

Novel Waypoint Generation Method for Increased Mapping Efficiency  
Using UAV

by

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## ABSTRACT

This project is to develop a new method to generate GPS waypoints for better terrain mapping efficiency using an UAV. To create a map of a desired terrain, an UAV is used to capture images at particular GPS locations. These images are then stitched together to form a complete map of the terrain. To generate a good map using image stitching, the images are desired to have a certain percentage of overlap between them. In high windy condition, an UAV may not capture image at desired GPS location, which in turn interferes with the desired percentage of overlap between images; both frontal and sideways; thus causing discrepancies while stitching the images together. The information about the exact GPS locations at which the images are captured can be found on the flight logs that are stored in the Ground Control Station and the Auto pilot board. The objective is to look at the flight logs, predict the waypoints at which the UAV might have swayed from the desired flight path. If there are locations where flight swayed from intended path, the code should generate a new set of waypoints for a correction flight. This will save the time required for stitching the images together, thus making the whole process faster and more efficient.

## DEDICATION

*Dedicated to my parents and brother*

## ACKNOWLEDGMENTS

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## LIST OF SYMBOLS

FR = Real focal length of the camera (mm)

GSD = Ground sampling distance (cm/pixel)

SW = Real sensor width (mm)

ImW = Image width (pixels)

H = Height (m)

W = Actual width on ground covered by image (m)

L = Actual length on ground covered by image (m)

ImH = Image height (pixels)

m = meters

m/s = meters / second

d = distance

R= Radius of earth

$\Theta$  = Latitude coordinate

$\emptyset$  = Longitude coordinate

## CHAPTER 1

### INTRODUCTION

Unmanned aerial vehicles (UAVs) provide a unique platform for orthoimagery and digital surface model (DSM) generation. UAVs are a potential low cost alternative for low altitude photogrammetry and mapping as compared to the expensive low altitude manual flights. The mapping process using UAVs is quicker as compared to the time required by ground based manual mapping methods. A quick high resolution, cost efficient image mapping can be extremely useful in case of search and rescue, and disaster management situations. This thesis describes a new waypoint generation algorithm to increase the efficiency of mapping which could be really useful in such case scenarios.

Current platforms for obtaining high resolution imagery for disaster relief consist of high altitude UAV drones such as: GlobalHawk, AeroStar, and Altus II. The lower altitude and short range UAVs that are used are: Boeing Scan Eagle, and USGS Raven. These platforms provide good high resolution images but price per unit of each platform is quite high. Additionally, image mapping using these platforms is rendered cost inefficient for a relatively small ground area. A more cost efficient and quick response method for disaster relief of smaller magnitude; area wise; can be using an off the shelf small UAV platform, integrated with a cheap daily use camera. However, using such a system may not be robust. Given the small size of aircraft, the wind effects on the flight are more and thus can cause problems for the UAV in following the designated flight path. This may lead to images being captured at wrong locations or the images being distorted.

The primary contribution of this thesis is to rectify above mentioned scenario. Given a set of waypoints a UAV has flown, the waypoint generation algorithm checks the GPS waypoints at which the images were captured. Then based on the GPS location and the attitude of UAV at the moment of capturing the image, calculates the probable image imprint on the ground and checks if the desired overlap between images achieved for proper image stitching. The waypoint generation algorithm takes as input, the camera specifications, and the desired ground sample distance (GSD), image overlap percentage, and GPS position and attitude of UAV at the time of capturing the image.

## CHAPTER 2

### BACKGROUND INFORMATION

- DEFINITION OF UAVs

“UAVs are to be understood as uninhabited and reusable motorized aerial vehicles.” [van Blyenburgh, 1999]. These vehicles can be remotely controlled manually, semi-autonomous, fully autonomous, or combination of these abilities. The obvious difference between manned and autonomous aircraft is that there is no pilot physically controlling the aircraft. The term UAV is commonly used in the Robotics and Artificial Intelligence, Aerial Photogrammetry and Remote Sensing fields of engineering.

Remotely Operated Aircraft (ROA), Remotely Piloted Vehicle (RPV), Remotely Piloted Aircraft (RPA) and Unmanned Aircraft Systems (UAS) are some of the terms that are synonymous with UAV. First use of term RPV can be tracked to the Department of Defense of United States during the 1970's and 1980's. National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) use the terms ROA and RPA instead of UAV. It is a common understanding that the term UAS stands for the whole system, including the unmanned aircraft and the Ground Control Station (GCS).

However, in this thesis, the definition of UAV is most similar to that of the American Institute of Aeronautics and Astronautics', which defines a UAV to be:

An aircraft which is designed or modified not to carry a human pilot and is operated through electronic input initiated by the flight controller or by an on board autonomous flight management control system that does not require flight controller intervention (American Institute of Aeronautics and Astronautics, 2004).

- EARLY INVESTIGATIONS

In 1858 Gaspard Tournachon captured the first aerial image from a hot-air balloon near Paris, France (Newhall, 1969). Since then, many different platforms such as kites, pegions, rockets, planes, and recently UAVs have been used for capturing aerial images (Berlin Correspondent of the Scientific American, 1909; Verhoeven, 2009; Batut, 1890; Mozas-Calvache et al., 2012; Newhall, 1969; Eisenbeiss, 2009;). German engineer Julius Neubronner used small cameras mounted on the breasts of pigeons to capture the path they flew (Berlin Correspondent of the Scientific American, 1909; Verhoeven, 2009).

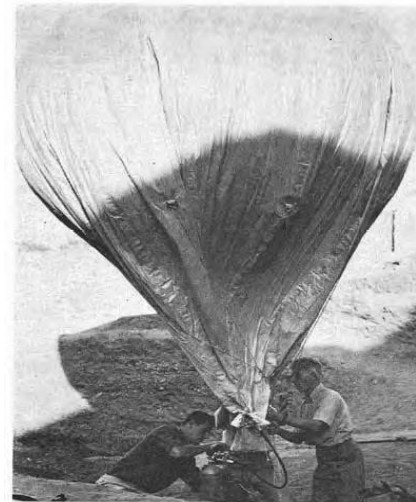


Figure 1, Figure on left shows example of pigeons (Neubronner, 1903) and figure on right is a tethered balloon (Whittlesley, 1970)

One of the earliest experiments in aerial imaging using a fixed winged UAV was done by (Przybilla and Wester-Ebbinghaus, 1979). The platform used for this purpose was a manually controlled fixed winged UAV made by the company Hegi. It had a flying height of 150m and a cruising speed of 11m/s. The plane was 3 meters long and the wing

span was 2.6 meters. The maximum payload capacity was 3 kg. In addition to terrestrial images, it was possible to capture images of an archeological area for reconstruction of the site. This application was limited by the runway necessity for takeoff and landing. The images were distorted due to velocity of plane and the vibrations of the engine. Therefore, the authors proposed to use model helicopters, which are less vibration-sensitive (Przybilla and Wester-Ebbinghaus, 1979).



Figure 2, Model airplane Firma Hegi (Przybilla and Wester-Ebbinghaus, 1979)

Wester-Ebbinghaus used a rotary wing UAV for first time for aerial imaging in 1980. The platform used for this application was the model helicopter with a maximum payload of 3 kg. The height range varied from 10m to 100m. The polystyrene walls installed on the helicopter successfully suppressed the vibrations from the engine. The pilot controlled takeoff, landing, and flying whereas the camera was triggered manually using radio link. The Schwebbahn (monorail) Wuppertal; a steel construction; was documented using this system (Wester-Ebbinghaus, 1980).



Figure 3, Model helicopter from Schlüter (Wester-Ebbinghaus, 1980)

- CLASSIFICATION OF UAVs

The UAVs can be classified based on different parameters such as: type, size, and level of autonomy.

- Type:

In reference to this thesis, the UAVs can be broadly classified as rotorcraft and fixed winged.

Rotorcrafts are popular research platforms due to their vertical takeoff and landing, and hovering capabilities. Recent advances in guidance, navigation, and control in the field of rotorcrafts can be found in “Survey of advances in guidance, navigation, and control of unmanned rotorcraft systems” (Kendoul, 2012). Rotorcrafts can be further subdivided into single rotors, coaxial, quadrotors and multi-rotors (Eisenbeiss, 2009).

Fixed winged UAVs are not as agile in maneuverability as rotorcrafts. But, they have significant advantage in terms of their ability to fly at higher altitudes. Rotorcrafts takeoff and remain in flight because of the downward thrust produced by the propellers. Whereas the fixed winged aircrafts move forward through air with help of propellers and generate



lift as the air passes over the wings according to Bernoulli's principle. Fixed winged UAVs can be in flight for longer time than rotorcrafts without requiring recharging or refueling. The time advantage is especially important for the mini class (see Table 1) UAVs that may need to fly a mission in remote areas.

➤ Size :

There have been different criteria to classify UAVs based on size. UAVs were classified on basis of their range endurance and weight by Bendea et al. (Bendea et al., 2007, 2008) (See table 1). Five categories, specifically for rotorcraft UAVs based on size and payload capacity were presented by Kendoul (Kendoul, 2012) (See Table 2). Eisenbeiss (Eisenbeiss, 2009) presented a three level classification for UAVs namely M-class, L-class, and OM-class. OM-class distinguishes between manual and autonomous systems. This thesis focuses on Mini (Table 1) or M-class (Table 3) UAVs.

Tactical UAV [Sub-categories]	Acronym	Max height [m]	Autonomy [hours]	Weight [Kg]
Micro	μ	250	1	< 5
Mini	Mini	150–300	< 2	5-20
Close Range	CR	3000	2–4	150
Short Range	SR	3000	3–6	200
Medium Range	MR	5000	6–10	1250
Medium Range Endurance	MRE	8000	10–18	1250
Low Altitude Deep Penetration	LADP	50-9000	0.5–1	350
Low Altitude Long Endurance	LALE	3000	>24	< 30
Medium Altitude Long Endurance	MALE	14000	24–48	1500

Table 1, Classification of Tactical UAVs (Bendea et al., 2007)

Category	Size	Payload
1	Full Scale	Significant
2	Medium Scale	> 10kg
3	Small Scale	2-10kg
4	Mini	< 2kg
5	Micro	< 100g

Table 2, RUAS Size Classifications (Kendoul, 2012)

Class	Explanation	Limitation
OM-Class	Open source and Manual controlled systems	Manually controlled
M-Class	Micro & Mini systems	<5kg payload
L-Class	Large payload UAVs	>5kg payload

Table 3, Categorization with respect to price and payload of UAV systems

(Eisenbeiss, 2009)

➤ Level of Autonomy

The Autonomy Levels for Unmanned Systems classification framework was published by The National Institute of Standards and Technology which is used to rank UAVs. The levels are categorized based on analyzing, communication, decision making, planning, sensing and perceiving, and acting and execution capabilities to complete a mission (Huang, 2008). There are five levels of classification. The scale increases in mission and environment complexity, and the lesser amount of human intervention required.

