Autonomous Quadrotor for the 2015 IARC by Team Elikos

Andre Phu-Van Nguyen, Alexandre Borowczyk, Antoine Mignon, Antonio Sanniravong

Team Elikos - Polytechnique Montréal, Canada

ABSTRACT

The aim of this paper is to present a system design for a fully autonomous micro-aerial vehicle capable of demonstrating behavior for the completion of the IARC mission 7. While outdoor navigation methods have been extensively researched and demonstrated in the past, the system we hereby present shall be able to demonstrate indoor navigation capabilities with the use of GNC sensors, a LIDAR, and cameras with a heavy emphasis on computer vision for localization.

INTRODUCTION

Statement of the problem

Mission 7a of the International Aerial Robotics Competition involves a sheep and shepherd problem wherein the team's aerial robot must herd terrestrial robots, hereinafter referred to as *targets*, by creating a change in the magnetic field on top of the targets or by triggering the bump sensor on their front side. The targets must be herded towards a green line within a 20x20 meter arena while dodging obstacle robots made of large PVC piping roaming the arena in a circular motion. Mission completion is achieved when at least 7 targets which have been interacted with cross the green line.

Yearly Milestones

Team Elikos entered operations in November of 2013 with the initial plan of getting an aerial platform up and running using off the shelf products for IARC 2014. The result was a Turnigy Talon V2 quadrotor frame modified to hold cameras, an embedded computer and some wireless communication peripherals. The system was capable of relative position estimation through optical flow and was controlled by an automated ground station

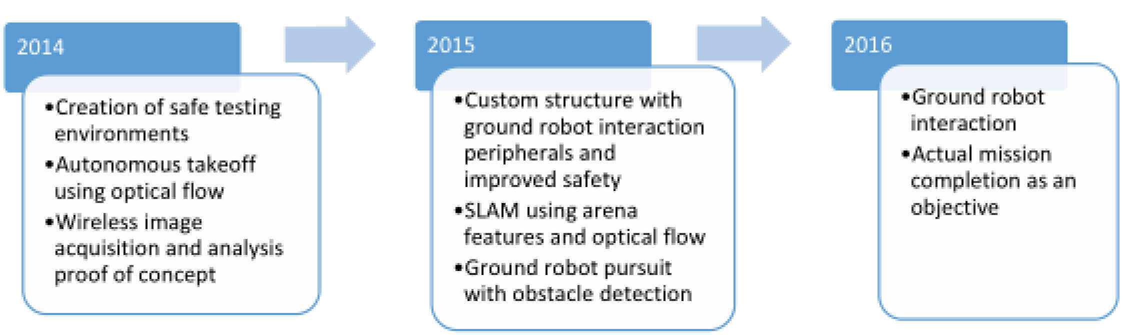

Figure 1 annual milestone plan

Figure 1 shows the annual milestone plan we presented at IARC 2014, following this plan we now present a new quadrotor platform with an improved positioning system and capable of target pursuit and obstacle detection.

Conceptual approach

Before outlining the details of our latest solution to mission 7, we must first go through the set of assumptions we are making about the competition. Though we do not claim them as being absolute facts, they are what we used to guide us in building a consistent solution for mission 7a.

Vehicle movement within the arena

Whether it be to land in front of a target to trigger the bump sensor or to get close with a magnet, having the vehicle make precise vertical movements is an inevitable part of the competition. The corollary to this statement is that the system must have valid position or velocity estimation at all times, including when very close to the ground to allow for stable takeoff. Although it could be possible to develop a novel vehicle design with a very low hanging magnet, we have not explored this option due to the potential instability of having an unmodeled pendulum effect within the control system.

Limitations of optical flow integration over time

Position estimation from optical flow integration can quickly diverge from ground truth since at every iteration small errors are added to the estimation. However, this can be mitigated by fusing the estimation in a Kalman filter with a secondary positioning system.

