Autonomous Quadrotor for the 2015 International Aerial Robotics Competition

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ABSTRACT

This paper describe the technical details of an autonomous quadrotor developed by Temasek Polytechnic robotics and automation team(TPRAC) to take part in 2015 International Aerial Robotics Competition(IARC). The unmanned aerial vehicle(UAV) is capable of autonomous navigation in an indoor environment without the help of GPS or large external physical point of reference. It can also demonstrate target identification of static and moving objects at airborne. Using sensors, controllers and mechanical system from current technology, we put together an UAV with the aim of fulfilling the tasks required of competition.

1. INTRODUCTION

2015 International Aerial Robotics Competition is the second year for mission 7. It will challenge teams to demonstrate three new behaviors that have never been attempted in any of the past six IARC missions. First, "interaction between aerial robots and moving objects (specifically, autonomous ground robots). Second, navigation in a sterile environment with no external navigation aids such as GPS or large stationary points of reference such as walls. Third, interaction between competing autonomous air vehicles. [1]

1.1 Problem Statement

The objective of IARC 7th mission is to develop an aerial vehicle that can track and interact with random moving ground robots. UAV must able to plan and herd ground robots toward a common direction of the competition arena. Navigation of the UAV will have to be done without use of GPS, obvious physical cues and any other external navigation aids. Second phase of the mission will require the task to be carried out together with multiple aerial robots. UAV needs to be able to avoid other moving aerial robots while executing its mission.

1.2 Conceptual Approach

The TPRAC team adopted a three-tier layered software approach to control the UAV flight. The lowest level module is a commercially off the shelf flight controller that provides the basic control of the four propellers just like an ordinary RC controlled quadcopter. This layer listens to the basic RC commands; namely pitch, roll, yaw and thrust respectively and keep the UAV in the air.

The middle layer module consists of multiple PID controlled loops that maintain the height, and velocity of the UAV. In doing so, it reads the height from a laser scanner that also double up as an obstacle avoidance sensor and an IMU that provides heading and speed information. This layer executes higher level commands that control the UAV flight and generates MAVLINK compatible messages to be sent to the flight controller. The module also constantly looks out for obstacle that is in the way of the flight and pause or detour if necessary to avoid collision. In addition there is a vision system module that analyses the images from three video cameras for target recognition and tracking purposes.

The top-most layer is the master control loop that integrates all the sensors inputs and generates a flight plan for the UAV to complete its mission. The master control module constantly communicates with the vision system module to determine the locations of the ground robots in sight. It identifies the target ground robot among those in sight basing on the ground robots' path of movements and distances. Once a target is identified, it generates a flight plan towards the targeted robot, lands at a location where the targeted robot is predicted to pass through and force the targeted robot to change direction towards the green line end of the arena.

Given that the mission time is only ten minutes and that the arena is huge, the strategy is to focus on the ground robots that have highest chance of crossing the green line. Three ground robots have been identified and targeted right from the beginning as shown in Figure 1. As soon as the UAV take off, it flies about 3 to 4m away from the green line and look out for the targeted ground robots in the order of A, B, and C and attempts to herd them towards the green line. In the event that there is still time after herding off the first three ground robots, the UAV will continue with other ground robots in sight.