Following is a brief description of each level:

Level One: Purely remote controlled UAVs. This level requires 100% human interaction and the autonomy is not present. This level is used for least complex missions.

Level Two: Requires a higher amount of manual control. This level is used for missions which have to perform simple tasks rather than just flying around. Autonomous attitude stabilized flight is an example of such a flight.

Level Three: This level requires medium amount of both manual and autonomous control of the aircraft. The environmental complexity in level three is of moderate complexity.

Level Four: This level requires very less amount of human interaction. The missions of this level fly in complex environment and need to have good decision making capabilities.

Level Five: Missions of level five require no human interaction at all. The environmental complexity is highest and extreme. Currently there are no known level five systems.

UAV photogrammetry and aerial mapping may require different level of autonomy based on environment in which the mission is carried out, and planning and decision making capabilities of UAV. The person that designs the mission may design a flight plan such that the takeoff is manual and the image capturing is autonomous. The person carrying out the mission may not be from technical background. Thus it is important for the flight designer to take such factors while deciding on level of autonomy.

The UAVs can be controlled in three different modes: manual, semi-automated or assisted, and autonomous (Eisenbeiss and Sauerbier, 2011). The manual mode

corresponds to level one of autonomy. All motion of the aircraft is controlled by human pilot. The information about the system status (attitude, altitude, battery level, wind speed) is monitored by secondary operator. Semi-autonomous flight requires the pilot to control flight attitude, velocity and heading. The other complexities of stabilization are controlled by on board auto pilot or GCS. This corresponds to level two and three of autonomy. Autonomous flight controls all aspects of the flight. The onboard auto pilot or the GCS take decision based on the flight plan that is fed. Such flight takes in account wind speed for turning the aircraft, captures images at designated locations, can change mode from flight mode to loiter mode. The takeoff and landing for such a flight has to be done manually. This flight falls in level three or four depending on the environmental conditions and complexities. Typically take off is manual, then the system is switched to auto mode to complete the mission and then back to manual mode for landing (Sauerbier and Eisenbeiss, 2010; Remondino et al., 2011; Eisenbeiss and Sauerbier, 2011; Rinaudo et al., 2012). For aerial mapping, the autonomous mode consists of predefined waypoints to fly over and capture images such that the given terrain is mapped properly.

For this thesis, above mentioned level of autonomy is used. The takeoff and landing requires human interaction but the image capturing is done based on predefined flight plan.

- RELATED WORK

- Path Planning

Flight Path Planning is very important part of planning any mission. A good flight path plan can be difference between an efficient and an inefficient system. Flight path should be able to cover the desired area in minimum amount of time while capturing images at desired locations. For image capturing, the UAV can fly to preplanned waypoints and capture images. The path should be designed such that the required terrain will be covered properly. For situations such as disaster management, and search and rescue operations which may have to accomplish complex tasks, advanced path planning techniques should be incorporated. These techniques consist of smart algorithm to avoid obstacles, calculate shortest path to fly to desired location based on turning radius of UAV.

Most of the literature for aerial imaging is based on flights that are either flown manually or on predefined waypoints calculated using method called 2.5D path planning (Eisenbeiss, 2009). In this method of path planning unique latitude and longitude coordinates for each waypoint are specified. Each waypoint is specified at same altitude. This ensures that the Ground Sampling Distance (GSD) is uniform in all the images. This method assumes that the terrain is flat. Using 2.5D method may cause trouble in case the terrain consists of slopes or hilly region. Eisenbeiss addresses the sloped terrain conundrum (Eisenbeiss, 2008). Topographic map of the mountainside that is being mapped is taken in account as the UAV flies over the terrain. The terrain to be mapped can be considered to be a convex or concave polygon. 2.5D method gives an efficient way to define a flight plan. The images are considered to be rectangles. Most efficient

way to cover the given polygon is to fly in back and forth motion such that the flight lines are parallel to each other. The parameters that need to be considered are: altitude of flight, and the distance between the parallel lines. It is desirable that both above mentioned parameters are constant for proper area coverage and uniform GSD. These parameters are calculated on basis of camera parameters, maximum flying height of UAV, image scale, necessary image overlap, and desired GSD (Eisenbeiss and Zhang, 2006; Eisenbeiss, 2009; Liu et al., 2012). Figure 4 shows an example of a flight path discussed above.

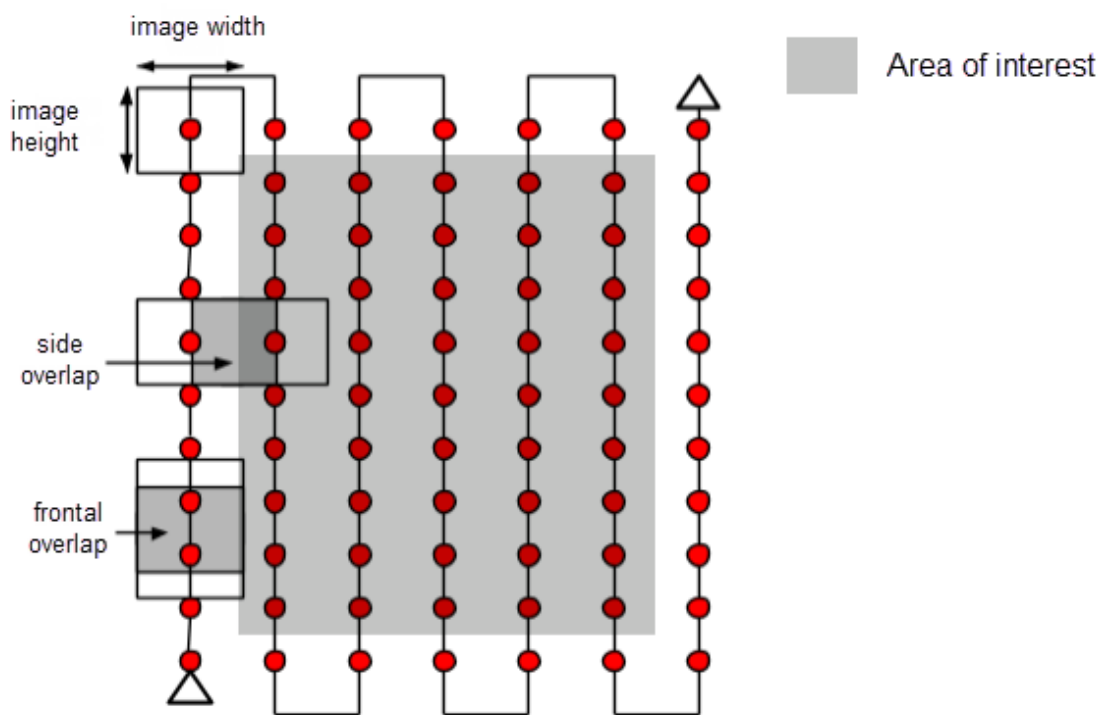


Figure 4, Lawn mower pattern (<https://support.pix4d.com>)

➤ Image capturing

Some standards regarding aerial photogrammetry parameters have been defined (DIN 18740-1:2001- 11 and DIN 18740-4:2007) (Mozas-Calvache et al., 2012). Location of terrain, required image overlap and desired GSD determine the resolution of final stitched mosaic. The desired GSD and the camera specifications determine the flight height and can be different for various applications. Desired GSD can vary from 1-10 cm up to 2m depending on application (Bendea et al., 2007; Sauerbier and Eisenbeiss, 2010; Liu et al., 2012).

There are mixed opinions regarding the required image overlap that produces best results. It is most likely that required image overlap is based on the software being used for the image stitching. For image capturing using rotor crafts, the UAV can either fly to the designated location and hover while capturing the required image or capture images in flight. Capturing images while hovering at required waypoints produce a less stable flight than capturing images in flight (Eisenbeiss and Sauerbier, 2011). Fixed winged UAVs however do not have the option to stop and capture image. The actual shutter triggering of camera is also a problem for fixed winged aircrafts. Rotorcrafts have option of hovering and a waypoint and triggering the camera using command from Ground Control Station. When this is not possible; as in case of fixed winged UAVs; the camera is programmed with an intervalometer script which captures images after particular time interval. Proper image overlap conditions can be determined by calculating the flight velocity and varying the time interval.

- **PROBLEM UNDER CONSIDERATION**

Capturing images for mapping requires flight planning, actual flight, and post processing of images. The flight plan is prepared based on various factors as discussed in above section. The images taken on field are “fed” into an image stitching software, which stitches the images together to form a map of complete terrain. Most of the image stitching is done in situ. Many times, the UAV gets deviated from its path due to wind and other factors. This leads to images being captured at wrong location, which in turn causes the terrain map to be incomplete or faulty. The discrepancies in the final map do not show up until all the images are stitched. Figure 5 shows a good example of this scenario. In such scenario a new flight has to be planned to capture the images of the terrain that were missed and then again go in field for the flight. This can cause delay in the process, thus reducing the efficiency. This can be critical in situations such as disaster management, and search and rescue operations, where time is a crucial factor.

- **SOLUTION PROPOSED**

A good way to avoid this from happening would be to find a way to predict the terrain map that is captured and check for discrepancies on the field itself. The flight logs of the actual flight can be used for such a solution. The flight logs can show the exact GPS location and the attitude of the UAV at the time when images were captured. A code can be written to quickly check if the mission requirements are met, using the information from flight logs. If not, the code should generate a new flight path for the corrective flight. This will save the processing time for image stitching and the whole process can be much more efficient.