The last 30 centimeters

Another limitation of our optical flow approach based on the px4flow sensor was that the measurements were nearly useless when close to the ground. Since the lens of the camera is fixed focus and the Maxbotix sonar onboard the px4flow has a minimum range of 30 cm, there is a dead zone where the landing area and the targets reside. The dead zone is further aggravated by the ground effect which can quickly make the vehicle drift with no means of knowing so [1] [2]. We dub this “the last 30 centimeters problem”.

Competition area sterility

The competition rules indicate that the spirit of the competition is to develop navigation tools which can function without external navigation aids such as a GNSS or large stationary points of reference. To compensate for this, the arena is filled with a 1x1 meter grid presumably to help in the development of visual odometry. We posit that the grid is merely a red herring and that the most valuable source of visual cues for positioning comes from the environment directly outside of the arena bounds, the competition area. A direct consequence of having the competition indoors is the obvious presence of a ceiling and four walls which can be rich in robust visual features for tracking and mapping, more so than the competition arena which is only guaranteed to contain weaker high frequency features. This is based on the assumption that this year the North American venue will follow the Asia/Pacific venue by laying down a textured surface before building the arena lines.

Our solution

The year's vehicle has a simpler frame machined out of a single plate of carbon fiber capable of supporting up to four cameras and an onboard computer based on an Intel i5 processor. Our previous vehicle was a victim of the last 30 centimeters problem and to this effect, we augmented our optical flow system by employing the Multi-Camera Parallel Tracking and Mapping (MCPTAM) algorithm for pose estimation and we add an infrared range finder as an altimeter.

