Comb Studio's Autonomous Aircraft for the IARC 2013

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ABSTRACT

This paper describes the details of an autonomous aircraft capable of exploring cluttered indoor areas without relying on external navigational aids. A Simultaneous Localization and Mapping (SLAM) algorithm is used to fuse information from a laser range sensor, an inertial measurement unit to provide relative position, velocity, and attitude information. Via front-facing camera, the doorplate can be identified. Thus, the aircraft could enter a specified room, find the flash disk, and put down the fake one. The vehicle is intended to be *Beihang University Comb Studio*'s entry for the International Aerial Robotics Competition in 2013.

1. INTRODUCTION

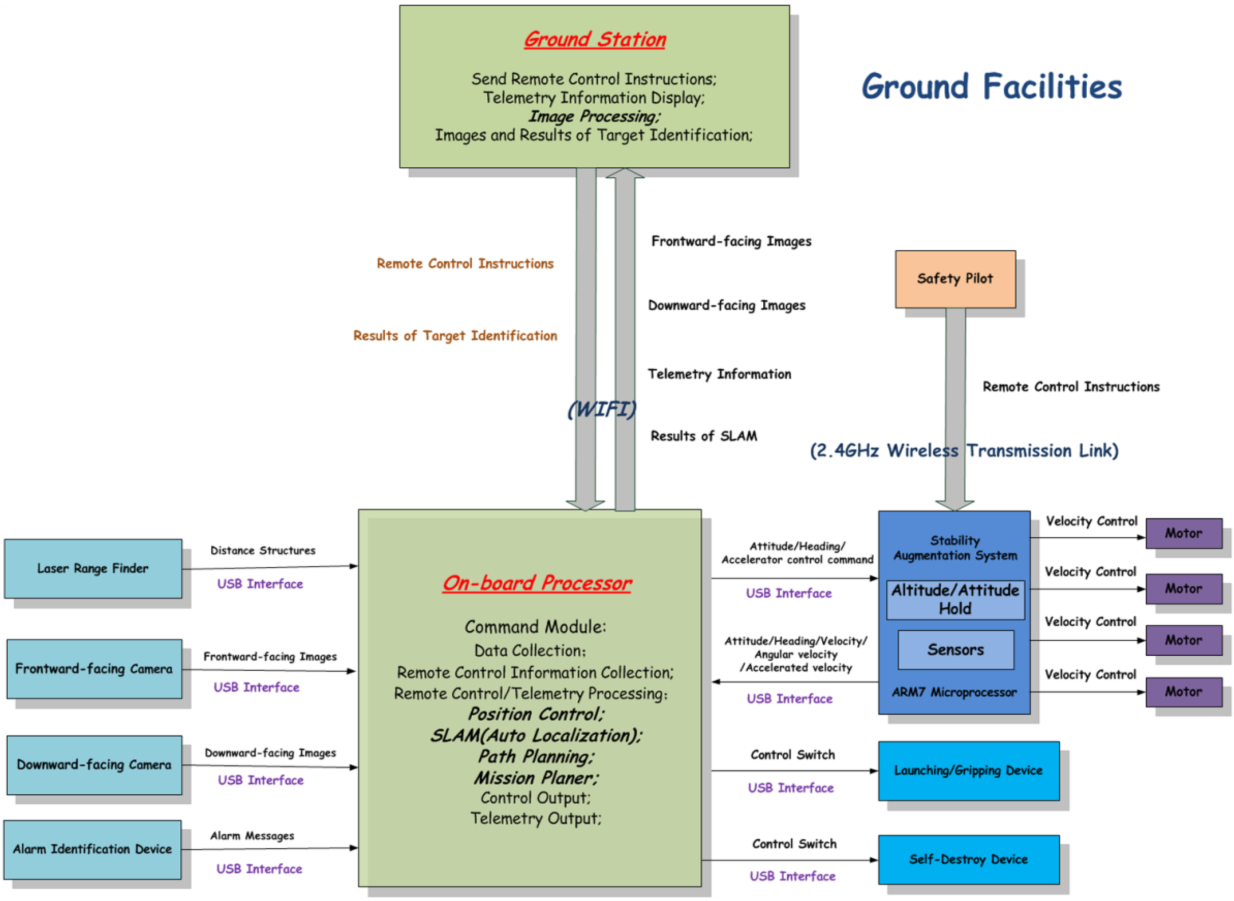
1.1 Statement of the Problem

The IARC 2013 requires the teams to apply completely autonomous aircraft. The takeoff weight cannot be over 1.5 kg. The aircraft should be 3 meters away from the starting point, passing through an about 1 square meter window to access to the building. At the same time when the aircraft searches for object regions, besides avoiding the barriers such as wall, pillar and furniture, it also needs to keep away from some visible security systems including the mobile surveillance cameras installed outside the window and laser trip wire in the corridor closed only by people to prevent untested aircrafts from going into each office. The aircraft should be able to follow the labels in the building to move into the specified room. Hence, it finds flash disk, puts down the fake flash disk, gets the real one through the grabbing device and finally goes back, giving the real flash disk to the referee.

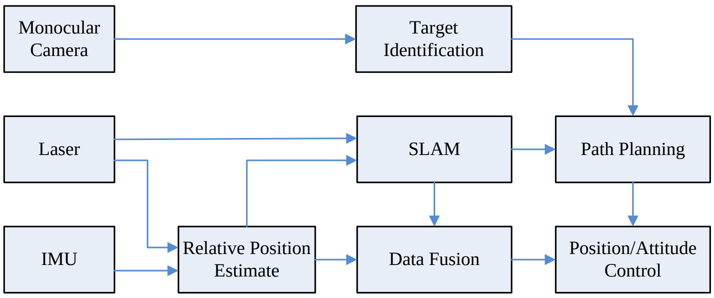
The whole task must be finished within 10 minutes. If the aircraft don't withdraw from the building at a set time, it must launch its self-destroy device to destroy the flash disk (through the start-up of beep imitation) when landing or turning off the propulsion system.

1.2 Conceptual Solution to Solve the Problem