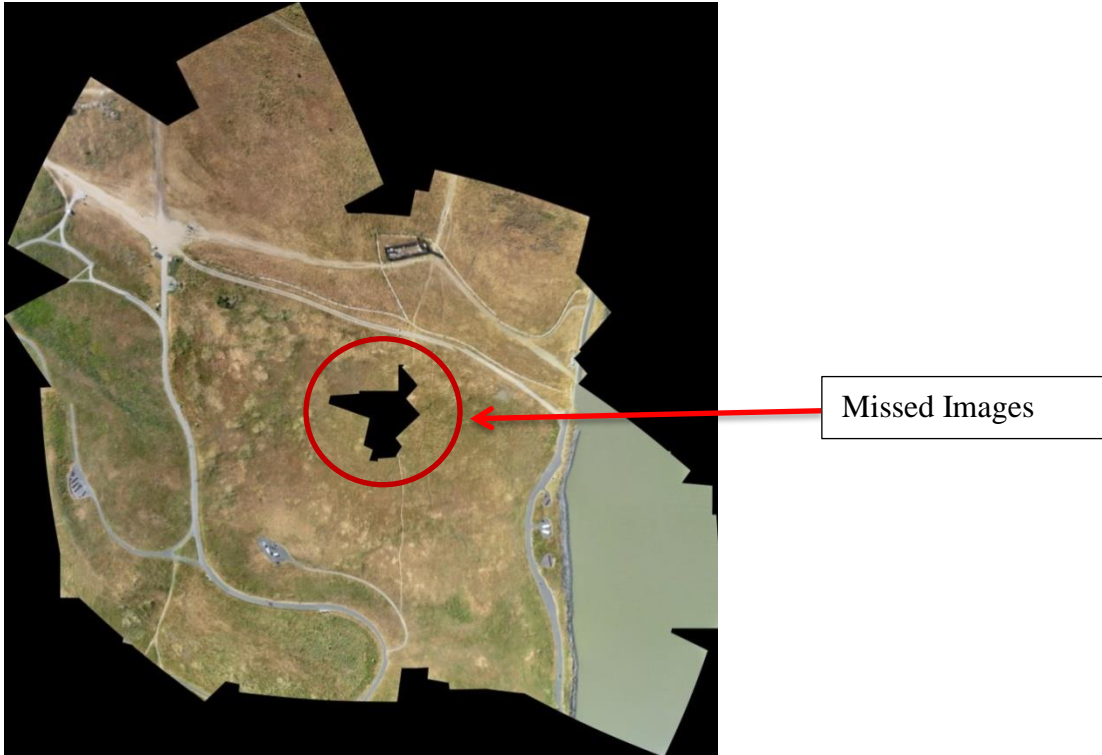


Figure 5, Example of missed images (<http://copter.ardupilot.com/>)

- SCOPE OF PROJECT

This project will help in making the mapping process faster. This can be helpful in for search and rescue operations where time is very valuable. Furthermore this can be expanded to be a multi UAV system so that the correction for missed waypoints can be done dynamically while in flight. A multi UAV system can comprise of fixed winged aircrafts or combination of fixed winged aircraft and quad rotors

## CHAPTER 3

### SYSTEM DESCRIPTION

A flight to capture images needs following components: An UAV platform, a ground control station to plan the flight path, an autopilot board to control the plane, a good camera for high quality images, and an image stitching software. Each of these components will be discussed in this section.

- UAV PLATFORM

UAV platform used for this project is a RC aircraft known as SkyWalker. It is ready to fly kit from Event 38 Unmanned systems. The pusher propeller configuration on Skywalker means there is more space for equipment in the fuselage. The cruising speed of the aircraft is 12m/s; which is a good speed for capturing images.

Following are the characteristics of the Skywalker Plane.

Wing Span	1800 mm
Length	1300 mm
Cruise Speed	12 m/s
Max Speed	42 m/s
Normal flight time	30-50 min 20-25 min with 1.2kg payload

Table 4, Sky Walker parameters

- GROUND CONTROL STATION

A ground control station allows planning a flight path, setting mission parameters, tuning PID gains, and simulating a flight. For this project Mission planner was used as the ground control station. A lawn mower pattern to capture images is generated for the required flight using MP. . MP has inbuilt support for various common map types such as Google Maps. Integrated Google Maps allows easy and accurate point and click mission planning. Figure 6 shows a lawn mower pattern generated in MP.

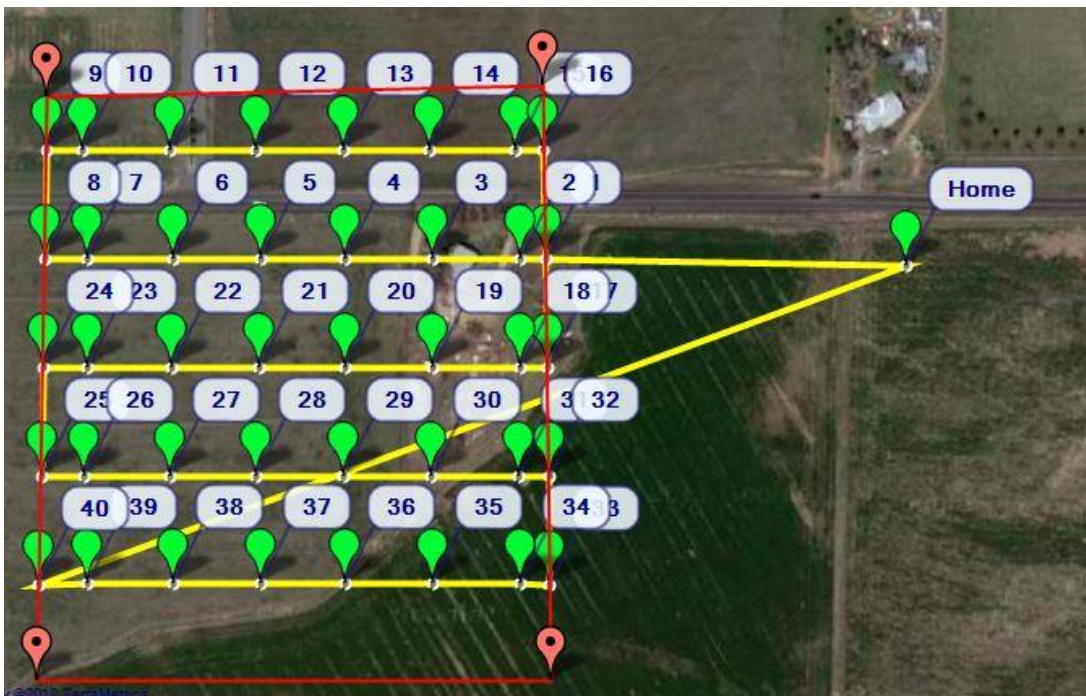


Figure 6, Grid in Mission Planner

- AUTO PILOT BOARD

An auto pilot board controls the UAV during a flight to complete preplanned waypoint mission. The mission plan generated in MP is uploaded to the board, which in turn takes the decisions regarding maneuvering the UAV. The auto pilot board used for this project is Ardupilot Mega (APM) 2.5. APM 2.5 is open source commercial off the shelf autopilot board from 3D Robotics. APM 2.5 is based on Arduino environment. APM 2.5 is used to power up the servo motors connected to control surfaces of UAV. It is also used to trigger the camera at the desired locations. This board has following features;

- 3-axis gyro, accelerometer and magnetometer
- With external GPS supporting Google Maps point and click waypoints
- Barometric pressure sensor for altitude measurements with 10 cm resolution

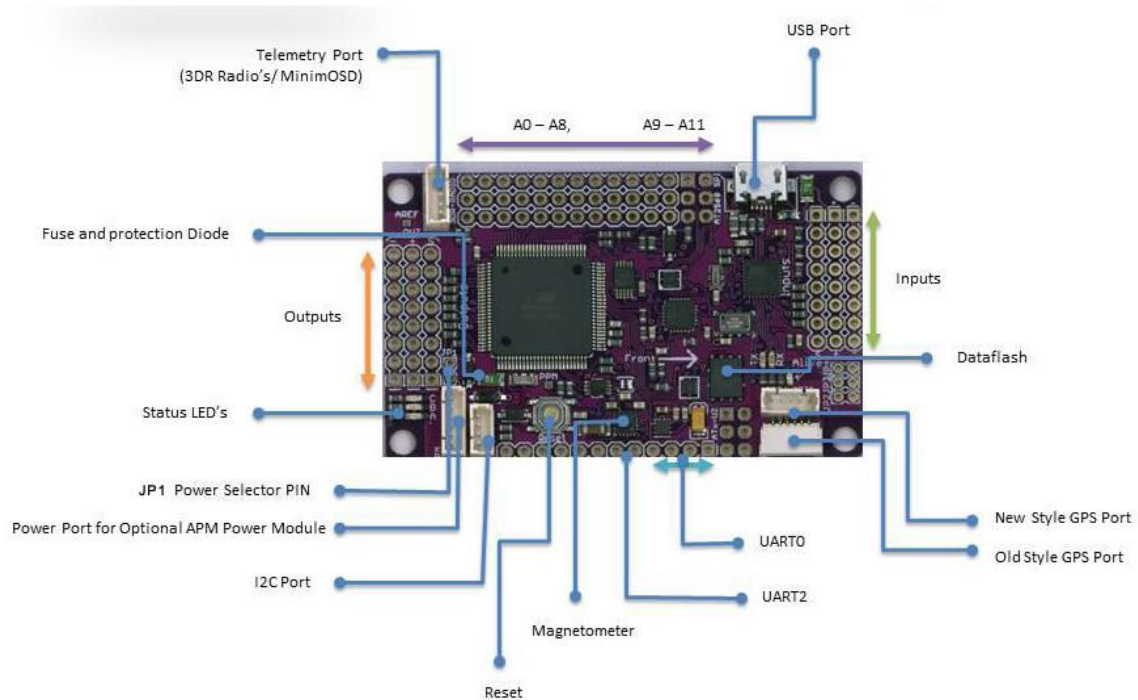


Figure 7, APM board layout (diydrones.com)

- CAMERA

The camera used in this project is Canon SX230 HS. The motivation behind using a Canon camera is that we can control the camera parameters and triggering by using a firmware update called CHDK. CHDK allows a normal point and shoot canon camera to be use features available in DSLR or SLR version of cameras. The following features allows Canon camera to be easily integrated with APM 2.5 board for mapping missions; With help of CHDK camera parameters such as exposure, shutter speed, remote triggering, and zoom can be controlled.