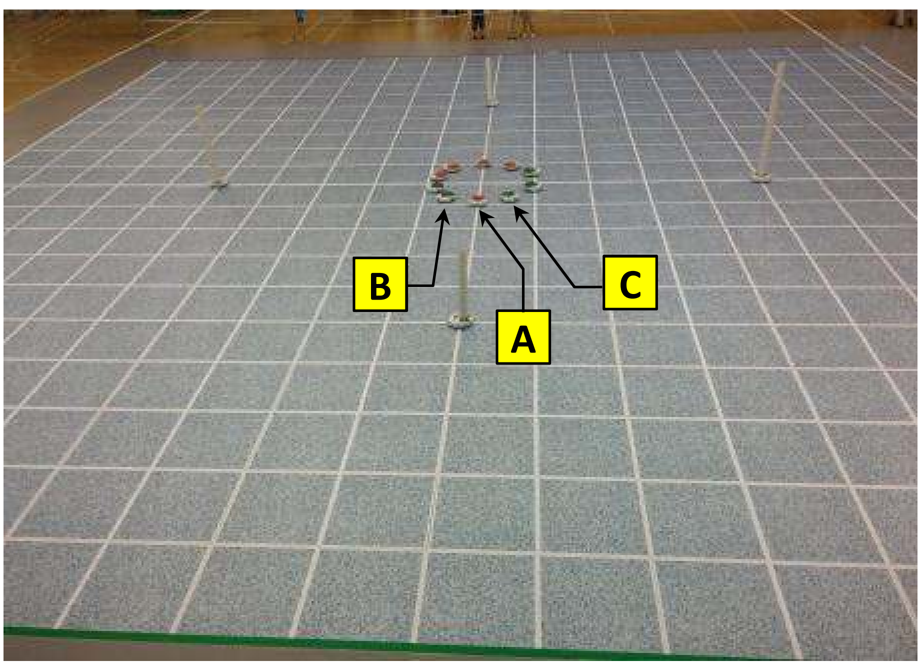

Figure 1. Target robots that UAV will focus

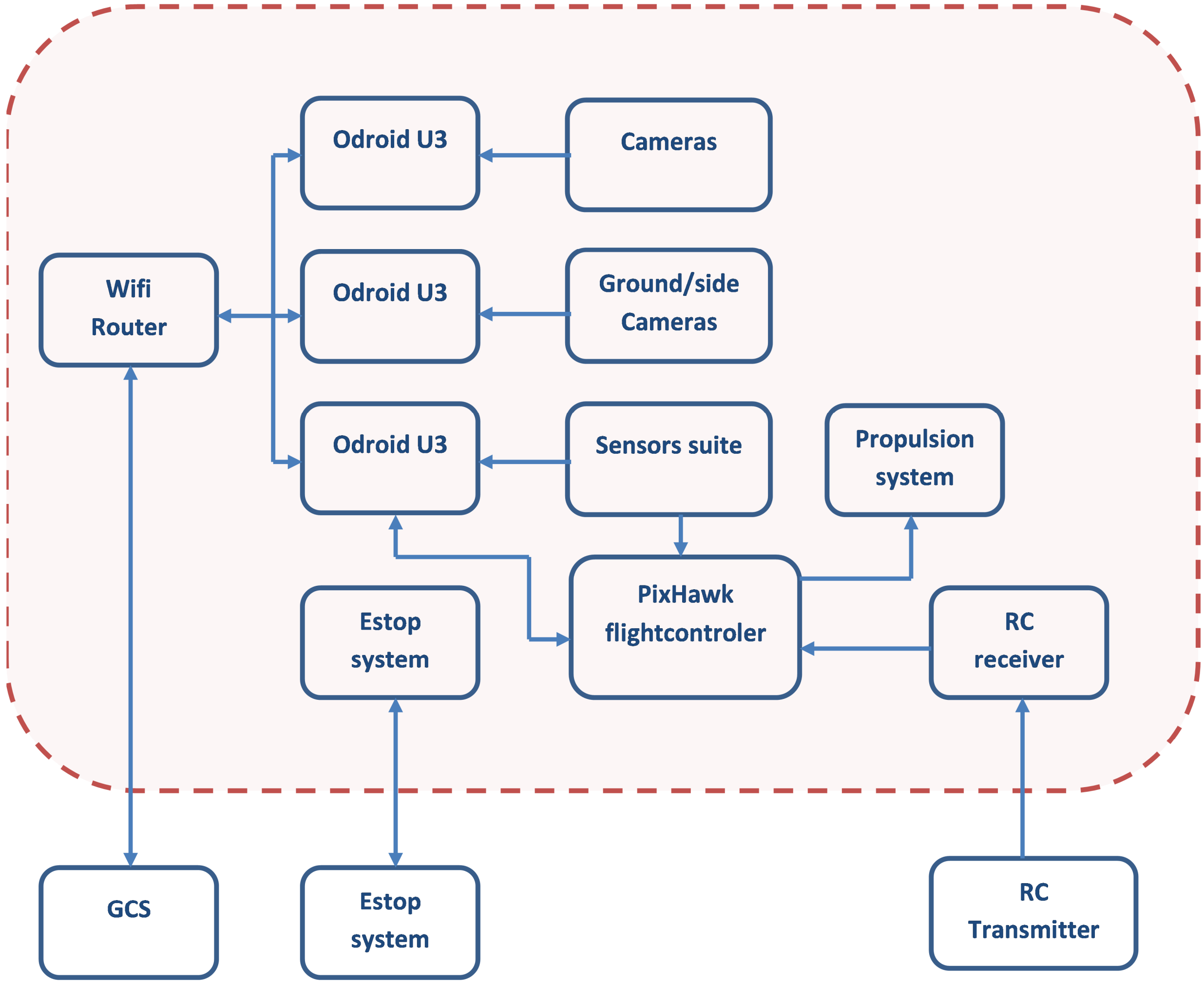

Figure 2. Overall system architecture

2. AIR VEHICLE

UAV was constructed using the mixture of carbon fiber and aluminum frame. Propeller guards are added to the end of the propeller blades for safety. Shock absorbent landing gears are made of flexible cable ties to ensure further safety. Three Odroid U3's and a flight controller are the main control systems on the UAV. Sensors suites include cameras, CMUcam5 Pixy, optical flow sensor and Hokuyo laser range finder. Two estop circuit boards are used to cut the power to UAV in case of emergency.

2.1 Propulsion and Lift

2.2.1 Hardware System

The UAV is lifted by four, 12x4 carbon fibre, two-blade propellers mounted on T-Motor MN3510-13 (700KV, 555W) navigator series brushless DC motors, which distribute symmetrically at the end of four 10.5" arms (see figure 2a). 4 T-Motor ESC's control the speed of motors and deliver maximum current up to 40A each. The overall weight of the UAV is about

