

# **Autonomous Unmanned Aerial Vehicle for Reconnaissance based on Robotic Operating System**

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## **ABSTRACT**

The Intelligent Flying Object for Reconnaissance (IFOR) is an autonomous aerial vehicle that has been developed by students of BITS Pilani, Dubai Campus. The vehicle is capable of localizing itself using the SLAM algorithm, stabilize its attitude (pitch, roll and yaw) and altitude using PID controllers, plan paths around obstacles and navigate an unknown indoor environment with wall following guidance. In addition, it has been designed to be capable of pattern recognition which would enable it to recognize images and signs. These features enable the IFOR to execute the 6<sup>th</sup> mission of the International Aerial Robotics Competition, which involves scanning an unknown indoor arena protected by laser barriers and cameras, bestrewn with obstacles, in search of a flash drive.

## **1. INTRODUCTION**

The field of robotics is witnessing a paradigm shift in the operation and use of robots. With various robots becoming autonomous and intelligent day by day, their application and use has increased tremendously. *Aerial robots* specifically have an edge over other autonomous vehicles due to their higher degrees of freedom and agile maneuverability. To tap these features and advance the applications and versatility of the vehicle is the aim of the team.

### **1.1 Problem Statement**

The 6th mission of the IARC requires teams to construct a fully autonomous aerial robot capable of self-controlled flight within a confined environment. The vehicle will first be required to enter a “military” facility through a one square meter or larger opening from a designated launch area 3m away. The vehicle will have to search for a target area (“Office of the Chief of Security”) while avoiding unknown obstacles such as walls, columns and furniture as well as visible security systems like a video camera and a laser barrier in a hallway.

The building will contain several signs indicating the route to the target area as well as appropriate indicators allowing avoidance of the security systems. Once the target area is found the vehicle is expected to locate a target object (Black colored pen drive), pick it up and drop a decoy in its place before proceeding to fly back out of the window which it had entered through.

## 1.2 Conceptual Solution

We have designed an autonomous vehicle which leverages the use of an off the shelf quadrotor as the base platform. This has allowed us to focus on the autonomy of the vehicle instead of the intricacies of flight dynamics. We have used the Ascending Technologies' (Asctec) Pelican as the quadrotor of choice for its payload capacity and high structural integrity. A quadrotor, by nature, is aerodynamically unstable. This demands the use of a Stability Augmentation System (SAS) which the Pelican is already equipped with. The SAS relies on data from the Inertial Measurement Unit (IMU) to keep the vehicle stable in flight. We have equipped the quadrotor with a scanning laser range finder to enable exteroceptive sensing of the surroundings. Simultaneous Localization and Mapping (SLAM) is used to calculate the coordinates of the vehicle in a global frame which are used to correct drift. The vehicle makes use of two camera's one situated in the front and the other at the bottom. The camera is used by the image processing module to detect and identify objects and words through the use of the SURF descriptors. All the modules are monitored by a Base Station which serves as the link between all systems and also allows for changes to be made dynamically to each of them. All processing of sensor data is done off board on the base station. The sensor data is pre-processed on board the vehicle itself.