The Comb Studio of Beihang University takes Pelican aircraft from AscTec Company to accomplish the task. The aircraft is equipped with two CMOS cameras, one laser range finder and one grabbing/releasing device. The Simultaneous Localization and Mapping (SLAM) algorithm of FastSLAM and particle filter are used to estimate the vehicle's position and the indoor area information. By fusing the information from laser range finder and the IMU, the elaborate navigation algorithm can provide relative position, velocity, and attitude information of the vehicle. The doorplate marking identification is achieved by feature extraction and matching using SURF algorithm. When the aircraft finds the position of flash disk, the flight controller will stabilize the aircraft. Meanwhile, the servo system will drive the releasing device to put down the fake one. The Overall System Architecture is as figure 1.



(a) Hardware Structure



(b) Algorithm Interaction

Figure 1. Overall System Architecture

1.3 Yearly Milestones

This is the second time for the Comb Studio to participate in IARC. In last year's mission, both our technology and experience are immature. The navigation and control are not quite accurate. We have made great progress on the accuracy this year. The experimental results show that the navigation error is less than 5cm when the vehicle flies 20m. The simulation of the path planning strategy indicates that the vehicle is able to find the right room and successful retreat using the FB_SRT-Star algorithm. In year 2013, we aim to find the flash disk, put down the fake one and then come back.

2. AIR VEHICLE

We choose the AscTec Pelican Quadrotor made by Ascending Technologies GmbH as platform. The vehicle structure, motors, and rotors of AscTec Pelican were used without modification. It is built in a modular fashion allows us to change our board quickly and easily. The main core is designed like a tower, making it plug-and-play. As a result of its high payload capacity and its modular design t is able lift laser scanners or different cameras. The size of Pelican is 50cm×50cm×20cm with a safety margin, and with a 6000mAh LiPo Battery, it can fly at least 12 minutes. Figure 2 shows the Pelican we use. Four little balls on it is used to identify the vehicle by the VICON System during our tests.