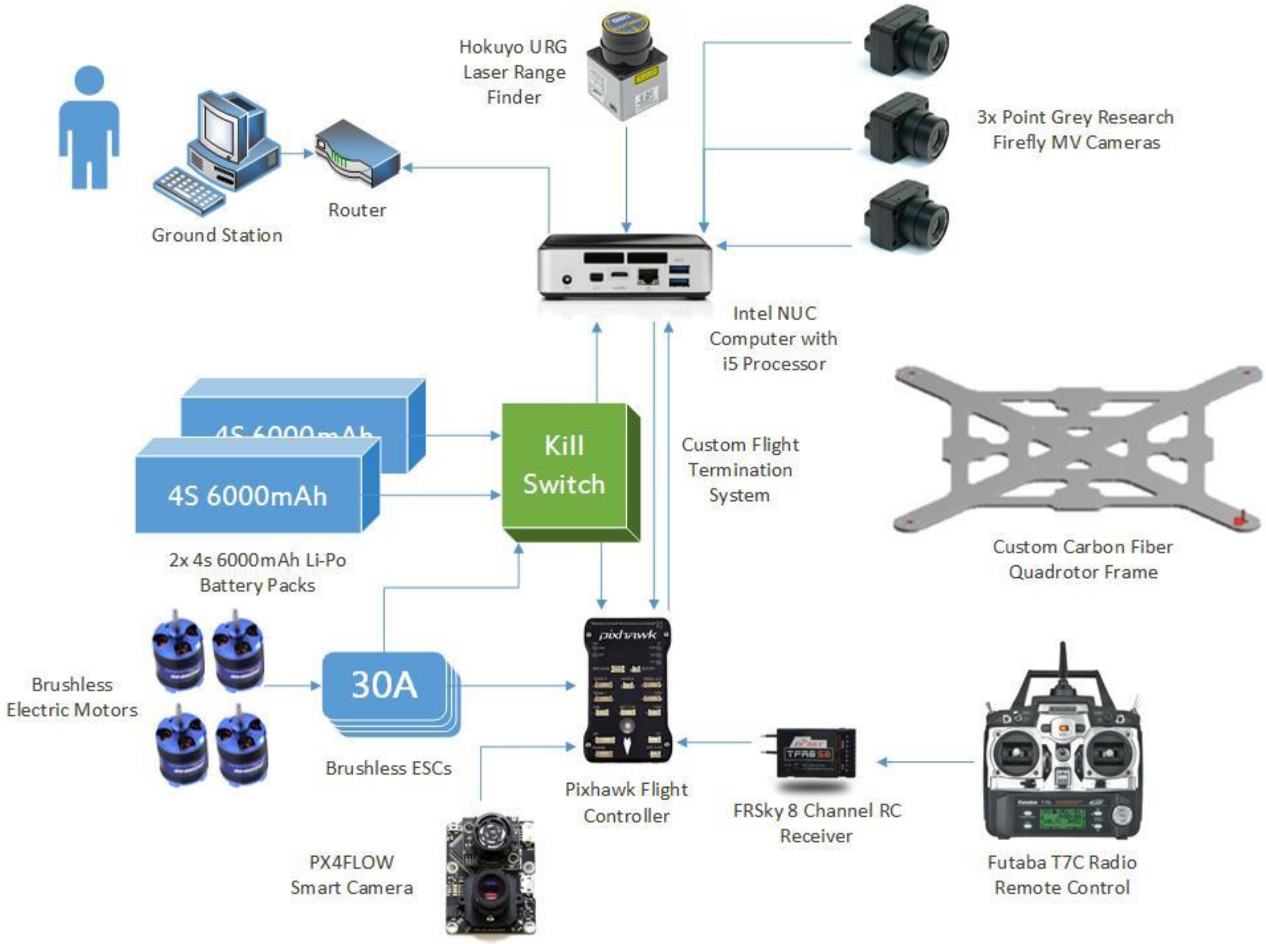

Figure 1 Overall system diagram

The vehicle now carries a target interaction payload in the shape of a small circular Halbach array of neodymium magnets as well as an obstacle avoidance sensor in the form of a laser scanner

AIR VEHICLE

Mechanical design and propulsion systems

This year's objectives being more oriented towards navigation and control, we needed to accommodate the mounting of more cameras and a larger computation platform. A quadrotor design was chosen again because of its mechanical simplicity and available documentation. We chose to make a frame out of a single, CNC machined carbon fiber panel to support our components. The final design also includes 3D printed parts to help mounting cameras and magnets for target interaction. The quadrotor is lifted by four 12" nylon-fiberglass composite propellers from APC propellers driven by electric brushless motors each powered by an electronic speed controller.

Guidance Navigation and Control

Stability augmentation

This year, we decided to consider the inflow velocity and the ground effect as stability issues. As the mission objectives requires our quadrotor to often operate close to the ground, the ground effect can have a significant effect on the quadrotor stability during ground operation. We also found that inflow velocity has a significant effect on performance [3] and verified its impact on our Simulink model. With our work, we aimed to compensate for both effects. For this purpose we developed and implemented on the open source Pixhawk autopilot a nonlinear control law called integral backstepping [4] instead of the position and attitude controller we used last year.

The integral backstepping allows us to account for many nonlinear dynamics such as inflow velocity and ground effect in order to obtain better stability performances during operation. This technique requires that the desired controlled system can be decomposed as a cascaded sub-system structure. A quadrotor is constituted of three interconnected sub-systems [5] : the under actuated sub-system (the x-axis, y-axis, roll and pitch states), the fully actuated sub-system (the z-axis and yaw states) and the propeller sub-system which deals with the aero and engine dynamics

The integral backstepping controller stabilizes the most-internal sub-system and backs-out recursively up to the global system input (radio or off board commands). The stabilization process is done with a nonlinear Lyapunov methodology. In the quadrotor case, this technique is called integral backstepping as the systems are connected through a series integrators. The weakness of this technique is that it relies on a high quality model of our system as it is explicitly used in the control algorithm. The explicit use of the quadrotor model in a nonlinear controller allows a broader flight envelope as there isn't a linearization domain restriction but requires a more accurate identification of system parameters.

In a near future, our team will work on an adaptive algorithm to compensate this weakness. This algorithm will be based on the optimal control theory and will be used to adapt our integral backstepping gains in flight operation.