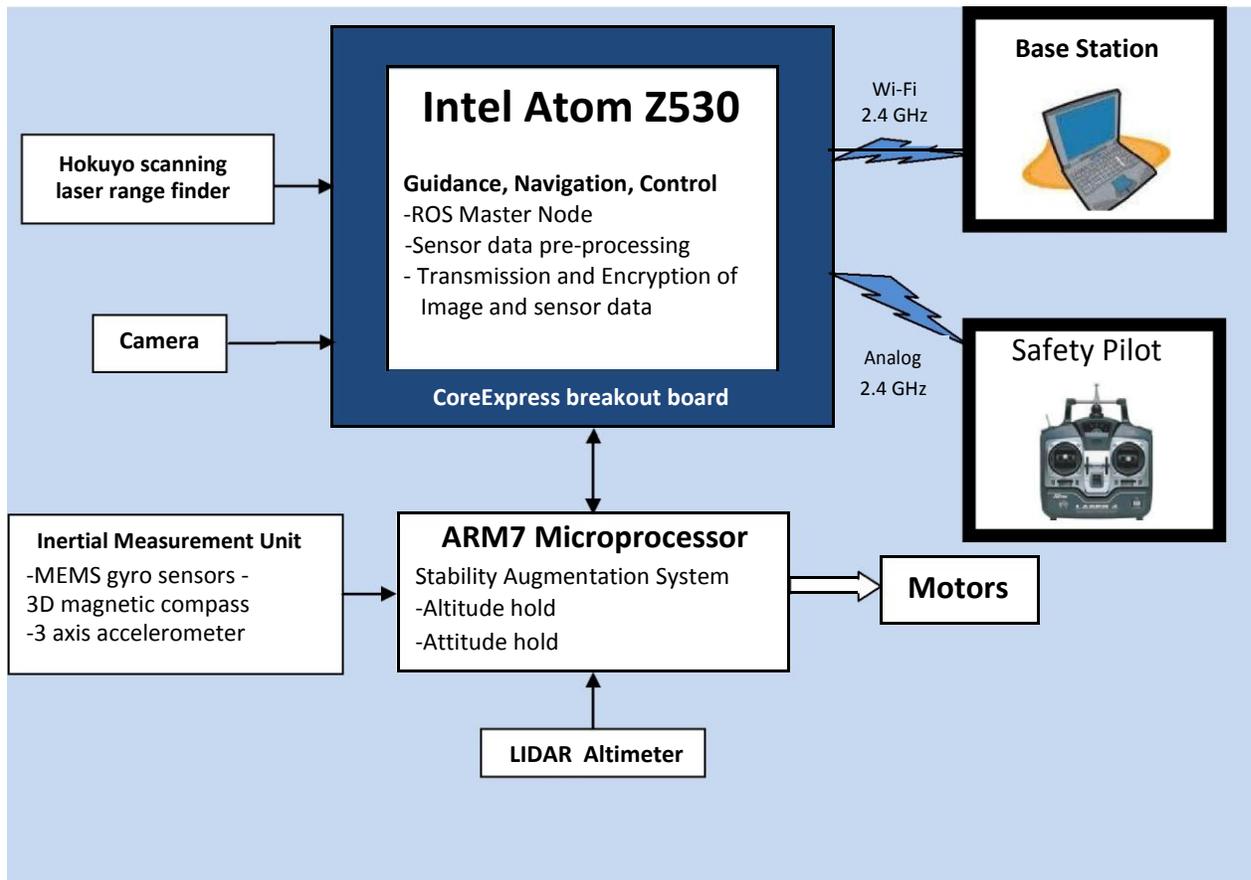


Figure 1: System architecture

### 1.3 Yearly Milestones

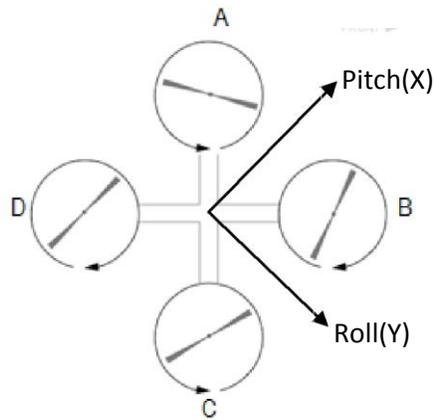
In our last attempt at the 6th Mission, we designed to design a vehicle that is capable of flying autonomously(i.e. without pre-programming the flight) by performing drift control, intelligent navigation through the arena, path planning and image identification (limited to recognition of the pen drive and signboards).

In our current iteration of the vehicle, the vehicle now has a new array of modules allowing for a improved real time performance. The vehicle uses a software backbone of ROS, for easy standardization of our modules as well as making sensor data readily available. We have also implemented robust image identification and matching module which has a real time performance.

## 2. Air vehicle

The Asctec Pelican, is a development platform for the design of a quadrotor based UAV's. It's a robust platform running attitude control algorithms at 1000Hz thus providing a very stable vehicle for the sensor suite. The quadrotor also provided filtered IMU data for use in other algorithms hence allowing for more robust pose and heading estimation.

The Pelican weighs about 980 g and has a payload capacity of 500 g. The payload capacity of the Asctec Pelican meets the flight time required, when loaded with the sensor suite.