Figure 2 The Quadrotor

2.1 Propulsion and Lift System

The Pelican equipped with four brushless DC motors(X-BL-52s) and four 10in propellers. Two pairs of propellers spin clockwise and counterclockwise respectively, such that the sum of their reaction torques is zero during hovering. And Unlike normal helicopters, the propellers of the quadrotor have fixed pitch angles. We used the Pelican flown with diamond configuration. And control is achieved by creating a relative thrust offset between the propellers. As Figure 3 shows:

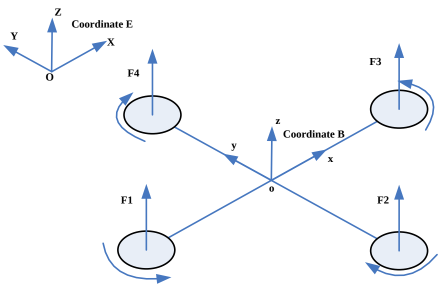


Figure 3 Lift system

- Pitching motion: Increase/decrease the speed of the motor 3, while decrease/increase the same amount of the speed of the motor 1.
- Roll movement: Increase/decrease the speed of the motor 4, while decrease/increase the same amount of the speed of the motor 2.
- Yaw movement: Increase/decrease the speed of the motor 1 and 3, while decrease/increase the same amount of the speed of the motor 2 and 4.
- X direction motion: from the pitching motion.
- Y direction motion: from the roll movement.

- Z direction motion: increase or decrease the speed of the four motors at the same time.

2.2 Guidance, Nav., and Control

Stability Augmentation System

The vehicle is an unstable system, in order to make it move as expected, an attitude and heading controller is needed. There are three different levels of communication with the Pelican: sending the vehicle direct motor commands, sending the vehicle angles (pitch, roll and yaw), sending the vehicle waypoints. We chose the level 2, sending the vehicle direct angles, and we don't need to concern how the vehicle can achieve the desired angles. That is to say, the stability augmentation system is done by the Ascending Technology GmbH; we just need to develop our position controller based on it.

Navigation

1) <u>Incremental State Estimation</u>

The relative movement of the vehicle is estimated by a scan-matching algorithm. Assuming structured indoor environment, a scan-matching algorithm estimates the most likely pose $\mathbf{X}_t$ of the vehicle at time t given the previous pose $\mathbf{X}_{t-1}$ and last two laser measurements $\mathbf{z}_t$, $\mathbf{z}_{t-1}$ as follows:

$$\hat{\mathbf{X}}_t = \underset{\mathbf{X}:=(x,y,\psi)}{\arg\max}\, p(\mathbf{X}_t \mid \mathbf{X}_{t-1}, \mathbf{Z}_t, \mathbf{Z}_{t-1}) \qquad (1)$$

We use the correlative scan-matching approach proposed by Olson[1]. The idea of the correlative scan-matcheing is to discretize the search space $\mathbf{X}_t = (x_t, y_t, \psi_t)^T$ and to perform an exhaustive search in the parameter space around a given initial guess. The complexity of the algorithm depends on the resolution of the grid map and the search range of discretized space.

Scan-matching only estimate the relative motion of the vehicle in x, y and ψ .The relative position in z must be accurately estimated in order to control the MAV. Since laser range-finder only emits beams in 2D plane, a mirror used to redirect a portion of the beams downward. The laser height estimation algorithm is proposed by MIT in [2].

2) <u>SLAM</u>

Though incremental state estimation enables the MAV to hover and move around the room accurately, small errors accumulate when the vehicle moves around larger areas. Hence, a real-time fast SLAM algorithm is proposed to solve the problem. Since Rao-Blackwellzed particle filters (RBPF) was proved to be an effective mean to solve the SLAM problem [3][4], we use RBPF to compute the pose of maximum likelihood based on current most likely map. According to literature [4], each practical carries an individual map of the environment, which is computationally expensive and requires a mass of memory. Our real-time fast SLAM algorithm generates a single best incremental map. Because the space of all maps cannot be searched efficiently, which seems to be brittle and incorrect in large cyclic environments, we adopt an adaptive technique of integrating laser scan of best pose into the most likely map.