Navigation

Navigation is done through the use of three key modules: the px4flow camera, two Point Grey Firefly MV cameras combined to run MCPTAM and the TeraRanger One infrared time of flight range finder.

Our primary 6 degrees of freedom pose (DOF) estimation system is provided by the Multi-Camera Parallel Tracking and Mapping algorithm. The original PTAM algorithm, as the name suggests runs tracking and mapping in two parallel threads. Mapping is done by extracting features from key frames and running them through bundle adjustment and an epipolar search. Tracking is performed by projecting map points onto an image according to a prior pose estimate, after an initial coarse pose estimate, the estimate is further refined using a larger set of fine features [6]. In the case of a loss of tracking due to sudden high velocity movements or obstruction of view, PTAM is capable of regaining tracking. Since we would like to maximise tracking quality, we employ

MCPTAM which differs from PTAM in many ways. The main features we are interested in are the larger field of view (FOV) provided by having multiple cameras and the possibility of resolving the real world scale when these cameras have overlapping FOV, which in turn allows us to skip the IMU fusion step to scale pose data into the world frame [7]. Furthermore, by pointing the cameras outwards, it should be possible to keep tracking features on the horizon, even when the vehicle is landed.

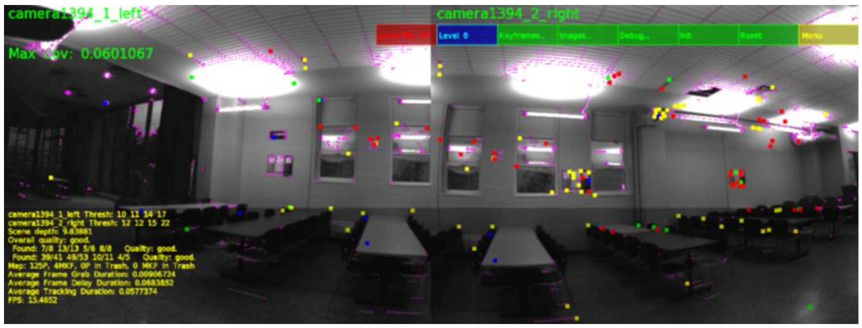

Figure 2 - MCPTAM example

Our secondary positioning system consists of the px4flow smart camera allows for optical flow calculations [8] which are then integrated over time to do position estimation in the XY-plane while the integrated sonar can be used for local altitude estimation. The TeraRanger One range finder serves as a primary altimeter as its performance surpasses the sonar onboard the px4flow.

All the data sources are finally fused in a Kalman filter to estimate the local position of the quadrotor and since all data is published with a covariance matrix or similar quality indicator only acceptable data will be fused into the filter.

Control System Architecture

This year control system architecture is very similar to the last year architecture. The only change is the replacement of the previous control loop (position and attitude controller) by our homemade integral backstepping controller. The Pixhawk's software main loop still runs at a frequency of 500 Hz. In the following diagram each sector represents interdependent internal process. The closer a process is to the center, the higher is its priority [7]. As we want to ensure uncompromised control on the vehicle's stability we set our integral backstepping controller process at a high priority.