4.1 kg with the flight time of about 10 min. The two bladed propellers instead of three bladed propellers were chosen since the overall diameter of the UAV is not a main concern so that the efficiency can be relatively high to ensure that the battery power is sufficient enough to achieve a full flight.

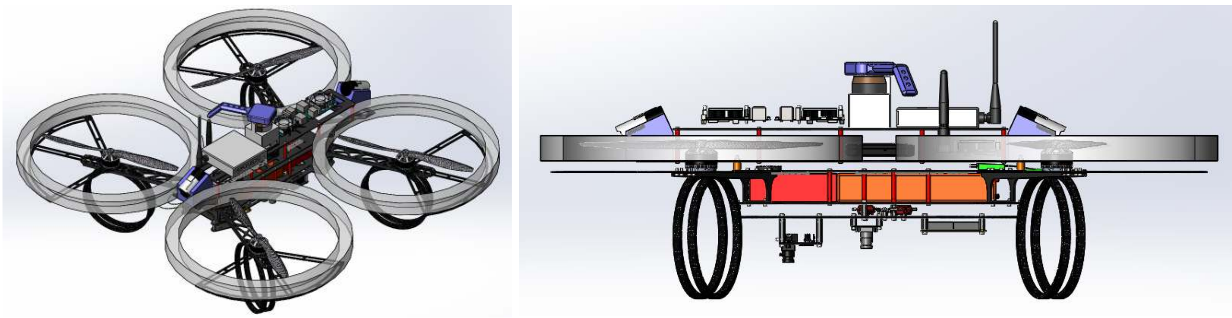

Figure 3. UAV 3D model isometric and left views

2.2.1 Propulsion and Lift Calculation

The propulsion and lift characteristics were simulated in the beginning of design, as shown in figure 2b. The UAV can be powered and driven by the combinations of 4S LiPo batteries with 13" propellers or 5S LiPo with 12" propellers. This provides the design flexibility of various UAV configurations with different component availability to cater for different needs of test or flight.