*Figure 2: The Asctec Pelican quadrotor and the propeller action.*

### 2.1 Propulsion and lift system

The quadrotor is a Vertical Takeoff and Landing (VTOL) rotorcraft which is propelled by four rotors. Unlike a helicopter, a quadrotor does not require a separate propeller to negate the angular momentum generated by the movement of the driving propeller/s; this is due to the fact that, in a quadrotor, a set of two propellers is made to rotate clockwise while the other set is made to rotate anticlockwise. Hence the net angular momentum about the centre is zero.

The vehicle can be flown in square or diamond configuration, in diamond configuration the pitch/roll axes are the diagonals between the propellers. In such a configuration only two propellers are involved in causing pitch/roll at any point of time. In a square configuration the directions of forward pitch and forward roll are as marked in the diagram above. Pitch (positive) is achieved by reducing the angular velocity of two propellers (A and B) and increasing the velocity of the other two propellers (C and D), whereas, Roll (positive) is achieved by increasing velocities of propellers A and D and reducing the velocities of B and C.

## 2.2 Stability Augmentation systems :

The quadrotor, by nature, is an aerodynamically unstable system. It hence demands to be one that is mechatronic in nature with its dynamics being controlled by PID generated signals. The inputs to the PID loops are the readings from the IMU which consists of three gyro-meters and a triple axis accelerometer. The raw readings from the sensors are mapped onto tilt angles which are then compared to the desired setpoint. The preset PID constants are then used to calculate the required output to the motor at a frequency of 1 kHz. The control loops ensure that the vehicle achieves a desired attitude with minimal error. The loops for Pitch, Roll and Yaw are implemented on the ARM7 processor of the Pelican and are tuned off-the-shelf.

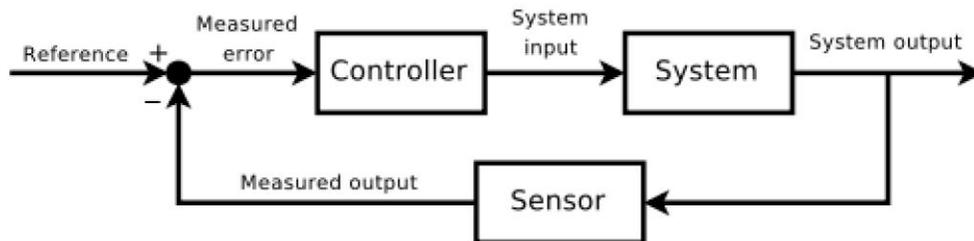


Figure 3: PID control system architecture

$$\text{Command} = \text{Bias Value} + K_P e(t) + K_i \int_0^t e(T) dT + K_d \frac{d}{dt}e(t)$$