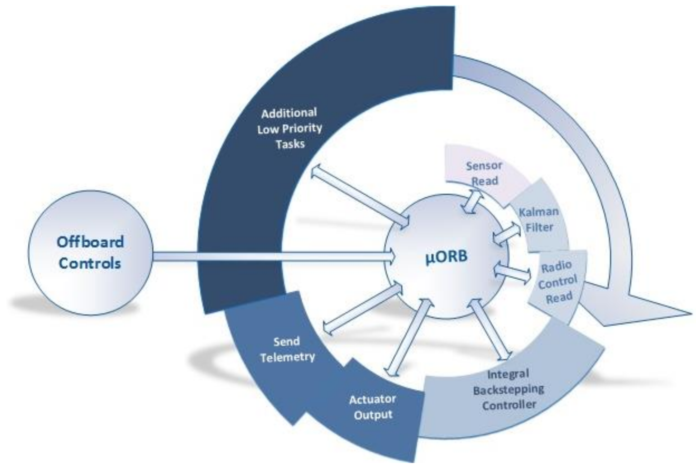

Figure 3 Control system architecture

Flight Termination System

At IARC2014 we presented a killswitch heavily based off the reference design (SOURCE) which killed the power to the entire quadrotor, this could lead to potential problems as our onboard computer would be hard reset without having the time to exit its running tasks and shutdown cleanly. Our new design now cuts off power solely to our propulsion system and includes an integrated RF module so as to reduce the complexity, weight and size of our system. The operating logic however, remains unchanged and similar to the reference design.

RF module

The Linx Technologies RF module used for the kill switch includes a receiver, a decoder and a handheld remote control (transmitter). The remote control has eight buttons paired to eight data lines on the decoder. With one planned to be use for the termination system (kill switch), we aim to use the seven lines remaining for diverse other purposes (e.g., set or reset the on-board microcomputer, activate indicators of the UAV’s current state, etc.). In addition to the new possibilities the RF module grants us, the latter provides a 128 bit security key, thus enhancing the uniqueness of the transmissions between the transmitter and the UAV and improving the security of our system.

PAYLOAD

Power management

Our system is powered by up to two battery packs containing either 3 or 4 lithium-ion polymer cells each. With this improvement we ensure a ten minutes autonomous flight and benefits of a longer setup period due to an autonomy upped to 15 minutes from 10 minutes.

The batteries power three systems: the propulsion system, the flight controller and sensors system, the onboard micro computer system. The propulsion system is powered through our killswitch to ensure proper power-off when needed. The Pixhawk, the cameras and the lidar are powered through a 5V regulator (LM2678 from Texas Instruments) which is a high efficiency step down regulator and allows for a very low overhead on our board. The Intel micro computer is powered through a 12V flyback regulator and we opted for a commercial power supply with a pinout configuration which allows for a simple integration into our system and easy replacement in case of damage. To protect our core components, we also added a fuse at the input of both regulators to add overcurrent protection.

Sensors

Mission Sensors

While looking at the best solution to interact with the targets, we found an interesting arrangement for magnets. Our constraints are to be as light as possible and avoid magnetic disturbance while optimising the distance and surface between our solution and the target. Because the sensor switches are based on the Hall Effect, we have to maximise the magnetic field as the output voltage of the sensor is almost proportional to it.

We place our neodymium magnets in a special arrangement called the Halbach Array. This array has a rotating pattern which augments the magnetic field on one side while almost cancelling it on the other side. We 3D printed a cylindrical structure to hold neodymium rare-earth magnets with the Halbach array pattern. The 3D printed structure is mounted below the quadcopter. The Figure 2 shows the magnetic flux diagram of a Halbach Array.

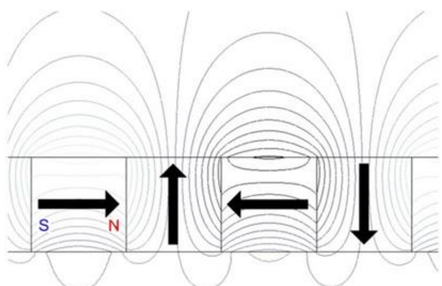

Figure 4 The flux diagram of a Halbach array [9]

Target identification

Detecting target robots consistently is without a doubt one of the most determinative factors in completing the mission. Our previous approach was based on object detection with the use of Haar classifiers. The main challenge we faced with this approach was that training the classifiers was a tedious process that resulted in an inaccurate end product. In fact, in our experience the false positive detection rate was too high for the algorithm to be of any use.