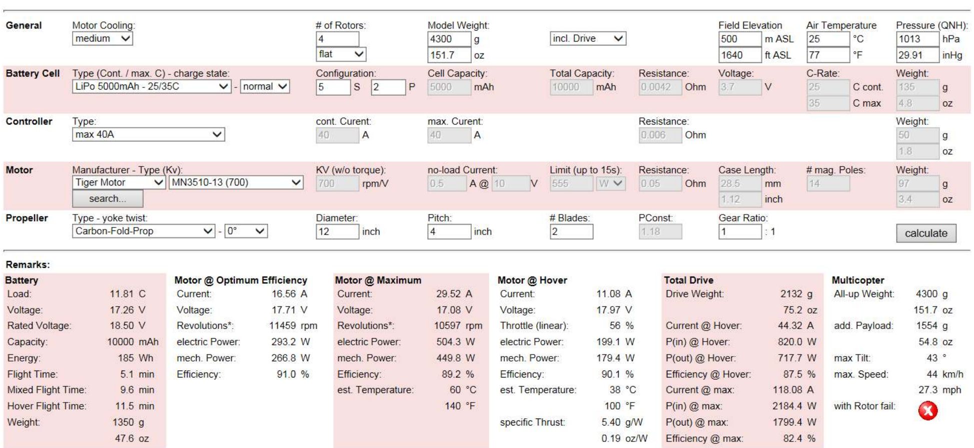

Figure 4. UAV propulsion and lift calculation

2.2.1 Speed and Motion Control

As shown in figure 2c, each opposite pair of motors is spinning in opposite directions. This allows the copter to turn (Yaw) right or left by speeding up one pair and slowing the other pair of motors. Horizontal motion is accomplished by speeding up motors (increasing thrust) on one side and reducing it on the other. This causes the copter to tilt (Roll or Pitch) in the desired direction of motion and thrust is re-equalized. The angle of the copter is generally representative of its speed in that direction. To hover the copter, it needs to compensate for disturbances (gusts of wind) by tilting automatically against the direction of the disturbance. In order to accomplish this, the copter has electronic "gyros" which sense level in 3 dimensions. In addition, they also have electronic "accelerometers" which sense displacement in 3 dimensions. Altitude control or change is accomplished by speeding up or slowing down all motors at the same time. In short, we can control the attitude of the UAV by adjusting the rotational speed of the four motors

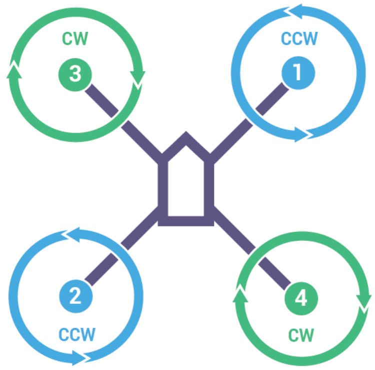

Figure 5. Quad motor order

2.2 Guidance, Navigation and Control

2.2.1 Stability Augmentation System

In order to jump start the development, we decided to purchase off the shelf flight controller which uses the popular open source ardupilot/APM flight control software. Figure 3 taken from ardupilot development website [2] describe the PID loops that helps to maintain the UAV in stabilize mode. The PID parameters were tuned when all the payload and structure were mounted to ensure optimum stability control.