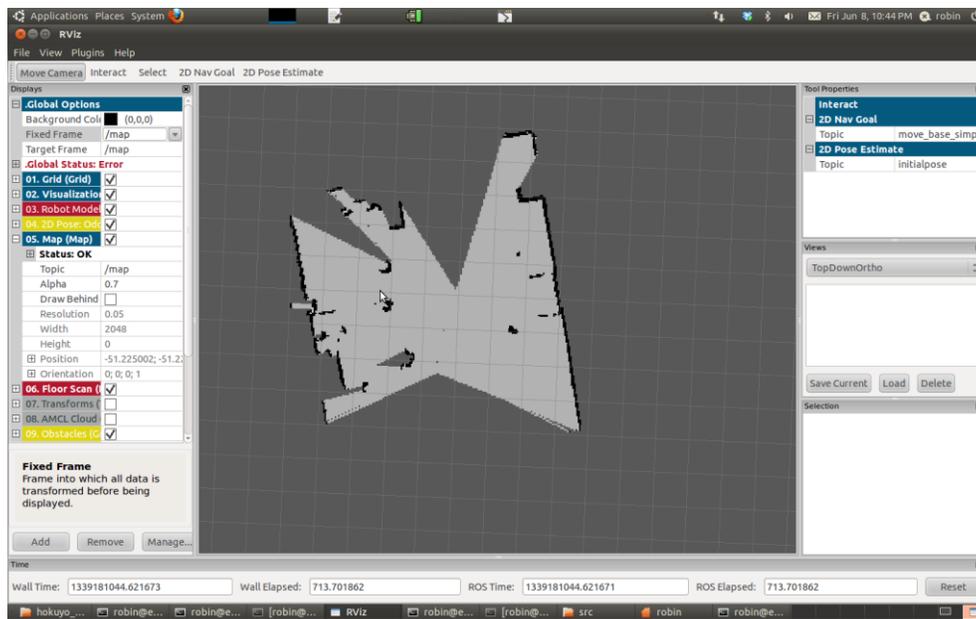
# Navigation & Path Planning

## *SLAM*

SLAM is an acronym for the Simultaneous Localization and Mapping algorithm. It consists of multiple parts; landmark extraction, data association, state estimation, state update and landmark update. The algorithm estimates the apparent change in position of landmarks (unique regions) between the current scan and the map assuming the surroundings to be stationary. The vector opposite to this one represents the change in position of the vehicle. “Global” coordinates hence calculated are used to generate a map of the environment. Therefore, the map and coordinates are simultaneously estimated from each other.

We use the Hector SLAM approach to the Simultaneous Localization and Mapping problem, a robust and efficient algorithm with good integration with the ROS framework. The Hector SLAM solution uses a 2D grid map representation which is updated using a scan matching approach. The algorithm has low runtime requirements and can run with an update rate of 40Hz all the while reducing the computation required as compared to other solutions to the SLAM problem. The system uses odometry data, along with the scan matching approach to result in a very robust estimation of pose of the vehicle. The input used for solving the SLAM problem are laser scans from the lidar as well as odometry data from the IMU and a secondary scan matching module; the robot state as estimated by the navigation filter. Data provided by the navigation filter is used for transformation of laser scans to take into account the attitude of the laser scanner and vehicle during acquisition of scans.

To enable autonomous cumulative mapping so as to take into account earlier made maps, a feature based map merging system has been developed. The robot detects SURF features for the estimated map, after which a registration approach is then used to arrive at a common coordinate frame for all pose states.



*Figure 3 : Hector Mapping*

### *Path Planning*

The path planning module uses a gradient planner which uses the cost map method to calculate the optimal path to the goal from the robot. The gradient planner is a wave front planner that computes the cost of getting to the goal at every cell (20x20cm) in the map. If the cost of a cell is higher than the cost of a neighbor's value added with the local transit cost, then its value is updated. The planner takes into account the local neighborhood of the cell to update the cost of the cell. The algorithm initializes the goal with zero cost and everything else with a very large cost. All goals are put into an open list, which is then popped from the list and then each of the cell's neighbors are updated. The neighbor cells with a lowered cost are then pushed back onto the list. The algorithm completes when the open list is empty.

The algorithm computes the configuration space for a circular robot and includes safety distances to obstacles. The obstacle points are entered as goal points, and the update algorithm is run over the list, generating a new open list. This is done till the distance of the obstacles has been determined to the resolution of cycles spent on the algorithm. After which a cost is associated with the distance; infinite cost within a specified safety radius and decreasing cost moving away from the radius.

Rapid switching of global paths are avoided by including hysteresis by lowering the cost along the path. This allows the algorithm to switch paths only when there is substantial evidence of the profitability of the new path.

After creating a map in navigating to a goal the map can be re-used so as to be more efficient at the same task.. A better global path can be computed for the same task if a map of the environment is already readily available. This allows for the algorithm to plan through shorter paths and even make use of shortcut, which may have been detected and validated on an earlier run.