This year, we turned to a simpler and less computer intensive approach which employs HSV (hue, saturation, value) color space filtering and morphological transformation algorithms found in the OpenCV computer vision algorithm library. The main motivation behind this approach is that the target robot markers have distinctive colors and sizes that make them stand out in the arena making it easier to filter out most of the hue and saturation spectrum. The morphological operations then allow the remaining blobs to be filtered out by dissolving the smallest instances that are considered as noise.

With this approach, further optional processing can be made to the detected blobs when possible. For example, when a detected target marker comes close enough for its shape to be properly identified, the robot orientation can be extracted from the blob.

Threat avoidance

In order to detect obstacle robots, we have used a LIDAR sensor, the Hokuyo URG-04LX, which has a maximum measurement distance of 4m and a 240˚ field of view. The first thing to do in obstacle avoidance is to determine which part of the environment is an obstacle, and which part is not. Starting from a 2D plane of the environment given by the laser data, we define an obstacle as a set of points that is forming a convex half-ellipse from laser's point of view with a 4 inch diameter by applying a RANSAC algorithm.

Strategies will have to the implemented to cover the case where the obstacle would find itself under the quadrotor, we hope to simplify this 3D problem into 2D by flying low enough below the smallest obstacle. Since obstacle avoidance is not the only nor the main goal of the mission, we must adapt our avoidance method to fit the main purpose of the mission, that is, to localize, approach and guide ground robots to the green line. We plan to develop a method of local obstacle avoidance through a two-step process where we first compute a path using Vector Field Histogram (VFH) [10] to a goal and feed it to a reactive module which will deform the final path if need be based on the evolution of the local environment. We choose a purely reactive obstacle avoidance scheme, due to the dynamic nature of the competition arena.

OPERATIONS

Flight Preparations

While many automated mechanisms implemented in our flight controller ensure that the most crucial sensor calibrations are checked before each flight, manual verifications are still required to validate these checks and also to verify unmonitored levels and system states. Mechanical integrity is one example of an aspect that cannot be monitored automatically but that represents a great risk for human safety and for the protection of the system components in the event of a heavy impact or a crash. This is even truer with the recent addition of more highly sensitive microelectronic circuits such as the onboard computer and computer vision cameras. The following is a checklist of elements that must be verified, at the very least, once before each extended flight session.

Pre-flight checklist

- Killswitch is functional
- Safety switch is enabled before any manipulation
- Overall mechanical structure is undamaged and propellers spin in the right directions
- Onboard computer, flight controller and peripherals power up and are mounted securely
- Li-Po batteries are sufficiently charged and well fastened
- Battery alarm is connected and functional
- Radio remote control has sufficient battery life
- Radio calibration and presets are correct
- Optical flow and computer vision cameras lenses are focused
- Inertial sensors are calibrated properly (magnetometers, gyroscopes, accelerometers)

- Telemetry is functional

After each flight attempt, the following checks have to be made.

Post-flight checklist

- Battery levels are over the safety threshold
- All component temperatures are within their normal operating temperatures
- Every mount, propeller and screw is properly tightened (especially after a hard landing or a crash).

RISK REDUCTION

EMI/RFI isolation

Last year, our magnetometer had some issues with EMI due to our flight termination system being too close and generating too much noise. To resolve this problem, the frame of the quadrotor was changed to attach the kill switch as far as possible from the magnetometer. We also changed the design of the kill switch from a two layer printed circuit board to a four layer PCB to have a large ground plane and to place all switching regulators on the bottom, away from sensitive electronics. In addition to this, we can also add a sheet of mu-metal right above the kill switch to absorb radiating magnetic fields. All these measures should be enough to make sure we won't have any problems regarding EMI.

Regarding radio frequency interference isolation we opted for an RF module from Linx Technologies which uses a frequency of 315 Mhz to stay away from the 2.4 Ghz band which is the frequency used in Wi-Fi and RC systems. This will make sure nothing interferes with our RF module and causes unwanted shut down of the quadrotor.