- RAW - CHDK can record raw files, giving access to every bit of data the sensor saw, without compression or processing. Raw files are helpful for post processing in image stitching.
- Motion detection - Trigger exposure in response to motion, fast enough to catch lightning.
- Triggering - Simple USB cable from Cannon camera to APM 2.5 allows manual and automatic triggering.

- HARDWARE IN THE LOOP SIMULATION (HIL)

APM 2.5 support both hardware and software in the loop simulation. The Hardware in Loop Simulations method was used over Software in The Loop Simulation as the thesis involved camera triggering at preplanned waypoints. The camera triggering is based on waypoint following mission. Whereas, SITL simulations are mainly used for testing the modifications made in control algorithm. The triggering is modified with changes in path followed by UAV; the detailed algorithm is discussed in later sectioned. The HIL

simulation helps to test this modified camera triggering algorithm with APM 2.5 autopilot board connected over a USB connection with computer.

A good hardware in the loop simulation can be setup using MP, APM, and X-plane flight simulator. A flight simulator can be used to simulate a real time flying environment for APM by generating GPS and sensor data. The APM takes the input data from X-plane and based on the flight plan generated from ground control station, commands the plane to fly in the simulator. The actual representation of the flight can be seen in the X-plane simulator. HIL can be used for in situ testing of the flight, tuning the PID gains, and change the weather conditions to estimate the behavior of the UAV in actual flight.

Figure 8 shows a schematic representation of the HIL.

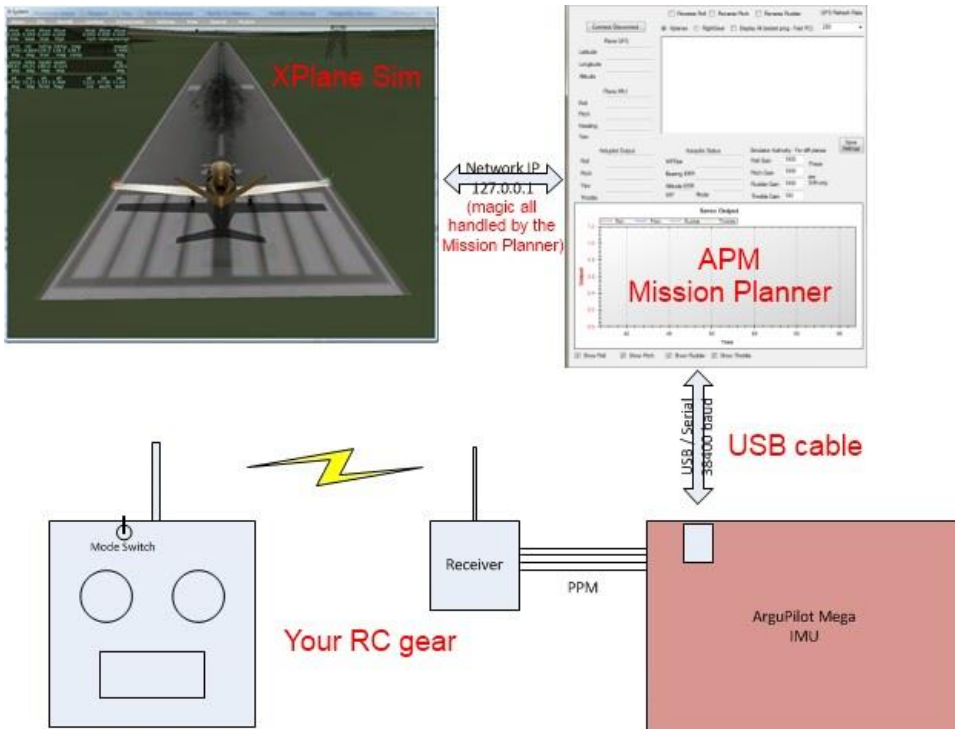


Figure 8, HIL flowchart (<https://code.google.com/p/ardupilot-mega/wiki/Xplane>)

- COMPUTING ALTITUDE OF THE FLIGHT

To calculate the altitude of the flight, first the desired Ground Sampling Distance (GSD) is chosen. GSD is the distance between pixel centers measured on the ground. A bigger GSD value will mean the actual spatial distance on the ground is lesser, which leads to lower resolution images and less details that are visible. The higher the altitude from which images are captured, the bigger is the GSD value. A GSD of 5 cm means that every pixel will capture 5 cm of spatial distance on ground. Likewise a GSD of 10 cm will capture 10 cm of ground distance per pixel resulting in lower resolution images.

For this project a GSD of 5 cm is chosen. Apart from GSD the altitude also depends on the camera parameters such as focal length, sensor width and image width.

Formula used to calculate height:

$$H = (\text{ImW} * \text{GSD} * F_R) / (S_w * 100)$$

Distance of image covered on ground can be calculated as:

$$W = (\text{ImW} * \text{GSD}) / 100$$

$$L = (\text{ImH} * \text{GSD}) / 100$$

## Calculations Based on Canon SX230HS

Camera specifications

$$F_R = 5 \text{ mm}$$

$$\text{GSD} = 5 \text{ cm/pixel}$$

$$S_W = 6.17 \text{ mm}$$

$$\text{ImW} = 4000 \text{ pixels}$$

$$\text{ImH} = 3000 \text{ pixels}$$

Calculating required height

$$H = (4000 * 5 * 5) / (6.17 * 100)$$

$$H = 162 \text{ meters}$$

Ground distance covered

$$W = (4000 * 5) / 100$$

$$W = 200 \text{ meters}$$

$$L = (3000 * 5) / 100$$

$$L = 150 \text{ meters}$$

Thus we get an altitude of 162 meters for the required flight conditions.



- WAYPOINT GENERATION FOR CORRECTIVE FLIGHT

The following flowchart shows a general methodology implemented in designing waypoint generation algorithm.

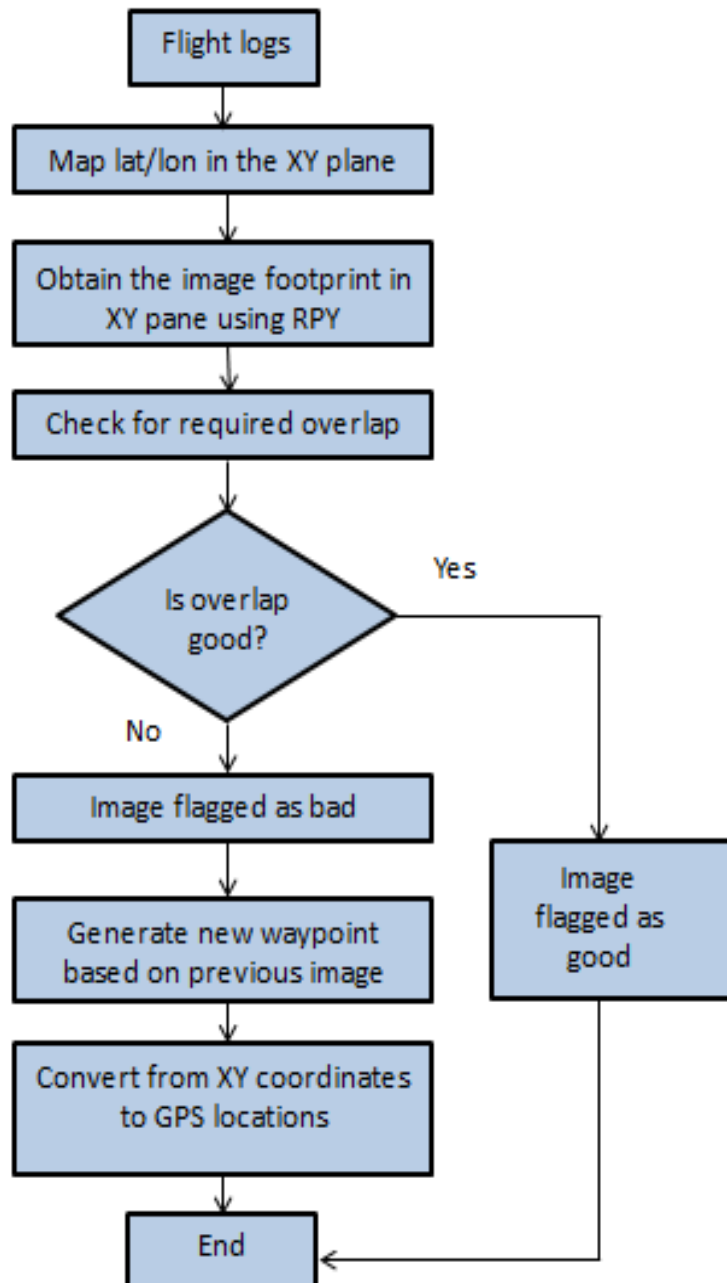


Figure 9, Flow chart of image checking process

➤ Obtaining the waypoints

The waypoints at which the camera is triggered are obtained from the tlogs and the dataflash logs in MP and APM respectively. A Microsoft excel sheet is prepared which shows the waypoints in consecutive order at which the camera is triggered. Information such as latitude, longitude, altitude, and RPY of the plane at time of triggering is saved in different columns in this sheet.

➤ Converting the GPS waypoints to actual distance

The GPS data doesn't reflect the actual distance on ground. To convert this data to actual distance, the Haversine formula is used. Haversine equation takes in account the radius and curvature of earth to estimate the actual ground distance between waypoints. To plot the actual image imprint on ground, the latitude and longitude are mapped in an X-Y coordinate plane. The 1<sup>st</sup> image that is captured is set as the reference image. This image is set at origin of the XY plane. The haversine formula then calculates the actual ground distance between the first and the consecutive image. This is done for all set of waypoints and they are mapped in the XY plane. The distance calculated by haversine formula is given by:

$$d = 2 * R * \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos(\phi_1) \cos(\phi_2) * \sin^2\left(\frac{\theta_2 - \theta_1}{2}\right)}\right)$$

Table 5 shows the original GPS coordinates and the mapped coordinates in the XY plane.

