pictures taken are stitched and/or reconstructed. The speed of the image-processing depends on the number of images taken and the quality of the images.

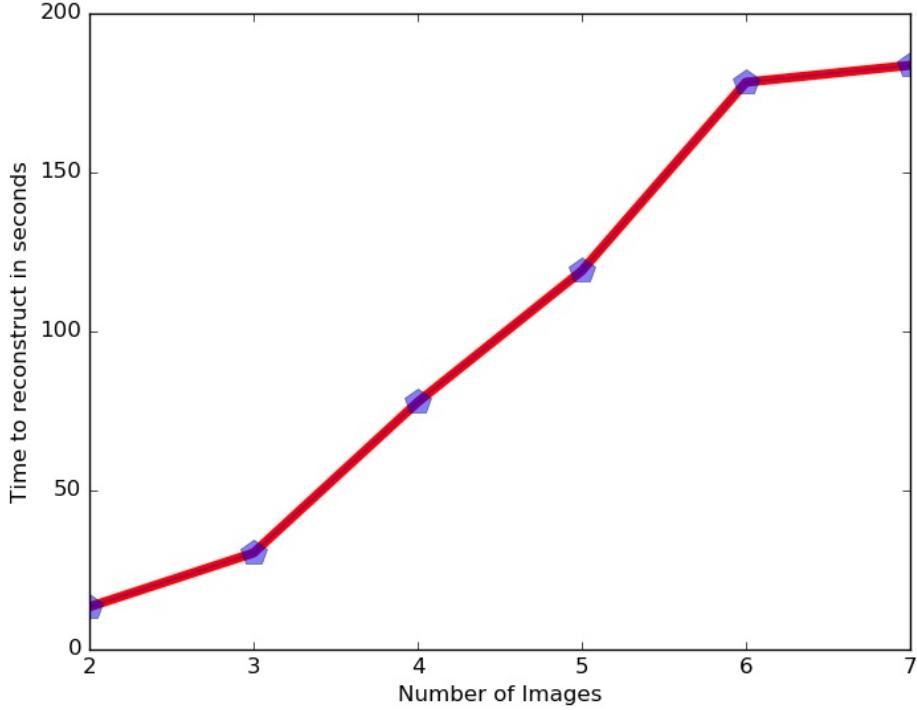


Figure 6.2: Time taken for computation of panorama stitching is directly proportional to the number of images. It stabilizes slightly when the image count is greater than seven.

Figures 6.3, 6.4, 6.5a and 6.5b depict the data obtained during a test run of the quadcopter, where the sensor/output(y-axis) data is plotted against time in seconds(x-axis).

The first 10 seconds show the data where the motors run at minimal speed, followed by intermittent high speeds to allow lift-off till the 20 second mark. At about 25 seconds the quadcopter had attained a height of roughly 1 feet from the ground and was hovering with mild oscillations. At about 45 seconds the quadcopter encountered a breeze causing it temporarily tilt in the direction of the breeze and oscillating with increasing amplitude till 55 seconds, at which point it was powered down.