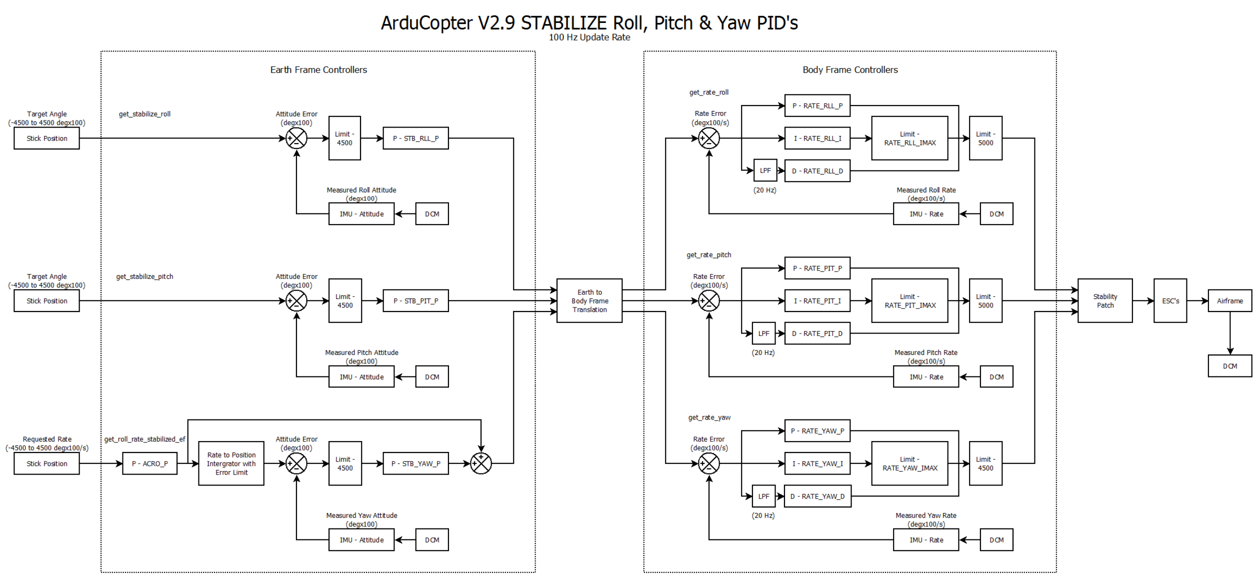

Figure 6. Ardupilot stability system

2.2.2 Navigation

With the constraints of indoor environment and without large physically feature points, the team relies heavily on optical flow sensor for localization and vision system to keep it within the arena.

Using dead reckoning technique, the optical flow sensor is used to estimate the current location of the UAV. As dead reckoning can have large cumulative error over time, vision cameras are used to augment the navigation preventing it from flying out of the arena. Cameras mounted on the UAV double up to feedback position of the UAV relative to the boundary. The periodical reading of the camera data will be used to correct the drift in the odometry data provided by the optical flow