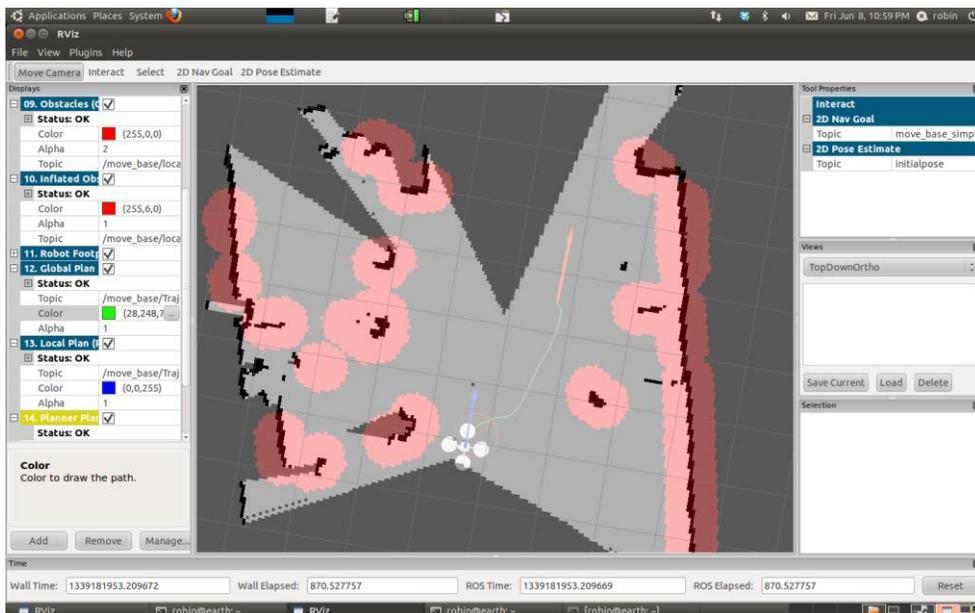
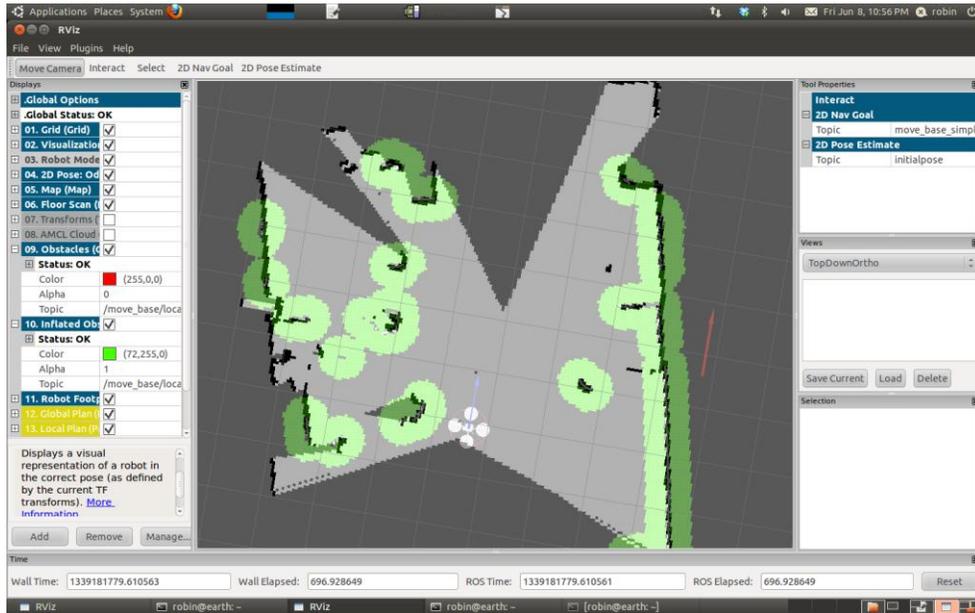


Figure 4 : Obstacle Growth and Path Planning

### *Drift Control*

Drift control is most important to the performance of the vehicle in the mission since milligram imbalances in weight, apart from other factors, cause a quadrotor to drift unintentionally. The coordinates which are output by SLAM are used by the Drift control algorithm to estimate the difference between the desired position and the actual position. The error in meters, for pitch and roll respectively, is then used in the following PID loops which are used to command the pitch and roll of the vehicle:

$$\text{Command Pitch} = \text{Pitch Bias} + K_{P_E} e(t) + K_i \int_0^t e(T) dT + K_d \frac{d}{dt}e(t)$$

$$\text{Command Roll} = \text{Roll Bias} + K_{P_E} e(t) + K_i \int_0^t e(T) dT + K_d \frac{d}{dt}e(t)$$

$K_c$ ,  $K_p$ ,  $K_d$  is the controller parameter. These constants are obtained as per the Zeigler-Nicholls tuning rule.