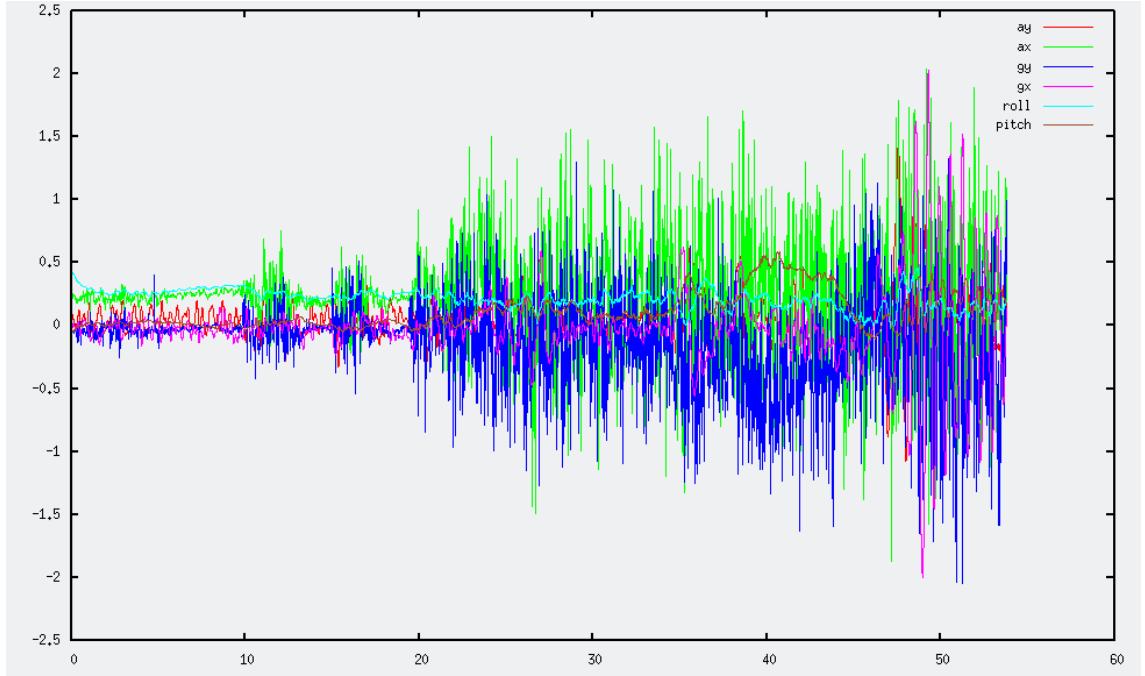


Figure 6.3: Measurement of pitch and roll using complementary filter

The orientation of the quadcopter is sensed using the accelerometer and the gyroscope present in the IMU sensor [Fig 6.3].

An accelerometer measures all forces that are working on the object, it will also see a lot more than just the gravity vector. Every small force working on the object will disturb our measurement completely and result in noise[Fig 6.3 ax and ay]. If we are working on an actuated system (like the quadrocopter), then the forces that drive the system will be visible on the sensor as well. The accelerometer data is reliable only on the long term, so a "low pass" filter has to be used.

A Gyroscope measures accurately the change in angle[Fig 6.3 gx and gy]. Accurate measurement of the current angle can be obtained that is not susceptible to external forces by integrating the change in angle over time to obtain the overall change in angle. However, due to the integration over time, the measurement has the tendency to drift, not returning to zero when the system goes back to its original position. The data is reliable for a short term, since it drifts on the long term.

The complementary filter combines the two to get a reliable sense of orientation[Fig 6.3 pitch and roll]. On the short term, we use the data from the gyroscope, because it is very precise and not susceptible to external forces. On the long term, we use the data from the accelerometer, as it does not drift. The filter looks as follows:

$$\text{angle} = 0.98 * (\text{angle} + \text{gyrData} * dt) + 0.02 * \text{accData} \quad (6.1)$$

The gyroscope data is integrated every timestep with the current angle value. After this it is combined with the low-pass data from the accelerometer (already processed with atan2). The constants (0.98 and 0.02) have to add up to 1 but can be changed to tune the filter properly.

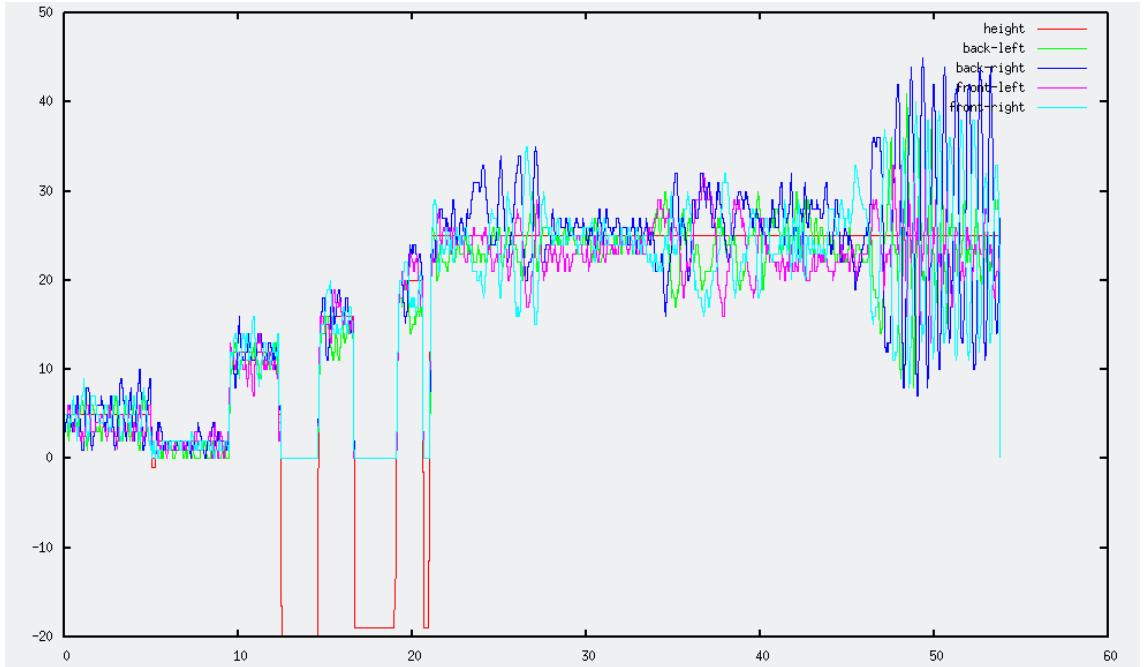


Figure 6.4: Output of motors with respect to height

The motor outputs require to be offset by the required height to allow the quadcopter to increase or decrease the overall height while balancing using the offset received from the PID controller[Fig 6.4].