Experimental results carried out by using laser range sensor and IMU on the vehicle in indoor environment show that the fast SLAM strategy has a better performance and can be applied in real-time. As figure 4(a) shows, the absolute error between estimated pose and the ground truth during the first loop is less than 5cm. Figure 4(b) describes the map built incrementally by integrating a new laser scan based on pose of the maximum likelihood.

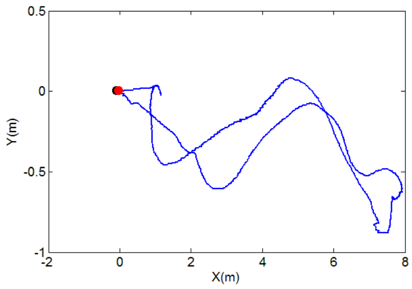


Figure 4(a)

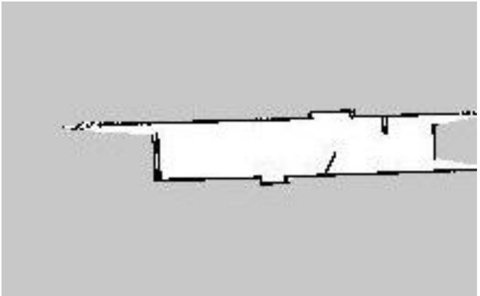


Figure 4(b)

Figure 4(a). Global location estimated by our SLAM strategy in a large-circle corridor environment, the red point and the black point mark the ground truth and the estimated position of the vehicle respectively. Figure 4(b). Incrementally mapping of corridor environment .

3) <u>EKF Data Fusion</u>

Principally, the data fusion part comprehensively deals with data of internal and external sensors of the aircraft, helping more precise positioning and achieving environmental information rapidly and accurately. This contest takes expanding Kalman filter as the scheme of data fusion. And the SLAM is the recursive estimation, that is, correction process as follows: the new position, speed and accelerated speed of the aircraft should be evaluated first through the mobility model; then we acquire the observation data of surrounding environment with the laser range finder and IMU accelerometer; next, we calculate the errors between the actual observation and estimate observation, count Kalman filter gain by synthesizing the system covariance and use this gain to revise the aircraft position we evaluated before. During the moving process of the aircraft, we continuously evaluate, correct and eliminate the errors, repeatedly [2].

4) <u>Feature Extraction</u>

Feature extraction part is based on the SLAM part. The feature extraction part, collecting distance data from laser rangefinder, attitude and position data from SLAM part, transmits continuously the location and direction of window, door as well as the cross information to the mission planning part.

By transforming the polar coordinates into Cartesian coordinate, a real time map of two-dimension can be made. Separating the range data by turnings and interval of each point, map of line segment is generated. Each line stands for flat that intersects the scanning flat. An accurate threshold is very important, as a large one would made the line segment not separated from each other, while a small one would separate even a line into several part. Re-line process is used to solve the dilemma and new thresholds are introduced to judge whether two lines are collinear.

Doors and windows are extracted by judging two collinear segments with appropriate interval. To ensure the validity of extraction, four procedures are taken, including restraint of the effective range of laser, a simple filter of position of windows and doors, an apposite threshold for interval and a judgment for wrong door extraction caused by potential obstacle. Once a door is detected, the information of the door would be transmitted to the mission planning part.

