Comb Studio's Autonomous Aircraft for the IARC 2012

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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 targets including LED light, laser trip wire label and 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 2012.

INTRODUCTION

Statement of the Problem

The IARC 2012 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.

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 front camera of the aircraft is used to judge the on and off status of LED, doorplate marking and laser trip wire identification with target recognition algorithm. Another camera on the bottom is mainly applied for the search and recognition of flash disk. The function of laser range finder is to achieve the information of distance, create 2D global maps and conduct accurate positioning of the aircraft by integrating with inertial measure unit data. 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.

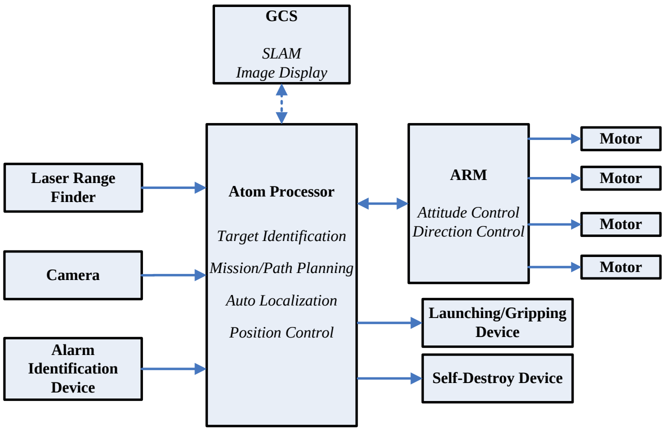


Figure 1. Overall System Architecture

Yearly Milestones

This is the first time for the Comb Studio to participate in IARC. Both our technology and experience are immature. Therefore, in this year, our objective is to find flash disk, put down the fake one and then come back. In the next year's competition, we aim to get the real flash disk, establish 3D global maps and position by integrating binocular vision together with laser range finder.

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 The Quadrotor

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 quadrotors 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:

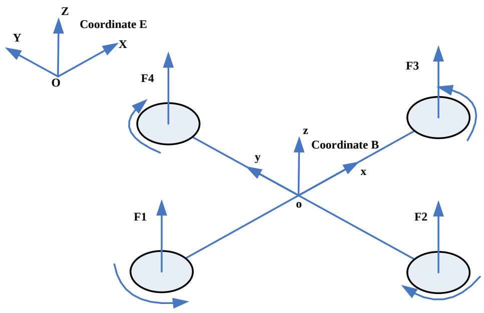


Figure 3 Lift system

- 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.

Guidance, Nav., and Control

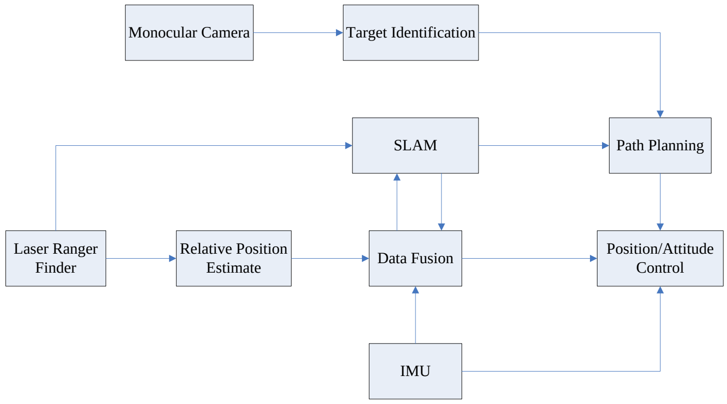
Stability Augmentation System

The quadrotor 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

Airborne two-dimensional (2D) laser range finder as the main external sensor is used to implement SLAM (Simultaneous localization and mapping)[1]. On airborne processor, we achieve the horizontal position and orientation estimation by matching the new scan data. Then, we fuse the relative position estimates with the acceleration readings from the IMU to compute the accurate self-position. On the ground station, its main role is to model the surrounding environment, and establish a global map. On the basis of aircraft self-positioning and the global map, we set the waypoint to achieve autonomous flying [2] [3].

Figure of control architecture



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. There is also a flight termination button in our ground station, if any emergency happens, someone can click the button to control the vehicle in a descent.