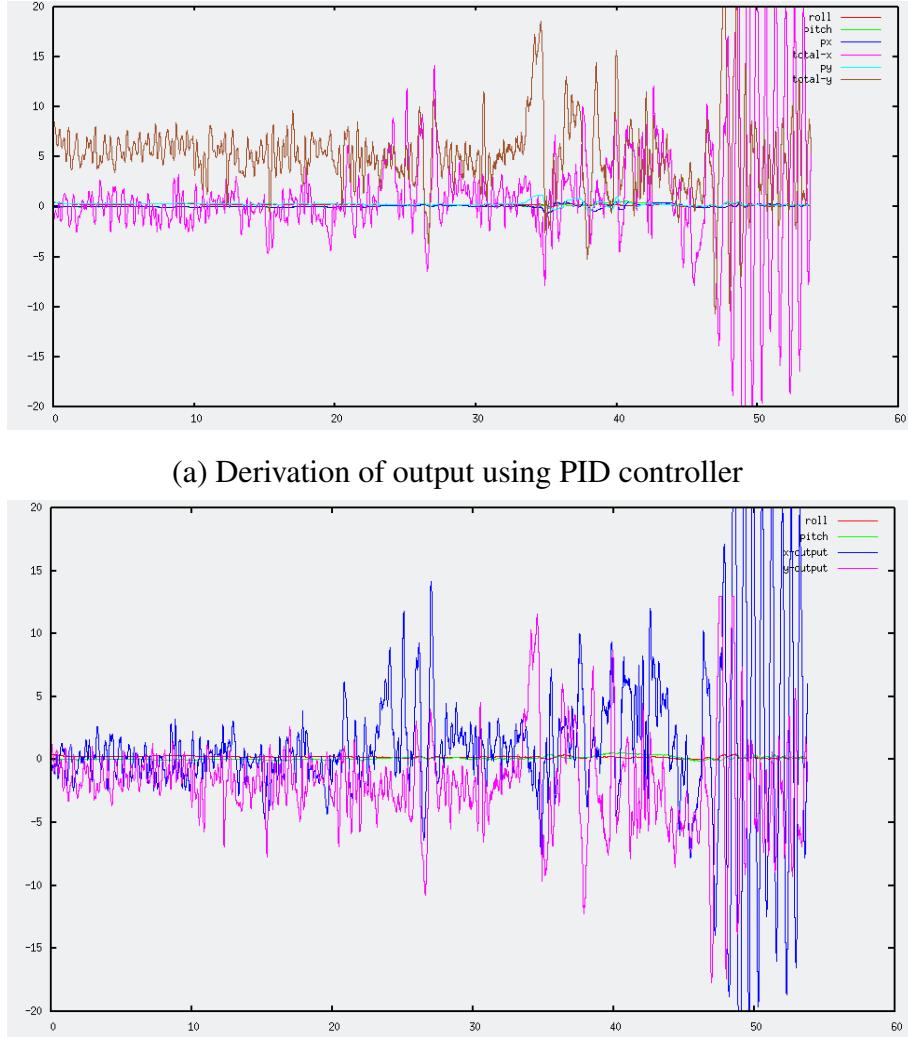


Figure 6.5: Derivation and final output from sensed angles

Figure 6.5a shows how the final output and Figure 6.5b shows how sensed pitch and roll are converted to the final output by the PID controller to be used as offset to the motor speed for balancing the quadcopter. The total-x and total-y are computed using the following PID formula:

$$motor_{command} = K_p^r * ((K_p^a(\theta_{input} - \theta) + K_i^a \int (\theta_{input} - \theta) dt) - \frac{d\theta}{dt}) \quad (6.2)$$

The last chapter discusses the project's contributions and future work.

## CHAPTER 7

# CONCLUSIONS

### 7.1 CONTRIBUTIONS

This project establishes a method to integrate the latest advances in aerial robotics and image processing that can ultimately be used for a multitude of applications in domains including aerial photogrammetry, terrain exploration and mapping, archaeological surveys, movie-making and security. The quadcopter combines the two most-often used image-processing functionalities - Panorama and 3D Reconstruction. The extreme mobility of the drone and powerful computing power of the Raspberry Pi form an effective combination for this purpose.