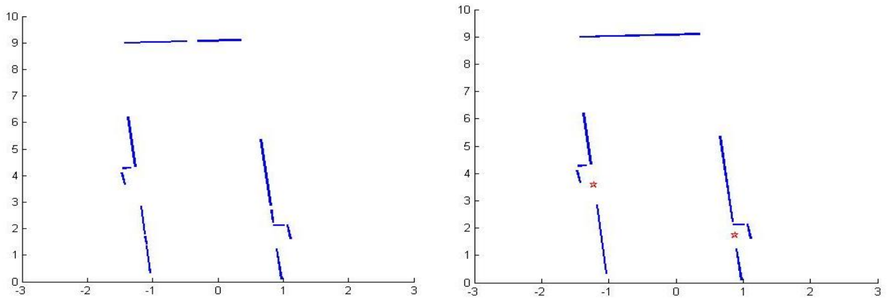


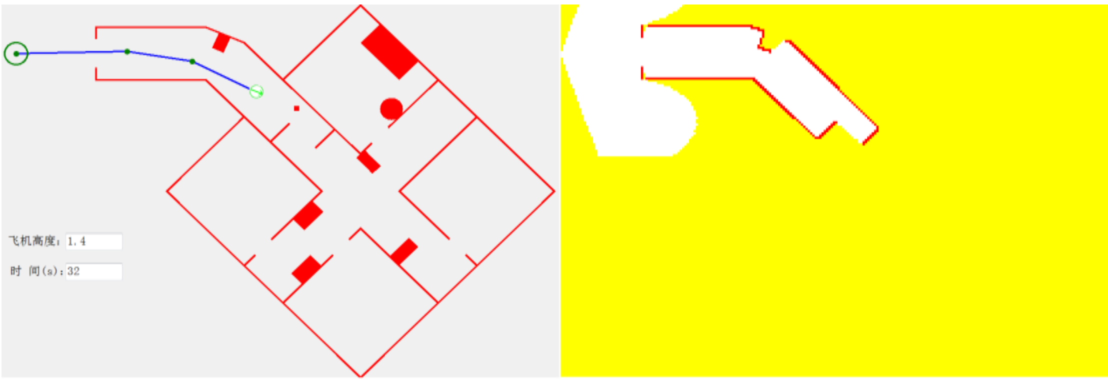
Figure 5 Re-line process and door extraction

5) <u>Path Planning</u>

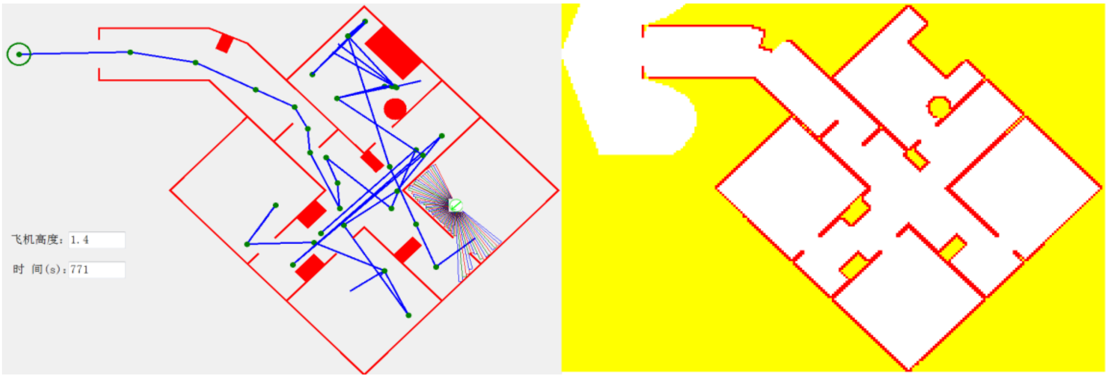
Path planning module is used to plan waypoints for vehicle so as to navigate vehicle to explore more unknown indoor environment and arrive the target point ultimately. In the 6th mission, the primary strategy we have chosen is one of the FB_SRT algorithm (Frontier-Based strategies for Sensor-Based exploration) which is FB_SRT-Star[5][6] .The principle of this strategy is “try to get as much new information as possible by going to a boundary between explored and unexplored territory”. In this approach, when vehicle arrived at a waypoint, scan data is applied to classify the surrounding environment of vehicle. The environment information can be divided into three categories including detected arc, obstacle arc and frontier arc. The vehicle could be navigated to the existing frontier arc , otherwise, it would backtrack to the last waypoint and cut off the current waypoint.

This exploration strategy can be utilized even without any other information such as the window or door feature points. When this information is available, it will be used to plan waypoints preferentially.

The strategy has been validated in the VC# simulation platform (*Figure*.6). FB_SRT-Star algorithm was applied in this simulation without any information of window or door feature point. The vehicle was navigated to explore unknown environment only using laser rangefinder data. Two pictures in *Figure*.6 show two different states of exploring. The right part of the figures displays the acquired map information. The ideal result of this algorithm is to obtain the global map and return the origin.