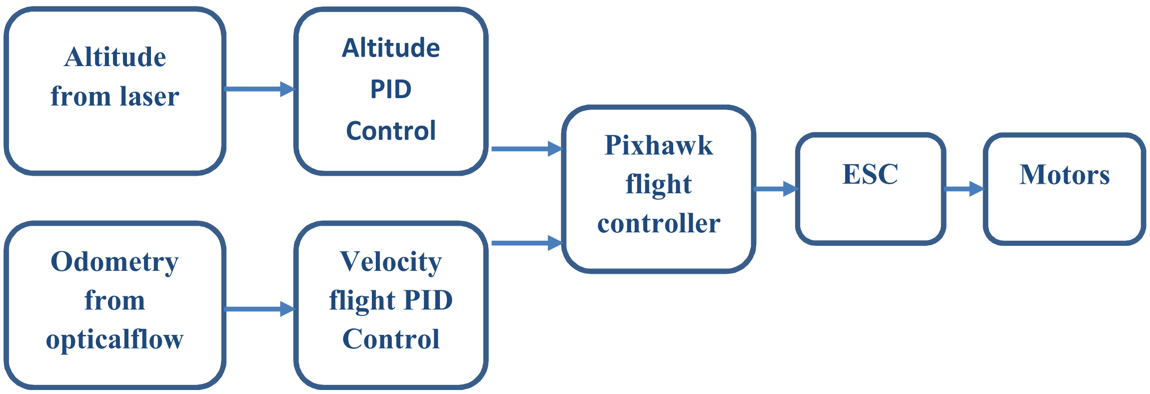

Figure 7. Control system architecture

2.3 Flight Termination System

There are two ways of manual pilot to take over autopilot in case of the air vehicle become unstable and become a threat to people's safety. First, operator can override the flight control by simply flipping a toggle switch on the RC controller. Upon detecting the change in value of the channel, U3 returns the flight control backs to the RC transmitter. Second, there will be another dedicated RC channel connected to kill switch module that recommended by the IARC committee. If the kill switch module can't detect the valid pulse from the RC receiver, the power to the propulsion system will be cut as a last resort to stop the run away air vehicle.

3. PAYLOAD

3.1 Sensor Suite

3.1.1 Navigation and Control Sensors

The UAV uses build in aerometer in the flight controller and an external compass for the primary stabilization control. It uses the px4flow optical flow sensor and Hokuyo laser range finder for odometry and altitude information.

Figure 8a. External compass

Figure 8b. Px4Flow

Figure 8c. Hokuyo Laser range finder

3.1.2 Mission Sensors

The UAV uses two Microsoft LifeCam Studio 1080p HD Webcam cameras and one Pixy CMUCam5 camera. One Microsoft camera is mounted on the side of the UAV and is intended to detect and estimate the distance and orientation of the UAV relative to the boundary of the arena. This is to aid the UAV in localizing and navigation around the competition arena. The other Microsoft camera is mounted at the front of the UAV to detect and track the ground targets and to locate the boundaries of the arena. The video outputs from both Microsoft cameras are processed by the onboard odroid U3 using the open-source computer vision library OpenCV and the detections are sent to the master controller via ROS for path planning and decision making. In addition, one Pixy CMUCam5 camera is mounted at the bottom of the UAV for high-rate detection and tracking of ground targets in close proximity to the UAV. This is to cue the UAV to descend to herd the ground target.

Figure 9a. Microsoft LifeCam HD Webcam

Figure 9b. Pixy CMUCam5

3.1.3 Threat Avoidance Sensors

The Hokuyo laser range finder that was used for altitude reading is used again as an obstacle detection sensor. Upon detection of objects in the path of the intended flight direction, flight control will stop the flight command immediately and hover on the spot.

3.2 Communications

The PixHawk flight controller receive RC signal via 2.4Ghz communication media. The data and command flow through the whole UAV system lies on the ROS backbone using local area network link. All sensor data are published by the direct embedded system that drives them and subscribed by systems that needs them. The Estop circuit works on the 2.4Ghz bandwidth which has a separated transmitter-receiver pairing. Ground control station are connected to the ROS system via the same network wirelessly via the router on board the UAV.

3.3 Power Management System

The air vehicle is powered by 2 five-cell 5000 mAh LiPo batteries with nominal voltage of 18.5 Volts. Each battery goes through an individual estop switch first, and then join a DPST mechanical switch together after which one battery powers motor 1, motor 3 and APM/PixHawk Power Module while the other powers motor 2, motor 4 and 3.3V output DC-DC converter.

Figure 10 shows the detailed arrangement of power management. It is designed in such a way that power consumption balance is considered, it is compatible for both 4S and 5S LiPo batteries and safety and flexibility is catered as well. The flight controller will monitor the battery voltage/current and switch to auto landing mode if the battery voltage falls below certain threshold.