The ability to take panorama pictures allows the quadcopter to reach remote destinations inaccessible by humans and perform a complete panorama stitching to enable survey of such locations. The ability of the quadcopter to do 3D object reconstruction allows recreation of navigable 3D scenes from locations where the pictures are taken.

### 7.2 FUTURE WORK

The quadcopter can be made completely autonomous by adding a GPS sensor for navigation and distance sensors or multiple cameras implementing obstacle detection to avoid obstacles. This will enable the user to input the location to the quadcopter where it flies and takes pictures that it will use for 3D reconstruction and panorama stitching.

The quadcopter's RPi camera currently takes pictures all at once and produces the final Panorama and 3D point cloud. This could be refined to perform the reconstruction and panorama stitching dynamically as pictures are clicked. Various options for panorama such as Polar, Cylindrical etc can be added. With regard to 3D reconstruction, the point cloud generated is a sparse 3D reconstruction of the object. This could be extended to create dense point clouds which would be more realistic.

The drone could also be equipped with heat sensors to detect people under debris in disaster-hit areas. With the integration of these new features, the drone could be used for dynamic terrain mapping, disaster relief, surveillance and tracking.

## **APPENDIX A**

### **PID Controller**

The quadcopter uses a PID controller where 'P' stands for proportional, 'I' stands for integral and 'D' stands for differential.

The Proportional term enables the quadcopter to receive a force proportional to the angle of deviation from the central angle as a corrective force to bring it back to its normal orientation. Thus, by giving a high proportional constant, the directive force that will be calculated for a deviation in angle will be large, however setting too large a 'P' value will cause overcompensation resulting in oscillations that will keep increasing.

The Integral term is used to provide a corrective force in cases where the Proportional term cannot compensate for the deviation and angle. In such cases, the deviation and angle is aggregated thereby allowing the quadcopter to get back to its stable state quickly even in cases where turbulence or any external forces are at play. Similar to the Proportional term, too high an integral term will cause oscillations but of a lower frequency than those caused by the Proportional term.

The Differential term is used to provide compensation proportional to that of the change in angle of the quadcopter. Thus, having a high differential term will result in a high corrective force being applied in cases where rapid changes in angle occur. This allows the differential

term to either boost or resist the effects of the Proportional and Integral terms because in cases where there are quick angular changes, the Differential term will enable the controller to resist that change and in cases where the compensation is too fast, the Differential term will correspondingly resist fast changes.

## A.1 SAMPLE PID CONTROLLER CODE

---

```
def compute_PID_output( self, kp, ki, kd, angle, old_i,
    old_angle, limit_p=100, limit_i=100, log=False):
    p = kp * angle
    i = old_i + ki * angle
    d = kd * (angle - old_angle)
    if p > limit_p:
        p = limit_p
    if p < -limit_p:
        p = -limit_p
    if i > limit_i:
        i = limit_i
    if i < -limit_i:
        i = -limit_i
    if log:
        log.write('\t' + str(p) + '\t' + str(i) + '\t' +
                  str(d) + '\t')
    return [p + i + d, i]

def compute_rate_PID_output( self, kpr, kp, ki, kd, gyro,
    angle, old_i, old_angle, limit_p=100, limit_i=100,
    limit_pr=100, log=False):
    p = kp * angle
    i = old_i + ki * angle
    d = kd * (angle - old_angle)
    if p > limit_p:
        p = limit_p
```

```

        if p < -limit_p:
            p = -limit_p
        if i > limit_i:
            i = limit_i
        if i < -limit_i:
            i = -limit_i
        total = kpr*(p + i + gyro)
        print total,p,i,kpr,angle,gyro,kp
        if total > limit_pr:
            total = limit_pr
        if total < -limit_pr:
            total = -limit_pr
        if log:
            log.write('\t' + str(p) + '\t' + str(i) + '\t' +
                      str(total) + '\t')
    return [total, i]