(a). The initial stage of simulation



(b). The stage of obtaining global map

Figure 6. The simulation of FB_SRT-Star algorithm

6) <u>Target Identification</u>

Recognition of the three Arabic signs is done by detecting the key points of the sample and matching it with the reference. We choose Surf (Speed Up Robust Features) for its good robustness which can detect features even under change in image scale, noise and illumination [7-10]. We also made some improvements to ensure its real-time and high speed. Ultimately, matches which didn't fit the affine transformation were eliminated by using RANSAC (RANdom SAmple Consensus) algorithm. Figure 7 below shows a demonstration of the algorithm.

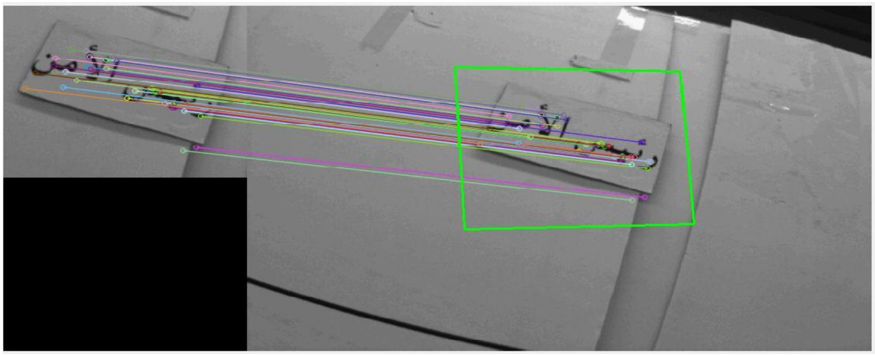


Figure 7 A sign recognized using Surf

The key points of Surf are the following four steps.

a) Detecting the feature points in scale space;
b) Assigning the main orientation of each feature points;
c) Choosing the right image descriptors;
d) Feature matching.

Aimed at the problem of repeat matching and many-to-one matching, the method of Two-way matching and Mahalanobis distance are used to improve the matching accuracy.

The flash disk is detected on the basis of its color and shape. If a black rectangle is found by the downward-facing camera and its perimeter is in a certain range, we consider it as the flash driver.

2.3 Flight Termination System

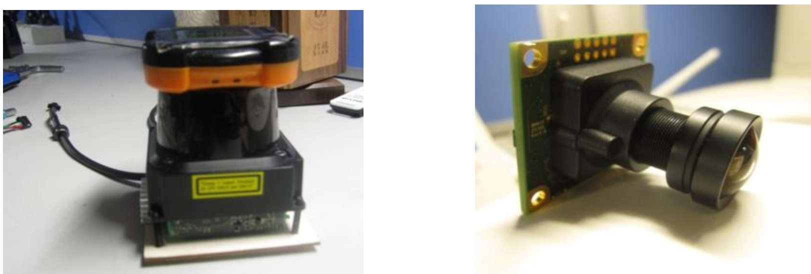
There are two ways to achieve flight termination. The vehicle can be changed from autonomous to manual control by a switch on the RC transmitter, then the safety pilot take manual control of the vehicle. The system is also provided with a remotely controlled “kill-switch” that ensures power to the motors is killed when triggered.

3. PAYLOAD

3.1 Sensor Suite

GNC Sensors

Our MAV is equipped with a laser rangefinder; two cameras and an airborne processor. The laser rangefinder select HOKUYO UTM-30LX. It is lightweight and provides a 270° field-of-view at 40Hz, up to an effective range of 30m. We deflect some of the laser beams downwards to estimate height above the ground plane.



(a)HOKUYO UTM-30LX *(b) uEye LE - UI-1226LE- C/M*

Figure 8 The sensors

Mission Sensors

The UI-1226LE-C is an extremely compact board-level camera with modern Aptina CMOS sensor in Wide VGA resolution (752×480 pixel). Its maximum frame rate is 87 fps and maximum field view is 80 degree. Hokuyo UTM-30LX laser rangefinder is used to avoid threat during flight.

3.2 Communications

A wireless WIFI module can be connected to the Atom Processor Board through a miniPCI，the vehicle can communicate with the ground station through the link.