GPS Coordinates		Image number	Mapping in XY plane	
33.43007	-112.012587	1	0	0
33.43007	-112.012426	2	-72.9397	2.557483
33.43009	-112.012039	3	-143.745	4.670187
33.4301	-112.011652	4	-216.685	7.22767
33.43012	-112.011265	5	-287.49	9.785154
33.43013	-112.010878	6	-360.43	12.34264
33.43014	-112.010491	7	-431.235	14.45534

Table 5, GPS Coordinates and their mapping in XY plane

➤ Checking for faulty images based on latitude and longitude coordinates.

The desired overlap in images is 60% frontal overlap and 40 % sideways overlap.

Anchoring the first image, the images closest in frontal and sideways direction are checked for overlap. If the image doesn't fulfill the requirements, it is flagged as faulty image. Figure 10 shows an example of good overlap between images. For purpose of illustration,

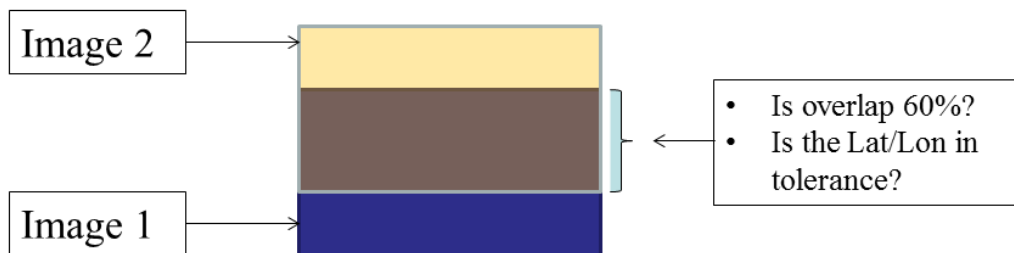


Figure 10, Good overlap between images

Figure 11 shows an example of a faulty overlap between images.

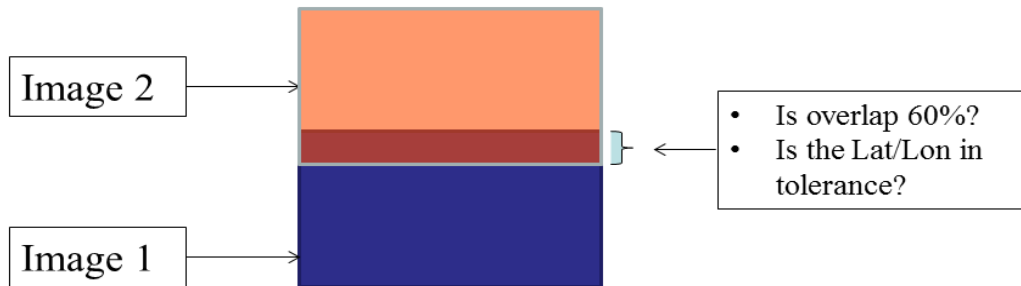


Figure 11, Bad overlap between images

➤ Checking for faulty images after incorporating RPY.

The effects of Roll Pitch Yaw are incorporated as follows:

Pictorial representations of how an image is affected by Roll Pitch and Yaw are shown below. Figures show effect of roll pitch and yaw respectively. The plane on the left represents a stable attitude whereas the images to the right represent RPY. The rectangles show the image footprint that will be captured in respective attitude.

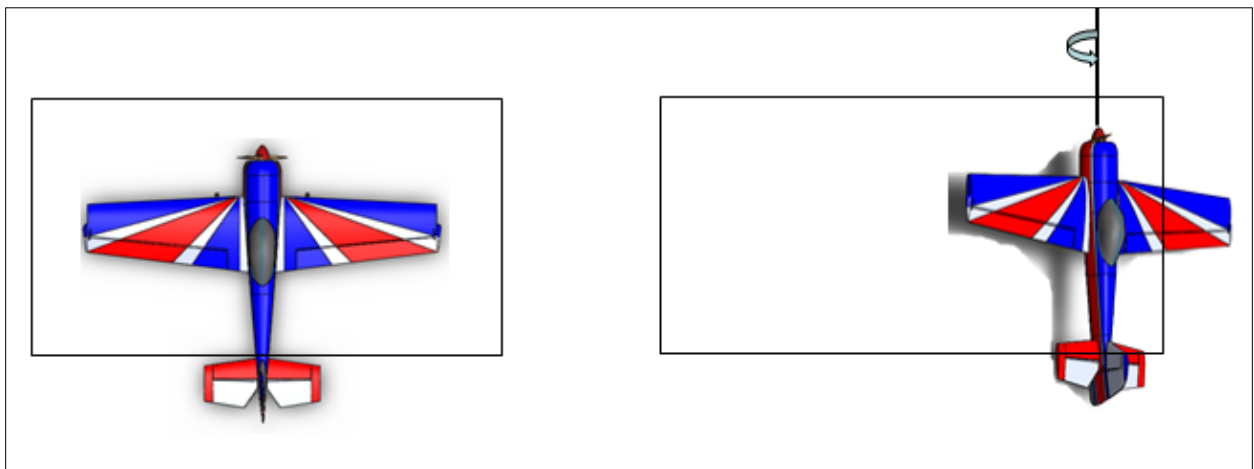


Figure 12, Effect of Roll on image footprint

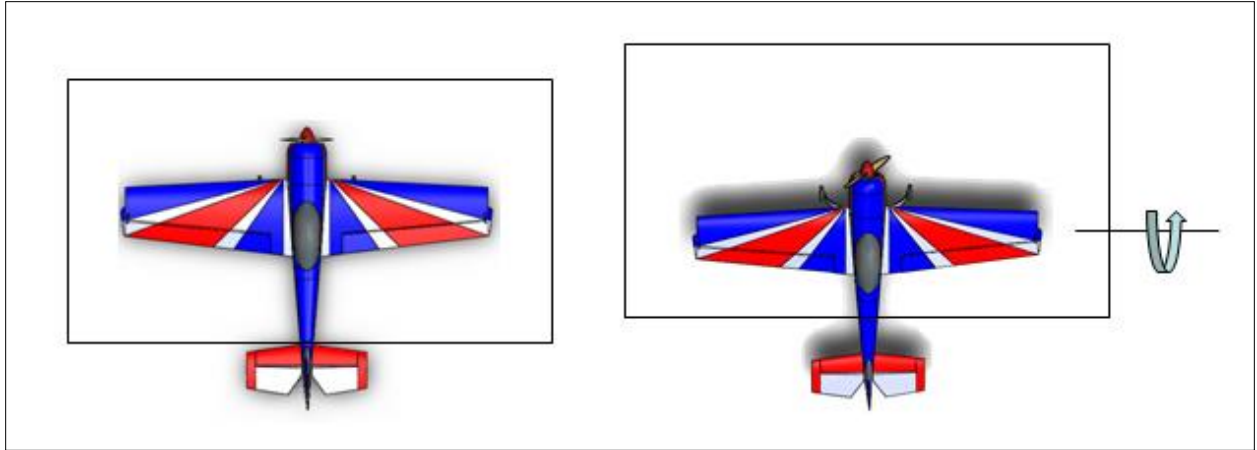


Figure 13, Effect of Pitch on image footprint

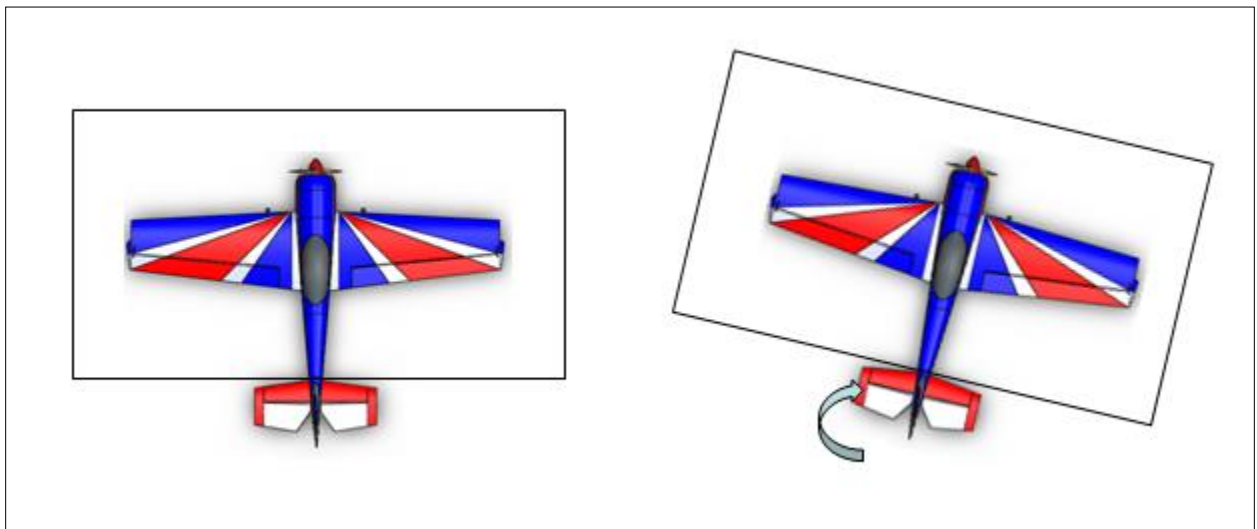


Figure 14, Effect of Yaw on image footprint

To map the GPS locations along with roll pitch yaw in to the XY plane, we use the transformation matrices. The transformation matrices are as follows:

Roll Matrix: 
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & -\sin \gamma \\ 0 & \sin \gamma & \cos \gamma \end{pmatrix}$$

Pitch Matrix: 
$$\begin{pmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{pmatrix}$$

Yaw Matrix: 
$$\begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Using these matrices the image footprint can be generated in the XY plane. Figure 15 shows the effect of RPY on image footprint and image overlap.