PAYLOAD

Sensor Suite

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.

Laser Range Finder

1) Location

Laser range finder, compared to the ultrasonic range finders and infrared range finder can provide high density and high-accuracy measurements. Using two-dimensional laser range finder for horizontal position and orientation estimates, it includes three parameter values: the horizontal displacement Δx, Δy, and yaw $\Delta\psi$ .Based on Line extraction, line matching and iterative closest point (Iterative Closest Point, ICP) algorithm, we achieve the horizontal position and orientation estimates.

Indoor structured environment, the line segment is the most important characteristics, using only the segment almost can describe the two-dimensional information of the whole environment. After the completion of the line segment extraction, followed thing is matching the line segments corresponding to the same objects in the real environment, that is, segment matching. Segment matching is the most crucial part; because of the mismatch error will result in a huge horizontal position and attitude estimation error, and bring disastrous consequences for UAV navigation. Compared to visual images, the matching of the laser scanning image difficulty is greatly increased, because the information contained in the laser image is much less than the information contained in visual images, and the measurement point is discrete, so the corresponding points in different scans maybe is not the same point in the environment [11].

UAV applied in indoor navigation requirements high real-time pose estimation, matching cycle is short, so the two scanned images have much overlap, so there is no need to predict a visible image based on the UAV's current location. According to the application of this thesis, the line match is main basis for the following three criteria [5]:

a. the difference between the length of a two line segments within a certain range;
b. the difference between the index of the starting point of two line segments in scanned image within a certain range
c. the distance between the center of gravity of the two segments within a certain range.

In above three criteria, of which the second criterion is the use of the nature that line segment is ascending ordered. That is because of the line extraction process is done based on laser scanning order [6].

The Iterative Closest Point (ICP) algorithm is used to achieve the horizontal pose estimation. The optimal rigid body transform (in a least-squares sense) between two sets of corresponded points can be computed in closed form [7], which is computational efficient.

2) Mapping

Geometry map was developed to describe the indoor environment based the sensor data of laser rangefinder. The new segments discovered in the sensor data should be merged with the existing world map. In fact, this process is logically split into two steps of undertaking decisions, which segments should be inserted into the map and how the insertion can be conducted.

The decisions whether two segments are corresponding are made based on evaluation of likelihood function for each possible pair. The likelihood value for a pair is a composite feature treating not only a membership of parts of segments but also takes into account similarity of other features like segment direction, neighborhood, etc. Two possible approaches are used for the selection of candidate pairs. These are based on cross distances of the segments end- points (*Figure 4*) and difference of slope and intercept.

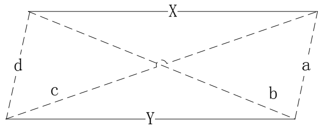


Figure 4 Cross distance of two segments

Applying the cross distance criterion the segments are declared as pair whenever at least two of the following conditions are satisfied for a threshold T: a+b < X+T; c+d < X+T; a+c < Y+T; b+d < Y+T. Once the segments are declared as pair, the direction relationship should be considered. Let $\Delta k\% = \left|\frac{k_1 - k_2}{k_1}\right| \times 100\%$, $\Delta b\% = \left|\frac{b_1 - b_2}{b_1}\right| \times 100\%$, the slope and intercept of two lines are (k1, b1) and (k2, b2). If $\Delta k\% \le A$ $\Delta b\% \le B$ two segments are decided to be corresponding, A and B are thresholds which were set through experiment. During the merging process the updated line segments are inserted into the world model. Fusion of the new and map segments can be treated in a simple and a fast way by association of the segment lines. The new lines are added to the existing world map; lines which are corresponding with existing lines are combined with the old lines.

3) EKF Data fusion

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; finally, the new environment features we observe are added into maps. During the moving process of the aircraft, we continuously evaluate, correct and eliminate the errors, repeatedly [12].

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.

1) Target Identification

Two UEye Cockpit cameras are mounted to the vehicle, one fixed forward-looking camera and the other pointed directly downward. Data from the frontward-facing cameras is merged to form a single image, and then processed in search of both the blue LED that indicates when it is safe to enter the building and any of the three Arabic signs labeling rooms of the compound. Images taken by the downward-facing camera are examined and combed for the flash drive.