3.2 Power Management System

A set of 3S LiPo battery applies the power to the vehicle, its capacity is 6000mAh. The brushless motor controllers and the laser range finder are directly connected to the battery, other electrical equipment on the vehicle are powered by a voltage regulator module which gives 5V voltage. A loud tone will appear if the battery voltage drops under 9.8V. The interval is getting faster the lower the battery voltage gets. The battery voltage will be send to the ground station to be monitored.

4. OPERATIONS

4.1 Flight Preparations

Before any flight test or trail is performed, a checklist of preparations is to be followed:

Flight Checklist

1. Make sure the battery is charged.
2. Check the whole vehicle hardware, make sure the attachments are fixed firmly and the propellers work well.
3. Plug in the battery. Turn on the remote control and start transmission.
4. Power on the vehicle.
5. Check the communication links between the ground stations and the vehicle.
6. Turn the motors on and start testing
7. If any emergency occurs, safety pilot takes charge and lands the vehicle.

4.2 Man/Machine Interface

Overview

GCS is an important part of the whole system, which is programming with C++ in QT Creator. The main functions of the GCS include the taking-off and landing, abrupt stop instructions, monitoring the state of the vehicle, displaying the video stream and realize the SLAM etc. According to the rules of the game our GCS is placed near the competition terrain, which realizes the communication between the vehicle and the GCS through WIFI.

Main Functions

1) Sending the taking-off and abrupt stop instructions

In the beginning of the competition we can send the taking-off instruction; once the aircraft lose control, we can send abrupt stop instruction to avoid some serious consequences through the man-machine interface.

2) Monitoring the flight state

Through the WIFI interface GCS can receive, analyze and show state information such as the attitude, speed, height, position etc., so that we can monitoring the state of the vehicle.

3) Displaying the image

We display the image on the screen of the GCS to facilitate the monitoring of the vehicle.

4) Simultaneous Location and Mapping

We call the SLAM algorithm to achieve the simultaneous location and mapping with the the distance gathered by the laser rangefinder, and display the map we regenerate on the GCS to facilitate the monitoring of the vehicle.

5. RISK REDUCTION

5.1 Vehicle Status

Shock/Vibration Isolation

The airborne electronic equipment and sensors have inherent tolerance to vibration. In addition, some damping measures have been applied when mounting the sensors, for example, the use of the shock absorber bracket and soft pad. The IMU is installed in the center of gravity of the vehicle, to reduce the disturbance from the vehicle. And we use a specialized vibration isolation bracket for the laser range finder.

EMI/RFI Solutions

The Pelican equips with brushless motors, which has reduced EMI disturbance. Furthermore, the autopilot is mounted in the center of the vehicle where is relatively far from the interference source. The transmitter and the WIFI data link are both 2.4GHz, we can reduce the possible disturbance by proper shielding and location of the antennas.

5.2 Safety

In order to guarantee the safety of aircraft and people around, we have taken some more effective measures based on the vehicle we used last year. First, we installed a new higher protective frame around the vehicle to prevent the propeller from hitting the wall or other objects. Each sensor, as well as the battery, is installed with appropriate damping measures to ensure gravity center coincide with the geometrical center. Besides, we have a safety pilot who has the priority to take charge of the vehicle.

5.3 Modeling and Simulation

When the elastic vibration and deformation of the vehicle is ignored, the aircraft can be regarded as a rigid body with six degree of freedom, which includes the movement along the line of body's three axial and the angular motion around the three axes of the vehicle. In the inertial coordinate, we establish the equation of angular motion and position movement based on the Newton's second law:

$$F = m\frac{dV}{dt}, \quad M = \frac{dH}{dt} \tag{2}$$

In (2), F is the sum of all external forces on the vehicle, m is the quality of the vehicle, V is the speed of center of mass of the vehicle, M is the sum the external torques on the vehicle, H is the sum of the moment of momentum on the vehicle.

The external forces on the vehicle include gravity, rotor lift force and drag. The vehicle moves in hover or low speed all the time, so the drag can be ignored, only the gravity and lift force act on the vehicle.