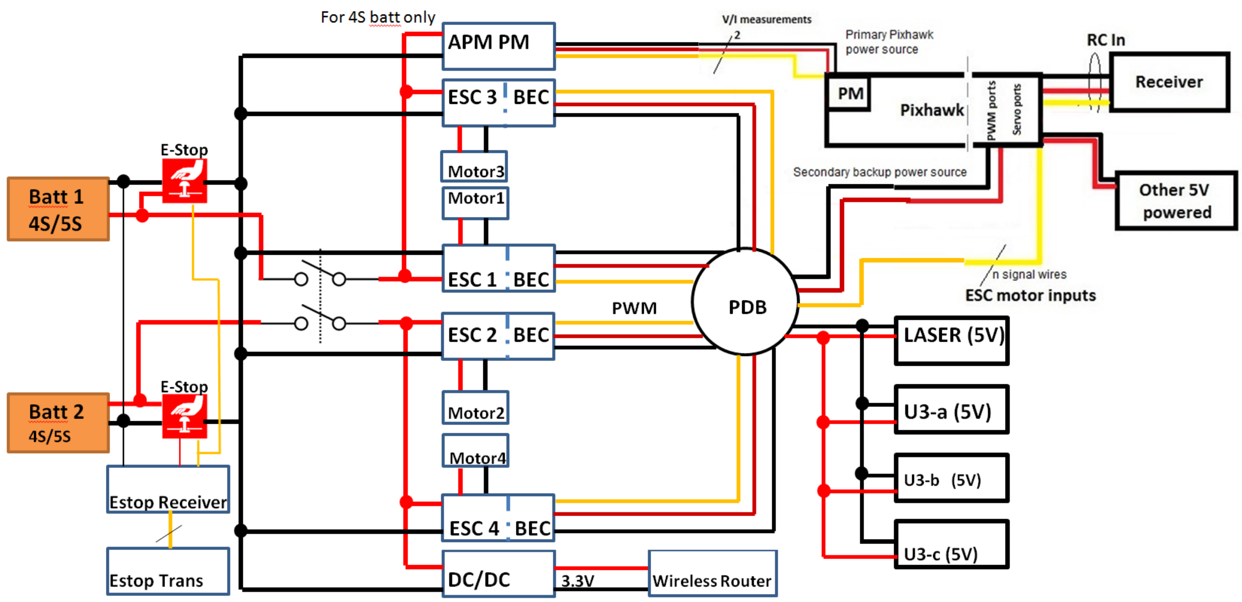

Figure 10. Power distribution

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4. OPERATIONS

4.1 Flight Preparation

The UAV flight preparation checklist is as follows:

1. Check battery voltage level.

2. Connect the power circuit.
3. Turn on the transmitter and termination system.
4. Power up the UAV
5. Connect to the ground control station
6. Activate the pre-arm check.
7. Set UAV to autonomous mode.

4.2 Man/Machine Interface

There are three man/machine interface methods implemented for the UAV. The highest priority is the termination system which is required to maintain a handshake throughout the entire flight of the UAV. Turning it off will shut off the power to the propulsion system. The second interface is transmitter which can switch the UAV from autonomous mode and manual flight mode. During manual flight mode, transmitter will take over the flight control of the UAV. The third interface is the GCS. GCS can change flight mode and issue flight commands to the UAC. It also displays flight information on the screen.

5. RISK REDUCTION

5.1 Vehicle Status

The air vehicle will broadcast its operating status via the telemetry module to the ground control unit using the mavlink protocol. The ground control unit will display the essential flight info such as attitude, altitude, heading, velocity and video stream from the on board camera.

The ground control station can also subscribe to any status topic published by the U3s on board the UAV for live status feedback.

5.1.1 Shock/Vibration Isolation

The UAV is separated into 2 parts: a "dirty" section and a "clean" section. Most electronics including flight cameras, Laser, U3's, flight controller, router, etc. are located on the "clean" part of the frame and are isolated from the "dirty" motor/prop section by 4 pieces of Orange RC Bobbins. Besides, key components like FC and optical flow sensor are mounted onto thick vibration foam tapes to further reduce vibrations. Reducing vibrations to the FC results in smoother flight performance. Reducing vibrations to the cameras results in smoother video quality. As known, vibrations to the FC are the equivalent of noise and static in the camera video signal. Finding a way to decouple the vibrations coming from the motors/props to cameras and the FC is one of the most important aspects of this platform.