### *Altitude Control*

The altitude of the quadrotor is estimated by deflecting the 9 beams of the LIDAR at 90 degrees, so that the beam hits the ground vertically. The average of the 9 beams is considered as the true altitude of the quadrotor. This value of the height is used in a PID control algorithm to provide the value for estimating the value of the thrust required to reach a specified altitude. The Throttle Bias value provides an option to the user to reach different setpoints with variable payload.

$$\text{Command Thrust} = \text{Thrust Bias} + K_{P_E} e(t) + K_i \int_0^t e(T) dT + K_d \frac{d}{dt}e(t)$$



*Figure 5: LIDAR mirror mount for height estimation*

## 3. Payload

### 3.1 Sensor suite

#### *GNC Sensors*

- *Asctec Pelican Inertial Measurement Unit (IMU)*: The IMU consists of MEMS gyro sensors, a triple axis accelerometer and triple axis magnetic compass. This allows for the calculation of tilt angles which can be polled up to 100 times per second.
- *Hokuyo UTM 30 LX Light Detection and Ranging Device*: A scanning laser range finder of weight 160 gm., angular resolution 0.36 degree, range 5.6 m and a frequency of 10 Hz
- *Point Grey Firefly MV cameras*: The cameras provide data to the *IP* module which allow for detection of the Blue LED and laser barriers in addition to recognition of signboards.

### 3.2 Mission sensor

#### *Image Processing (IP) module*

We have equipped the vehicle with two high resolution cameras that provide the input for the image processing module. The cameras have been placed on the front and bottom of the quadrotor. The front facing camera will provide the inputs for the word recognition algorithm in order to identify the signboard of the “Office of the Chief of Security”. The competition involves recognizing a given set of Arabic letters from a set of words; the target room can be identified by this particular word. We do word identification by calculating a shape descriptor for the entire word via SURF (Speeded Up Robust Features), and then matching these descriptors with the those found in the target sign board via the RANSAC brute forcing method. We identify the words by their shape instead of the individual letters contained within. This approach is similar to how humans reading works, and provides a better performance in matching and identification than normal OCR based methods.

For the pen drive as well we use shape based descriptors via SURF. Calculating the SURF features of a 3D object such as a pen drive must be done with camera as distortion can occur due to the change in orientation of the object. To solve this problem we constrained the detection of features of the pen drive to those of the two largest faces, as SURF calculates more robust descriptors for a planar feature set. The descriptors calculated are then matched to those in the scene by counting the number of positive matches in the scene image and translating them into real space coordinates. As our camera is bottom facing it is possible to constrain the coordinate axes to only two dimensions making it simple to calculate a transformation matrix for the image pose to real space pose.