Modeling and simulation

Finite element analysis

In order to optimize and validate our custom frame design, we make a static analysis using a finite element software (ANSYS) by importing the final geometry and defining the material as a quasi-isotropic carbon composite. We then determine the failure criteria which are generally based on constraints in the case where we don’t have heavy payloads. Finally we determine the thickness of our frame according to the maximum deformation. Too much deformation can result in bad flight behavior. Figure 5 shows the results of our deformation analysis. As expected, the maximum deformation is only a few millimetres.

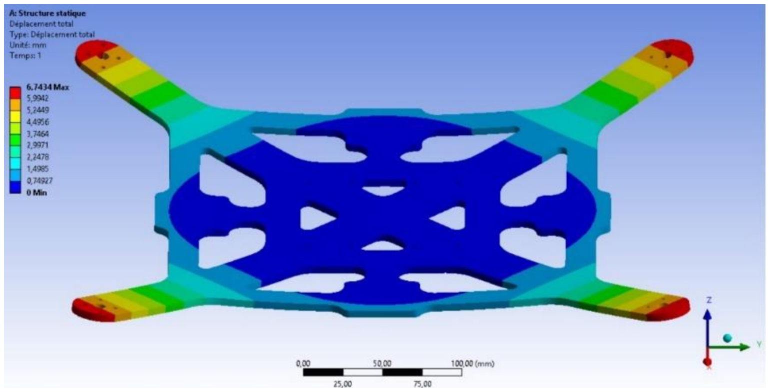

Figure 5 FEA results

Quadrotor's dynamics model

In regards to the control section, we had the objective of developing a nonlinear control law which allows us to compensate for highly nonlinear aerodynamics effects such as the ground effect and the inflow velocity. This required us to develop a high fidelity model of our quadrotor to test and validate the control law implementation as well as compare different controller structure. The model's equations of motion and mechanization equations were first assembled, then implemented in Matlab Simulink. The model is divided in to sub-modules creating structure and facilitating further add-ons and modifications. Among the current sub-modules you will find the 6dof kinematics module which implement the 6 DoF kinematics, the input coupling module which account for the quadrotor motor disposition, the inflow velocity module which computes the effective thrust generated by each propeller and the ground effect module which reproduce the thrust variations due to ground proximity. The Figure 6 illustrate the closed loop Simulink diagram which allows us to develop and tune our controller as well as validate its performance.

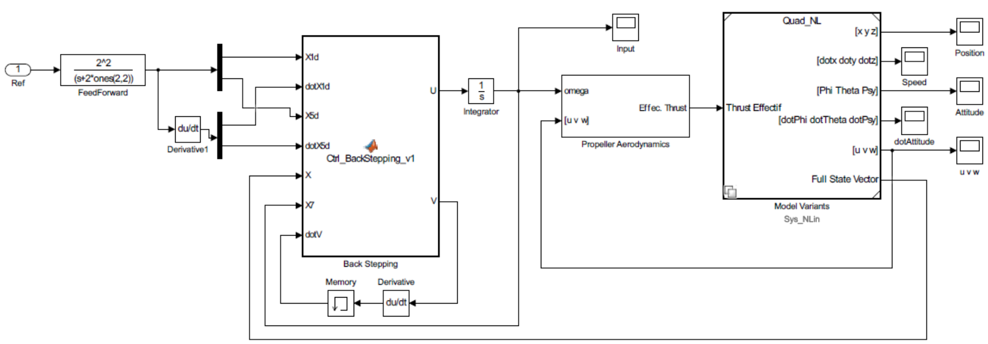

Figure 6- Closed loop Simulink diagram

Although there still missing a good analytical equation for the ground effect as current proposition don't hold up against experimental results but it is possible to approximate the ground effect for a specific quadrotor-propeller configuration from experimental data [5]. As for the inflow velocity, results obtain from our Matlab-Simulink model using a the same propeller data than in [3] paper shows that for a vertical climb speed of 1 m/s the effective thrust is lower by close to 20% versus the expected thrust obtain without accounting for inflow speed. In Figure 7 the effect of the inflow velocity on a closed loop climb maneuver is clearly visible in response speed when compared to traditional model.