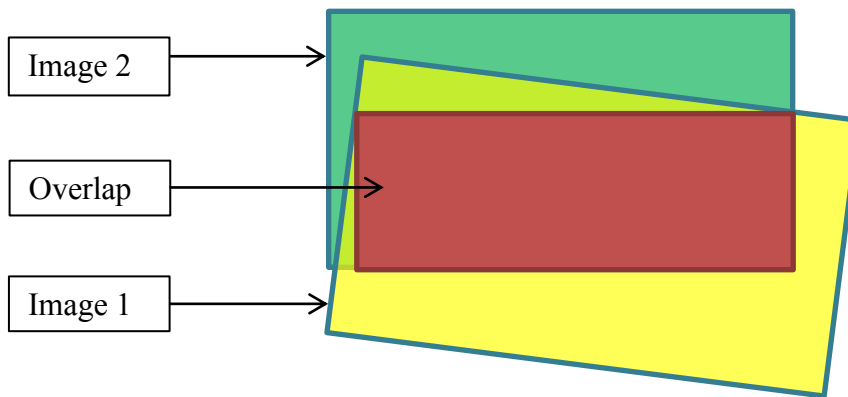


Figure 15, Compensating for effect of Yaw on image footprint

In such case, a rectangle which fits the overlap quadrilateral is chosen. This rectangle is basis for the next calculations to check for overlap.

➤ Generating waypoints for corrective flight

Based on the flagged images, a set of waypoints in coordinate space is generated. These waypoints are generated such that the overlap conditions are satisfied properly. In figure 16, the image 3 is generated at such a waypoint that the overlap is satisfied properly in next flight. These waypoints are then mapped in actual GPS locations using the reverse Haversine equation. The altitude for the flight is same as the first flight.

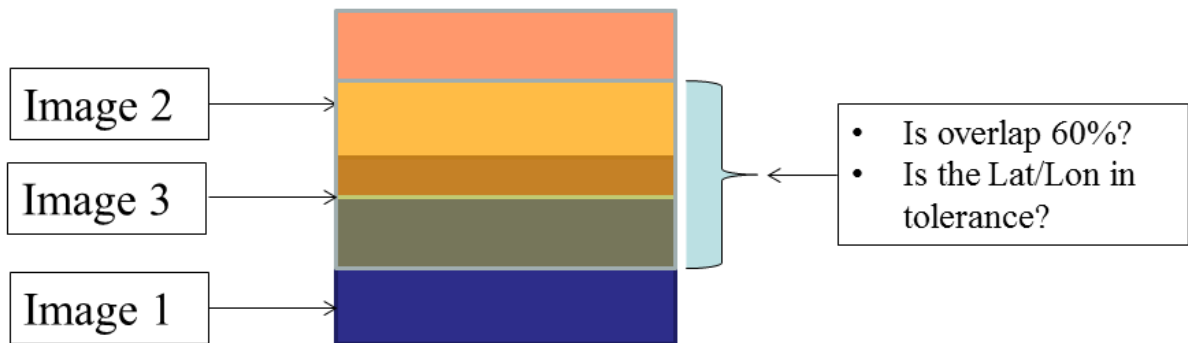


Figure 16, Corrective image generated between flagged images

## CHAPTER 4

### VALIDATION TESTS

To validate the new waypoints generated, a five phase method is incorporated. Figure 17 shows the flow of validation tests undertaken to make sure that the process is effective.

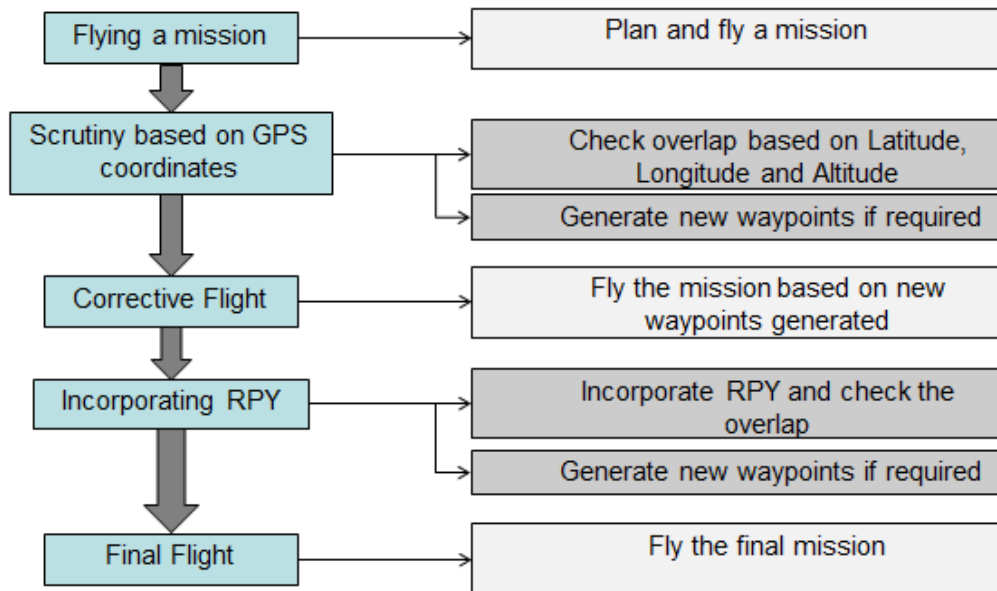


Figure 17, Flowchart illustrating the validation tests

- PHASE 1: FLYING A MISSION

In phase 1 an actual mission to map a particular terrain is flown. While planning a mission various factors are taken in consideration. The flight plan is designed in MP. The MP can generate a good lawn mower grid for capturing images. The flight plan also contains information about the positions where the camera should be triggered. The camera can be triggered in three different ways: based on distance covered, based on time interval, based on servo command. If the triggering is based on distance, a PWM signal from APM triggers the camera based on the designated value of distance covered. If the



triggering is based on time, the APM send the trigger command after a particular time interval. The third method is based on waypoints achievement. The APM sends the trigger command at particular waypoints. Other factors while planning a mission are weight, cruising speed and camera tilt angle. The flight logs generated from this flight are used for processing. The flight parameters that acquired from this flight are the GPS location, altitude and Roll Pitch Yaw (RPY) of the UAV while capturing the image. Both the dataflash logs and the tlogs saved in APM and MP respectively are used for further processing.

- PHASE 2: SCRUTINY BASED ON GPS COORDINATES

Phase 2 is about checking if already flown plan for discrepancies. Using the flight logs from the primary flight, a sheet is prepared which shows the following information about the plane while capturing the images: Latitude, Longitude, Altitude, Roll, Pitch, and Yaw. This sheet is the input for the code. The code checks each and every location of the camera trigger and then estimates if the overlap between images satisfies the required overlap. If discrepancies arise, a new set of waypoints is generated for the corrective flight. In phase 2, the correction for RPY of the UAV is ignored. It is assumed that the attitude of the plane is parallel to ground. This step is to ensure the code runs properly. The new waypoints are based only on the GPS latitude and longitude, and altitude of the UAV. The new waypoints are then fed into MP to check if the graph generated by code and the estimated positions in actual GPS plane match properly.

- PHASE 3: CORRECTIVE FLIGHT

Phase 3 is corrective flight. This flight is based on the waypoints generated in the phase 2. After the flight, the logs are again checked for faulty images. If the discrepancies show up again, process in phase 2 is applied to generate new waypoints.

- PHASE 4: INCORPORATING RPY

In phase 4, the RPY parameters are taken in consideration for a better image prediction ability. Here all the parameters are taken in consideration while predicting the actual ground distance of the images. The RPY transformation matrices are implemented in the code to calculate the coordinates. Again the overlap between the images is checked to find the faulty waypoints. A new set of waypoints is generated based on all the parameters: GPS coordinates, altitude, RPY. These waypoints are used to generate a new flight plan for the corrective flight.

The Roll Pitch Yaw rotation matrices are used to transform the coordinates in XY plane to reflect the attitude of the plane while capturing image.

- PHASE 5: FINAL FLIGHT

The final mission with a proper set of corrective waypoints is flown to capture the faulty or missed images. It is similar to phase 3, but with more comprehensive set of parameters. If there are discrepancies even after this flight, process in phase 4 is applied for next corrective flight.

## CHAPTER 5

### RESULTS

- HIL RESULTS

A normal mission was flown and simulated to capture images at required waypoints.

Figure 18 shows the flight plan.



Figure 18, Primary flight mission

Figure 19 shows the actual flight flown in HIL. The yellow line shows the desired waypoints and the blue line show the actual waypoints followed. Just by looking at the waypoints that were followed it can be seen that few images are missed while the UAV is turning.