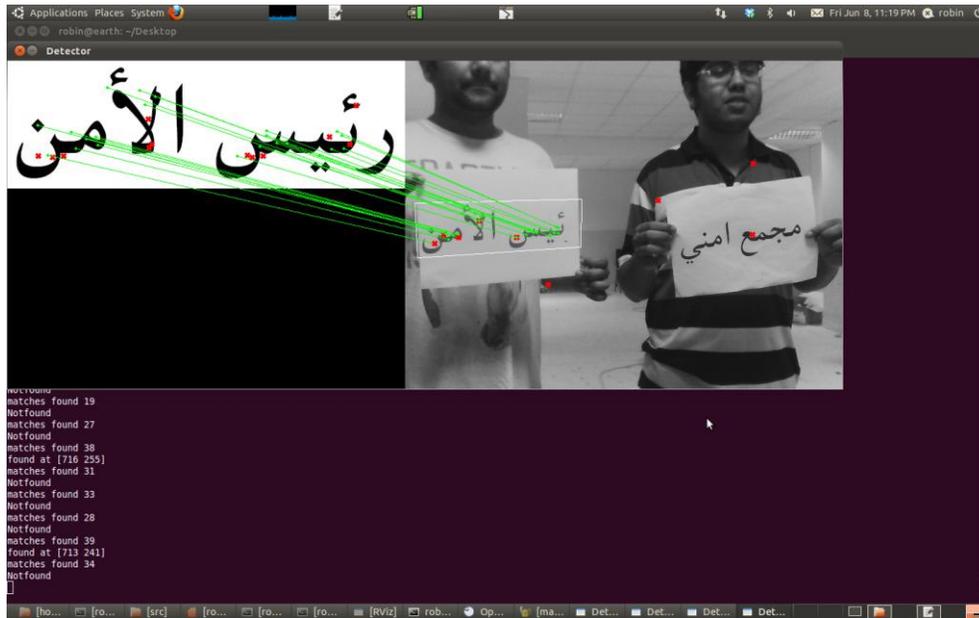


Figure 6 : SURF Bruteforce Matching via RANSAC

### 3.3 Communications

The vehicle makes use of multiple communication links with the base-station via WiFi and Xbee modules. The Xbee module is used for sending the control input to the vehicle from the base station through the reliable and fast Zigbee protocol. We use the Wi-Fi link to transmit both the LIDAR and the video data, the handling of the sensor data is managed by the ROS Messaging Framework. A safety pilot can take control over the vehicle at any time using a Futaba radio controller operating at 2.4 Ghz.

### 3.4 Power system

The quadrotor is powered by an 11.1V Lithium Polymer Battery. A power board is used to distribute power and communication lines to all motor controllers and other systems on board. The power board comprises of a switching power regulator to generate a stable 6V supply for the Auto Pilot board and a high power MosFET to switch current ON and OFF.

## 4. Operation

### 4.1 Flight preparation

Each flight test is performed with utmost precaution following the mentioned safety procedure which ensures a safe and smooth flight of the quadrotor.

### 4.2 Checklist

1. Double Check LiPo battery voltage using voltmeter
2. Examine the propellers, safety mounts, nuts and screws for any damage
3. Test communication link between the quadrotor and the Ground station
4. Enable safety pilot and check kill switch action before flight
5. Check status LED"s

## 5. Risk reduction

### 5.1 Vehicle status

Two status LEDs allow for a check on certain critical vehicle states. The blinking of a Red LED on the processor board of the Pelican indicates the initialization and calibration of the sensors. Once the sensors are calibrated a green LED blinks rapidly indicating the flight control software is running. In case the battery voltage drops under 9.8 volts a loud tone is emitted, with the beeping becoming faster as the voltage drops.

### 5.2 Shock / Vibration isolation

The Asctec Pelican is built on a carbon fiber frame which has a very high Ultimate Tensile Strength (UTS); thus it can withstand a heavy impact without necking. It is also fitted with soft pads below the arms to cushion impacts.

### 5.3 EMI/RFI Solutions

The magnetometer is very sensitive to EMI, hence it is mounted above all electronics such as IMU and the processors.

#### *Safety*

The quadrotor though autonomous in its flight can also be manually commanded to abort. A safety kill switch mechanism has been developed in order to attain this feature. The Pelican has a built in termination system due to which, the vehicle lands the moment the transmitter falls out of range. This feature is used for flight termination via a kill switch which shuts the transmitter off and hence causes the vehicle to descend.

The IFOR is equipped with landing gear designed in a manner to deflect shock from the electronic system. The propellers are also covered, which ensures safety to both bystanders and the vehicle in case of a mishap.

The ON/OFF switch on board is designed active low, so if for some reason the mechanical switch breaks or loses connection the vehicle will remain ON. However this mechanism is overridden by the safety kill switch.

## Testing

<b>Device / Routine</b>	<b>Testing</b>
<b>HOKUYO LIDAR</b>	<b>Tested while running the intelligence software.</b>
<b>SLAM</b>	<b>Real time execution and experimental Determination of localization accuracy</b>
<b>Cameras</b>	<b>Real time execution and experimental Determination of localization accuracy.</b>
<b>Drift Control</b>	<b>Onboard as well off board testing for suitability to tuning</b>

## Conclusion

We have designed IFOR to be a fully autonomous quadrotor that would be able to successfully accomplish the tasks of the IARC. The IFOR system comprises of Simultaneous Localization and Mapping which has been optimized for real-time localization, drift control using simple PID controllers and a detailed set of Intelligence algorithms. The navigation of the quadrotor is handled by the path planning module ensuring that indoor environments can be explored regardless of the presence of unknown obstacles. Finally, image processing enables the quadrotor to scan for patterns, edges and symbols and make corresponding control outputs through a master program in order to guide the vehicle to its target.

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