```

---

## A.2 SAMPLE PANORAMA STITCHING CODE

---

```

import cv2,math,time,sys, numpy as np
from threading import Thread

def extract_features(image1,image2, surfThreshold=1000,
                     algorithm='SURF'):
    try:
        image_gs1 = cv2.cvtColor(image1,cv2.COLOR_BGR2GRAY)
    except TypeError:
        return
    try:
        image_gs2 = cv2.cvtColor(image2,cv2.COLOR_BGR2GRAY)
    except TypeError:
        return
    detector = cv2.xfeatures2d.SURF_create()
    (keypoints1,descriptors1) =
        detector.detectAndCompute(image_gs1,None)

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(keypoints2,descriptors2) =
    detector.detectAndCompute(image_gs2,None)
keypoints1,keypoints2 = np.float32([kp.pt for kp in
    keypoints1]), np.float32([kp.pt for kp in keypoints2])
return (keypoints1, descriptors1,keypoints2, descriptors2)

def find_correspondences(keypoints1, descriptors1, keypoints2,
    descriptors2):
    matches = match_flann(descriptors1, descriptors2)
    points1 = np.float32([keypoints1[i] for (_, i) in matches])
    points2 = np.float32([keypoints2[i] for (i, _) in matches])
    return (points1, points2)

def calculate_size(size_image1, size_image2, homography):
    (h1, w1) = size_image1[:2]
    (h2, w2) = size_image2[:2]
    top_left = np.dot(homography,np.asarray([0,0,1]))
    top_right = np.dot(homography,np.asarray([w2,0,1]))
    bottom_left = np.dot(homography,np.asarray([0,h2,1]))
    bottom_right = np.dot(homography,np.asarray([w2,h2,1]))
    top_left = top_left/top_left[2]
    top_right = top_right/top_right[2]
    bottom_left = bottom_left/bottom_left[2]
    bottom_right = bottom_right/bottom_right[2]
    pano_left = int(min(top_left[0], bottom_left[0], 0))
    pano_right = int(max(top_right[0], bottom_right[0], w1))
    W = pano_right - pano_left
    pano_top = int(min(top_left[1], top_right[1], 0))
    pano_bottom = int(max(bottom_left[1], bottom_right[1], h1))
    H = pano_bottom - pano_top
    size = (W, H)
    X = int(min(top_left[0], bottom_left[0], 0))
    Y = int(min(top_left[1], top_right[1], 0))
    offset = (-X, -Y)
    return (size, offset)

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def merge_images(image1, image2, homography, size, offset,
    keypoints):
    (h1, w1) = image1.shape[:2]
    (h2, w2) = image2.shape[:2]
    panorama = np.zeros((size[1], size[0], 3), np.uint8)
    (ox, oy) = offset
    translation = np.matrix([
        [1.0, 0.0, ox],
        [0, 1.0, oy],
        [0.0, 0.0, 1.0]
    ])
    homography = translation * homography
    cv2.warpPerspective(image2, homography, size, panorama)
    panorama[oy:h1+oy, ox:ox+w1] = image1
    height, width = panorama.shape[:2]
    crop_h = int(0.05 * height)
    crop_w = int(0.015 * width)
    panorama = panorama[crop_h:-crop_h, crop_w:-crop_w]
    panorama = panorama[int(oy*0.7):,:]
    return panorama

def match_flann(des1, des2, ratio=0.75):
    matcher = cv2.DescriptorMatcher_create('BruteForce')
    rawMatches = matcher.knnMatch(des1, des2, 2)
    matches = []
    for m in rawMatches:
        if len(m) == 2 and m[0].distance < m[1].distance * ratio:
            matches.append((m[0].trainIdx, m[0].queryIdx))
    return matches

def pano(images, i):
    if (i+1) <= (len(images)-1):
        try:
            image1 = cv2.imread(images[i])

```

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except TypeError:
    image1 = images[i]
try:
    image2 = cv2.imread(images[i+1])
except TypeError:
    image2 = images[i+1]
else:
    return
(keypoints1, descriptors1, keypoints2, descriptors2) =
    extract_features(image1, image2)
(points1, points2) = find_correspondences(keypoints1,
    descriptors1, keypoints2, descriptors2)
try:
    (homography, _) =
        cv2.findHomography(points2, points1, cv2.RANSAC, 4)
except Exception:
    print 'Not enough matches!'
    return -1
(size, offset) = calculate_size(image1.shape, image2.shape,
    homography)
images[i] = merge_images(image1, image2, homography, size,
    offset, (points1, points2))
if(len(images) == 2):
    filename = 'pano_multi_final'+str(i)+'.jpg'
else:
    filename = 'pano_multi'+str(i)+'.jpg'
cv2.imwrite(filename, images[i])

if __name__ == '__main__':
    st = time.time()
    images = sys.argv[1:]
    n = len(images)
    val = int(math.ceil(math.log(len(images), 2)))+1
    for q in range(val):
        for i in xrange(0, len(images), 1):

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```
print 'i: ',i,' len: ',len(images)
t = Thread(target=pano, args=(images,i))
t.start()
t.join()
if i+1 <= len(images)-1:
    del images[i+1]
```

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## REFERENCES

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