Figure 11. Orange rc bobbins

Landing gear is so important to absorb the shock when landing and to protect the UAV when crashing. A very unique land gear is custom developed to meet those requirements. The landing gears are made of heavy duty nylon 66 cable ties. They are creatively designed and developed in such a way that they are strong enough to support the UAV while flexible enough to absorb the shock when landing or even crashing. During test, they helped to save the UAV when crashing down from up to 10 meters height several times. The unique and innovative design of the landing gear is one of the most compelling aspects of the platform.

Figure 12. Landing gear

5.1.2 EMI/RFI Solutions

During test, it was noticed that the Yaw of UAV tended to drift by itself. And it was suspected that there was something to do with the inference to the Flight Controller. In order to minimize the EMI, all ESC's were shifted away from the center of UAV to the four arms of the UAV frame. Besides, other high current wirings were also routed away from FC as far as possible. Furthermore, a layer of aluminum foil was put below the frame plate on which FC is mounted, with grounding connection to the foil.

There are 2 receivers on the UAV, one for RC control and the other for estop control. To minimize the RFI, they were mounted far away in different locations.

5.2 Safety

To prevent people from being injured by the fast spinning razor sharp propellers, four propeller guards are mounted around the side of the propellers. These prop guards can be used with propellers up to 13". Different colors are chosen to indicate the head or tail of the UAV. Throughout the testing, the air vehicle is confined in a safety cell surround by safety net and no one is allowed to go in the safety cell while the air vehicle is armed

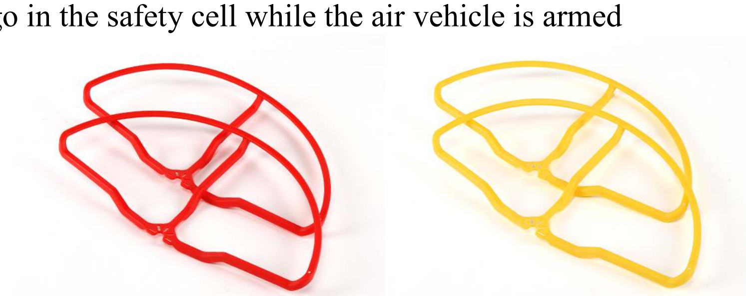

Figure 13. Prop guards

5.3 Testing

The on board flight controller has a build in self-test system and the flight controller will not take off unless all the self-test is passed. The self-test will test on the functionality of:

1. IMU

2. Compass
3. RC channel
4. Optical flow
5. Laser Range finder
6. High level auto-pilot system

6. CONCLUSION

This paper has presented that TPRAC has developed an UAV which is capable of autonomous navigating in an indoor environment without large physical feature. Using the optical flow sensor and vision recognition data, it is able to maneuver within the competition arena. With the streaming video from the camera mounted, computer vision is able to identify the target and send tracking path information to the UAV. UAV is able to track the random moving ground vehicles and interacting with it. The flight controller module on board uses the ROS platform subscribes to various sensors information for low level control. It takes in command published by the master U3 for flight path and capable of navigating in the arena safely.

With the capability of the UAV, we developed a possible solution to IARC mission 7. TPRAC team will like to thank Temasek Polytechnic for the support in manpower and funding for the project.

7. REFERENCES

[1] IARC, Official Rules for the International Aerial Robotics Competition Mission 7, http://www.aerialroboticscompetition.org/rules.php

[2] Leonard, T, ArduCopter 2.9 PID Loops for STABILIZE, ACRO and ALT_HOLD, http://dev.ardupilot.com/wiki/apmcopter-programming-attitude-control-2/