In the body coordinate, the lift force is as follow:

$$T = b\Omega^2 = b({\Omega_1}^2 + {\Omega_2}^2 + {\Omega_3}^2 + {\Omega_4}^2) \tag{3}$$

So, the equation of position movement of the vehicle is:

$$\begin{cases} \dot{x} = u \\ \dot{y} = v \\ \dot{z} = w \\ \dot{u} = (\cos\varphi \sin\theta \cos\phi + \sin\varphi \sin\phi)\dfrac{U_1}{m}, \quad U_1 = T = b(\Omega_1{}^2 + \Omega_2{}^2 + \Omega_3{}^2 + \Omega_4{}^2) \\ \dot{v} = (\sin\varphi \sin\theta \cos\phi - \cos\varphi \sin\phi)\dfrac{U_1}{m} \\ \dot{w} = -g + (\cos\theta \cos\phi)\dfrac{U_1}{m} \end{cases} \tag{4}$$

The structure and mass distribution of the quadrotor are symmetrical and the center of gravity and the geometrical center of the vehicle are coincident. Based on that, we assume that its inertia matrix is a diagonal matrix I.

The relationship of attitude angular rate and the angular velocity is as follows:

$$\begin{cases} \dot{\theta} = p + (\sin\phi \tan\theta)q + (\cos\phi \tan\theta)r \\ \dot{\phi} = q\cos\phi - r\sin\phi \\ \dot{\varphi} = (q\sin\phi + r\cos\phi)/\cos\theta \end{cases} \tag{5}$$

The aerodynamic torque effects the vehicle includes lift torque and anti-torque of the propeller, as follows， in which l_1 is the distance from the propeller center to the center of gravity:

$$\begin{bmatrix} \tau_\theta \\ \tau_\varphi \\ \tau_\phi \end{bmatrix} = \begin{bmatrix} bl_1(\Omega_1{}^2 - \Omega_3{}^2) \\ bl_1(\Omega_4{}^2 - \Omega_2{}^2) \\ d(-\Omega_1{}^2 + \Omega_2{}^2 - \Omega_3{}^2 + \Omega_4{}^2) \end{bmatrix} \tag{6}$$

The angular momentum of the vehicle is:

$$H = I\omega = \begin{bmatrix} I_x p & I_y q & I_z r \end{bmatrix}^T \tag{7}$$

Combined with the moment of momentum theorem (1), the angular motion equation [4] of the vehicle is:

$$\begin{cases} \dot{p} = (\dfrac{I_y - I_z}{I_x})qr + \dfrac{l_1}{I_x}U_2 \\ \dot{q} = (\dfrac{I_z - I_x}{I_y})pr + \dfrac{l_1}{I_y}U_3 \\ \dot{r} = (\dfrac{I_x - I_y}{I_z})pq + \dfrac{1}{I_z}U_4 \\ \dot{\theta} = p + (\sin\phi \tan\theta)q + (\cos\phi \tan\theta)r \\ \dot{\phi} = q\cos\phi - r\sin\phi \\ \dot{\varphi} = (q\sin\phi + r\cos\phi)/\cos\theta \end{cases}, \begin{cases} U_2 = b(\Omega_1{}^2 - \Omega_3{}^2) \\ U_3 = b(\Omega_4{}^2 - \Omega_2{}^2) \\ U_4 = d(-\Omega_1{}^2 + \Omega_2{}^2 - \Omega_3{}^2 + \Omega_4{}^2) \end{cases} \tag{8}$$

The mathematical model of the vehicle is composed of (4) and (8).

5.4 Testing

Gradual work has been done to test the whole system. The VICON camera based object tracking system is being used to precisely navigate to adjust the parameters of the controller. A ground robot with laser rangefinder is used to test the SLAM algorithm. After all the simulation and unit testing, flight tests are being done to verify the system's reliability.

6. CONCLUSION

Based on the research of Pelican quad-rotor platform, the aircraft was made to have the ability of autonomous navigation and control in the unknown environment to accomplish some specified tasks such as obstacle avoidance, online path programming and target identification. We expect our vehicle to be able to navigate the competition arena and find the flash drive.

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