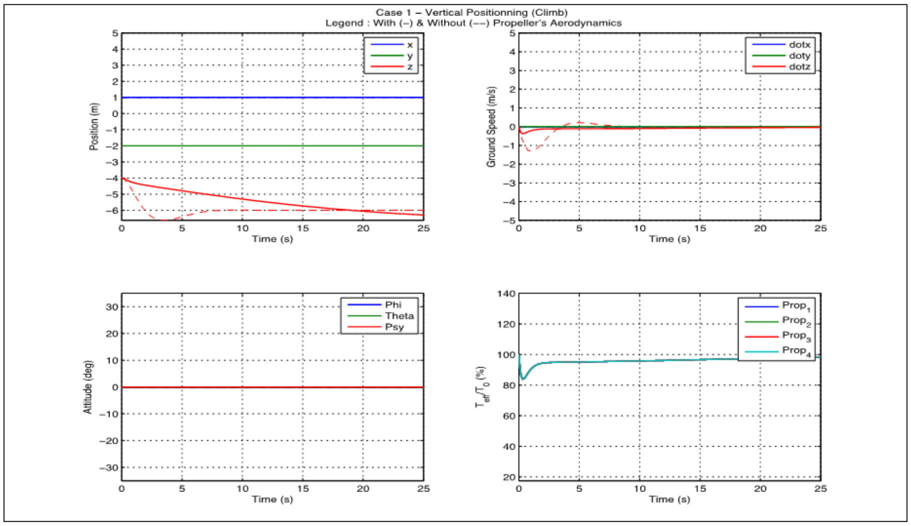

Figure 7 - Induce speed effect on effective thrust

High level AI simulation

In order to plan and predict the outcome of high level routines and strategies, we use the PX4 software-in-the-loop simulation framework where the autopilot firmware modules are run as ROS nodes. Quadrotor dynamics and sensor simulations are managed by Gazebo. In Figure 8 we see an Iris quadrotor mounted with a laser scanner hovering at a 1m altitude to help us understand obstacle avoidance strategies. This environment can also be used to simulate the general competition.

However, our aim in using this simulation environment is not necessarily to have a perfect representation of the physical world but rather to be a visual reference for studying the overall behavioral response of our system. Although high level AI routines were not our main focus for this year, this simulation environment proves itself useful for developing features such as path planning and obstacle avoidance. When the time comes, we expect to add more noise into the simulated sensors to get a more realistic testing environment for our algorithms.

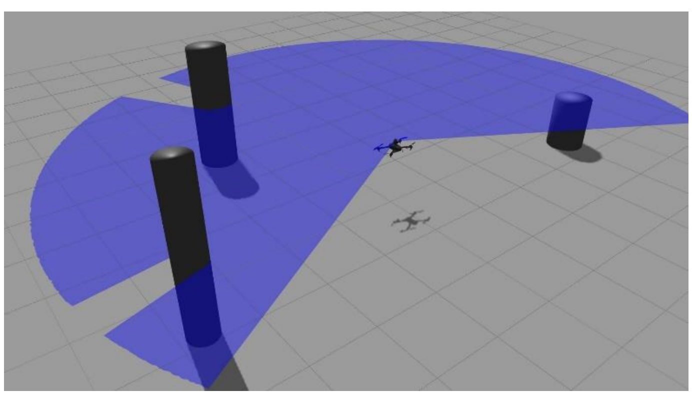

Figure 8 Quadrotor in flight within the Gazebo simulation environment. The jagged edges of the laser scan are due to Gaussian noise being injected in the simulated sensor.

CONCLUSION

The design we showcase for this year's competition features many new improvements, ranging from the frame design to the addition of supplementary onboard processing capabilities, allowing us to implement more reliable and complex algorithms. In addition, we designed and built our new quadrotor with a better understanding of the challenges of mission 7 which we are confident will result in an improved performance.

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