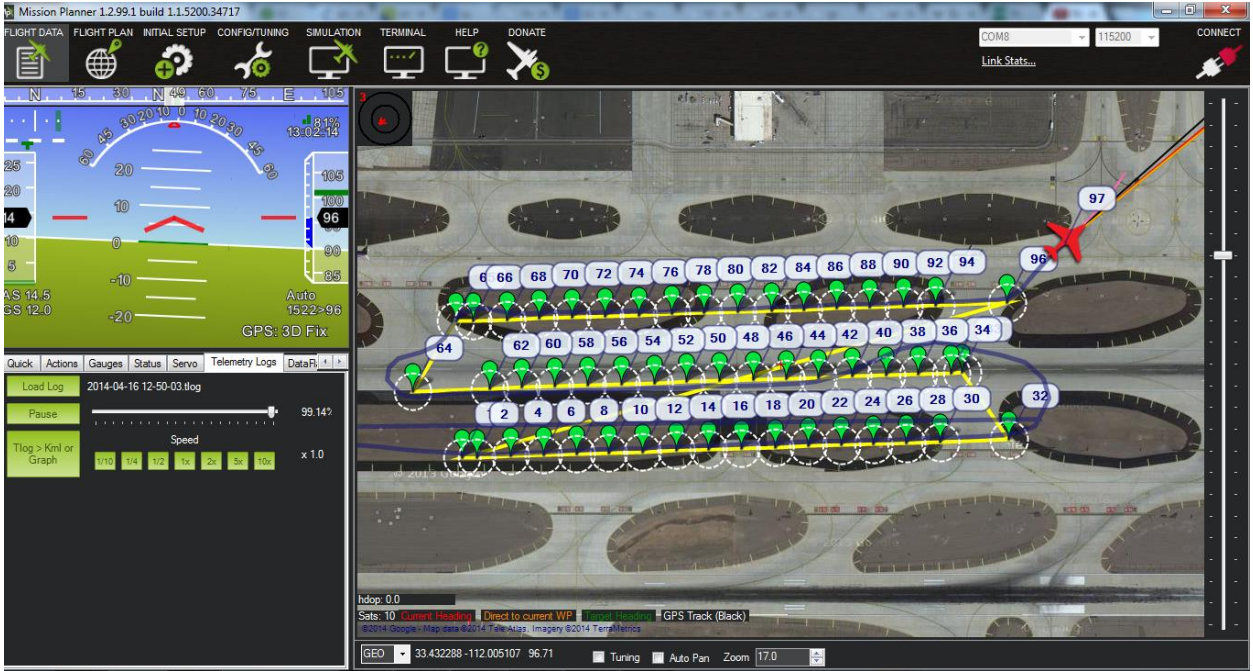


Figure 19, Actual Flight path



Figure 20, Google Earth simulation of flown mission

Figure 21 shows the image footprints generated using the code. It can be seen that the side overlap between rows 1 and 2 satisfies the required amount of overlap percentage. But the side overlap between rows 2 and 3 doesn't seem to satisfy the desired percentage. To get a clearer idea of improper overlap, waypoints achieved while turning the plane are considered in figure 22.

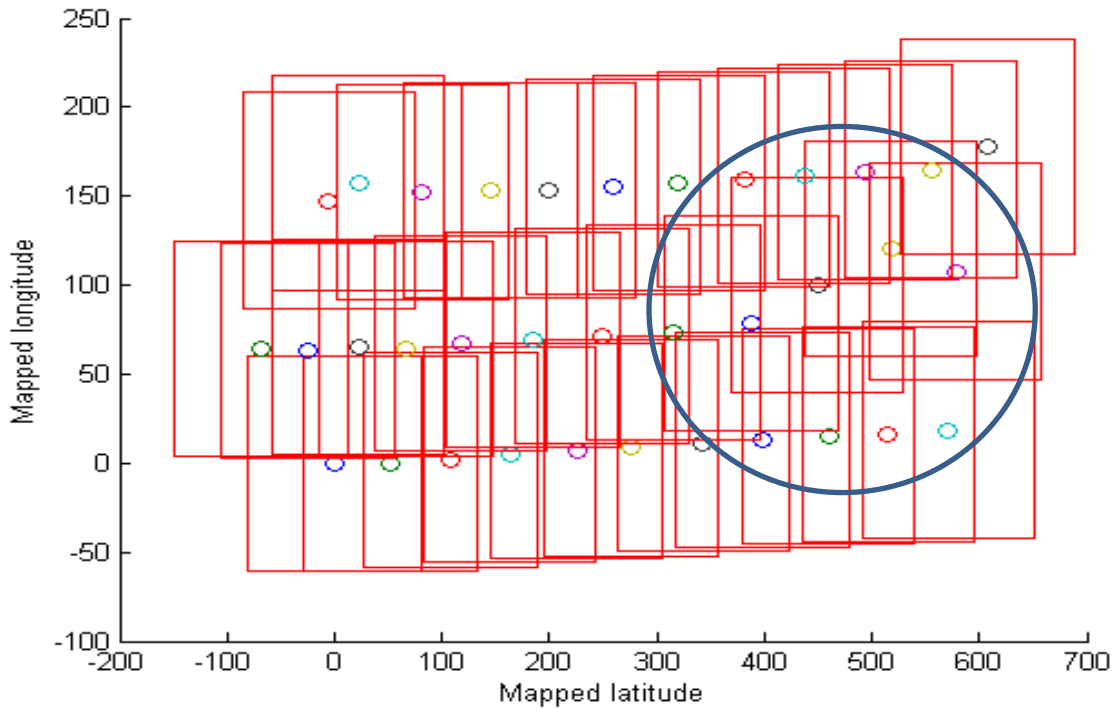


Figure 21, Distorted waypoints

Figure 22 shows magnified perspective of the images encircled in the figure 21. It can be seen clearly that the image overlap is not proper and new set of waypoints are required to be generated to get a proper overlap.

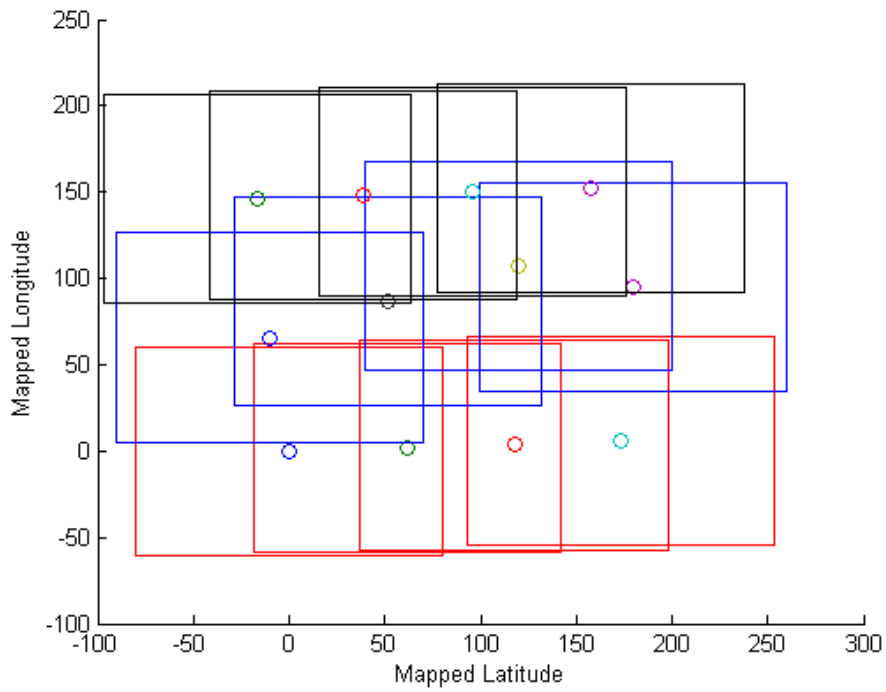


Figure 22, Magnified view of distorted images

Figure 23 shows the new generated waypoints and their image footprints. These new waypoints cover the areas missed while turning from row 1 to row 2, and also cover the area between rows 2 and 3 where the image overlap is not proper. These waypoints are then transformed into real GPS waypoints using the reverse haversine formula. A new set of waypoints is generated for the corrective flight. Figure 24 shows the new corrective flight that is planned in mission planner.

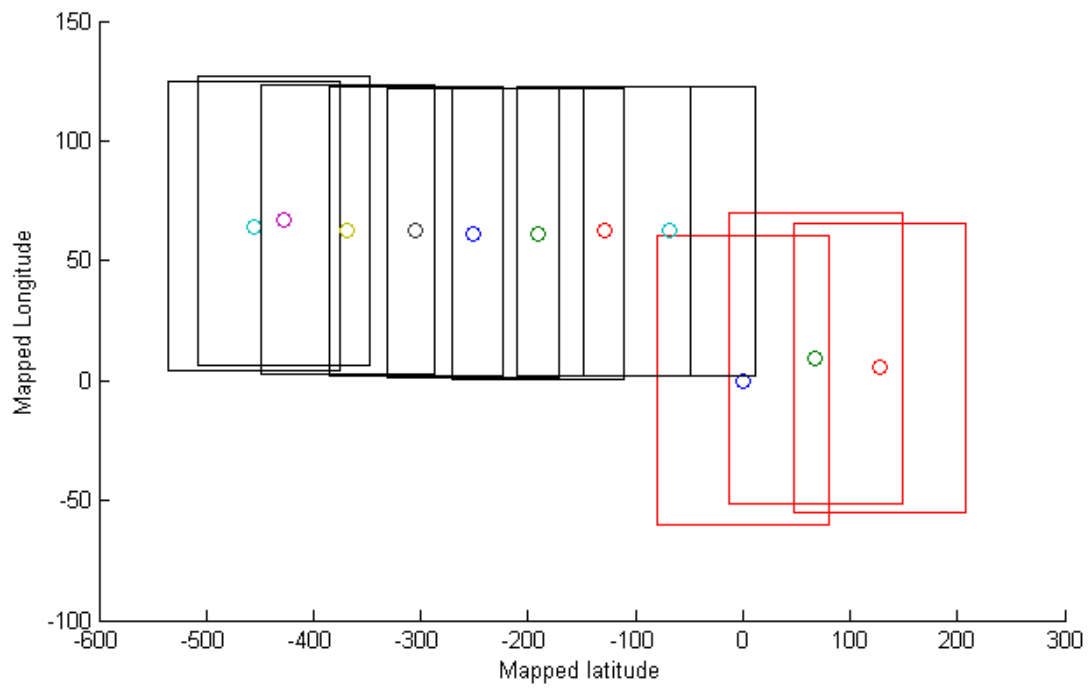


Figure 23, Waypoints generated for corrective flight

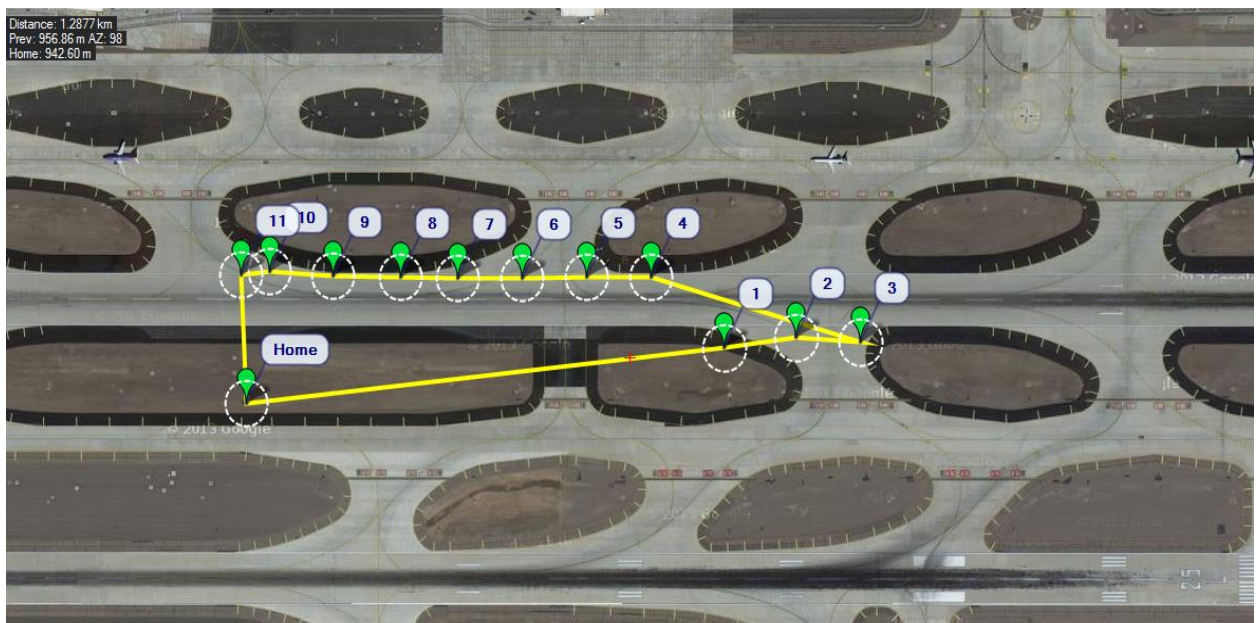


Figure 24, Mission plan for corrective flight

- INCREASE IN EFFICIENCY

To demonstrate the change in efficiency a flight is simulated in HIL such that it follows lawn mower pattern and captures images. Following are the aspects of the mission:

Number of images: 44

Area covered: 180452 m<sup>2</sup>

Number of strips of lawn mower: 4

GSD: 5

Flight height: 162m

Wind speed for simulation: 5 m/s

Figure 25 shows the mission that was planned in mission planner. Note that the waypoint numbers are not consecutive because of the camera trigger function at each waypoint.



Figure 25, Mission plan for primary flight



Figure 26 shows the actual flight flown. Blue line is the actual flight, whereas the yellow line represents the desired waypoints.



Figure 26, Actual path followed in simulation

It can be seen from the actual flight path that the images at waypoints 2, 6, 25, and 50 seen to be away from the desired waypoints. To check for the overlap between the images, the waypoints are put through the code. Figure 27 shows the image imprints generated by code. Using the code, new waypoints are generated. Figure 28 shows the new waypoints generated for the corrective flight. The waypoints 5 and 8 are generated to assist the UAV in making a smooth turn.

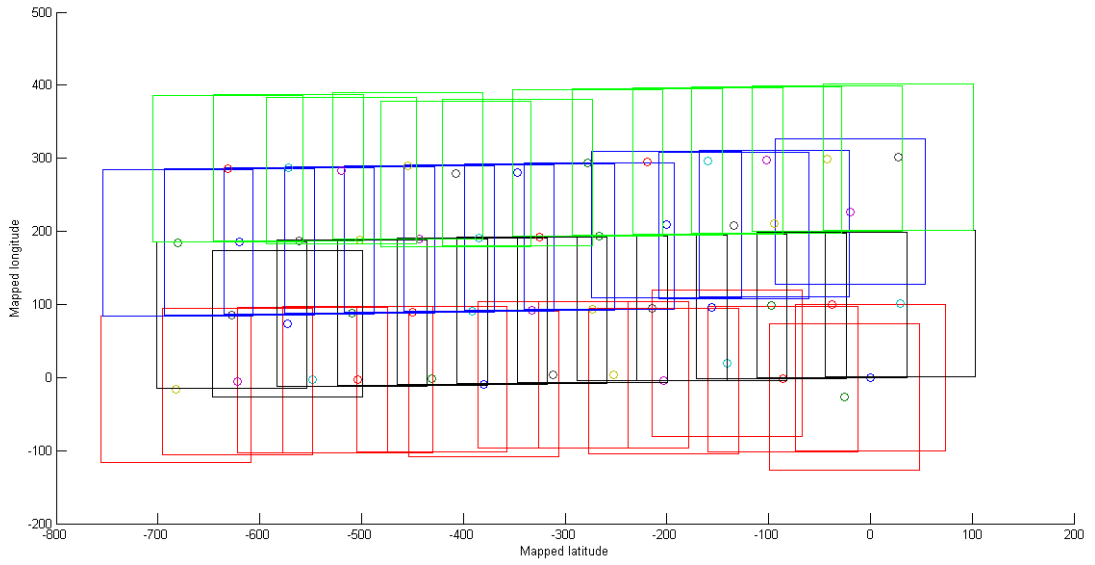


Figure 27, Image footprints generated from code

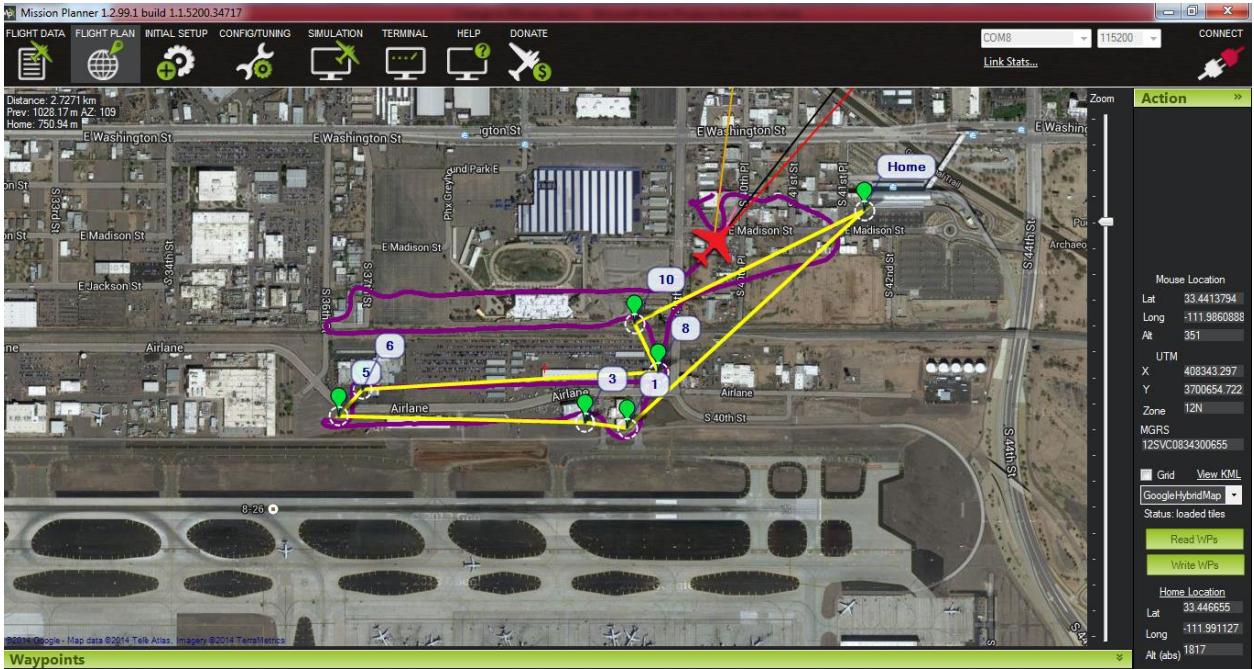


Figure 28, Mission planned for corrective flight

The number of images to be captured in corrective flight; as generated by the code; was 4. Therefore, we can calculate the image capturing efficiency of the first test flight based on number of images to be captured and the number of images missed.

$$\text{Efficiency of first flight} = \left(1 - \frac{\text{number of images missed}}{\text{total number of images}}\right) * 100$$

Therefore, we get an efficiency of 90.9 % from the first flight. Though this number does not seem bad, the wind conditions for this flight need to be taken in account. At higher winds and due to real world dynamics, the number of missed or distorted images may be more. To account for the 9.1% of lost efficiency the corrective flight is quickly planned and flown. Now the mission compensates for the earlier loss of 9% and the images that were flagged as bad images can be used for processing. Thus the image capturing efficiency of the process increases.

## CHAPTER 6

### CONCLUSION AND FUTURE SCOPE

- CONCLUSION

This thesis document has presented a new way to increase the efficiency of terrain mapping using an UAV. From results we can see that the new set of waypoints was generated at the desired positions. The MATLAB code not only helps in generation of waypoints but is also useful in visualization of the faulty images. The plot generated by the code can be used for checking the generated waypoints manually. If the corrective flight misses the waypoints again, the code can quickly generate a new set of waypoints.

This process compensates for the decrease in efficiency of a flight due to missed images. The images rendered bad due to improper overlap can be useful after the corrective flight. The overall processing time can be reduced as the corrective flight is generated immediately after the first flight. The time required for stitching images can be saved significantly as the set of images will completely cover the area in one mission itself.

In cases where multiple flights are required to capture the images with proper overlap due to high wind, it becomes tedious when the missed or improper images show up after stitching. With help of this method, stitching process can be eliminated and the images can be stitched only after a good set of images are captured and the code doesn't flag an image as bad.

This method can be very helpful and time saving for the applications in field of UAV photogrammetry.

- FUTURE SCOPE

The Waypoint Generation method implemented in this approach does satisfy the requirements of the problem statement. However, there are scenarios where the algorithm can be smarter and more efficient. As of now the algorithm checks for overlap with the adjacent images only. But this approach is nullified if the windy condition is too high and the deviation from path is more than 5 percent of the intended.

This approach can be implemented in a multi UAV system so that the waypoints can be generated dynamically in case of a faulty image. First UAV will capture images and the second UAV can use the telemetry logs of the first UAV to dynamically calculate the image overlap and capture images on the locations that were missed.

This algorithm is developed in MATLAB. Not all the systems have access to MATLAB. This process can be implemented in the Ground Control Station itself so that no special software will be required for the code to run.

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