Detection of the blue LED is accomplished by identifying the blue region: have the blue channel image subtract the red(or green) channel image after extracting the image of RGB channels, then the pure blue region is obtained in a new image. Calculate the size of the contour in a binary image; a certain threshold is set to tell if the blue LED light is on or off.

Detection of the laser mark is accomplished by identifying the triangular contour. In order to clean up the background, the binary image needs to go through a series of dilations and erosions. Then determine whether the polygon contour has three sides, if so, compute the cosine of three angles and determine whether they can form a triangle. Using this method, the side-placed laser can also be detected.

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.

Recognition of the three Arabic signs is done by detecting the key points of the sample and matching it with the reference. We choose SIFT (Scale Invariant Feature Transform) for its good robustness which can detect features even under change in image scale, noise and illumination [1-4]. We also made some improvements to ensure its real-time and high speed. 5 below shows a demonstration of the algorithm.

Figure 5 A sign recognized using SIFT

The key points of SIFT 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.

2) Threat Avoidance

Hokuyo UTM-30LX laser rangefinder is used to avoid threat during flight.

Communications

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

Power Management System

A set of 3S LiPo battery applies the power to the vehicle, it’s capacity is 6000mAh. The brushless motor controllers and the laser range finder are directly connected to the battery, other electrical equipments 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.

OPERATIONS

Flight Preparations

In order to keep the vehicle safe and to complete the competition task, we developed a series of flight preparations [8]

Check List

1) Check the whole vehicle hardware, make sure the attachments are fixed firmly and the propellers are well.
2) Check the vehicle battery and plug into the vehicle, and check the RC transmitter battery.
3) Power on the ground station and open the control software.
4) Power on the vehicle.
5) Check the communication links between the ground stations and the vehicle, make sure it is well.
6) Check the sensors, and confirm they are normal.
7) Turn the motors on, and then click on the take-off button.
8) Monitor the status of the vehicle, if there is any unusual circumstance, sent landing instructions immediately.
9) If any emergency happens, the safety pilot changes the vehicle from autonomous to manual control by a switch on the RC transmitter, and control it landing.

Man/Machine Interface

Overview

GCS is an important part of the whole system, which is programming with visual C++ 6.0. 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.

RISK REDUCTION

Vehicle Status

Shock/Vibration Isolation

The airborne electronic equipments 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 [9].

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.

Safety

In order to make sure the safety of aircraft and personnel around, we have taken some effective measures. First, we installed a protective frame around the vehicle to prevent the propeller to hit the wall or other objects. Every sensor is installed with appropriate damping measures to ensure the sensor is working normally. The control system of the vehicle will detect the battery voltage and the status of the data link in real time, if any emergency happen, the vehicle will perform a controlled descent to the ground. We have a safety operator who has the manual override capabilities to ensure safety.

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 [10]:

$$F = m\frac{dV}{dt}, \quad M = \frac{dH}{dt} \tag{1}$$

In (1), 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:

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

Lift force T discomposes in the ground coordinate as:

$$F_T = \begin{bmatrix} \cos\varphi\sin\theta\cos\phi + \sin\varphi\sin\phi \\ \sin\varphi\sin\theta\cos\phi - \cos\varphi\sin\phi \\ \cos\theta\cos\phi \end{bmatrix} T \tag{3}$$

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:

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \tag{5}$$

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

$$\begin{cases} \dot{\theta} = p + (\sin\phi\tan\theta)q + (\cos\phi\tan\theta)r \\ \dot{\phi} = q\cos\phi - r\sin\phi \\ \dot{\varphi} = (q\sin\phi + r\cos\phi)/\cos\theta \end{cases} \tag{6}$$

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:

$$\begin{bmatrix} \tau_\theta \\ \tau_\varphi \\ \tau_\phi \end{bmatrix} = \begin{bmatrix} bl_1(\Omega_1^{\,2} - \Omega_3^{\,2}) \\ bl_1(\Omega_4^{\,2} - \Omega_2^{\,2}) \\ d(-\Omega_1^{\,2} + \Omega_2^{\,2} - \Omega_3^{\,2} + \Omega_4^{\,2}) \end{bmatrix} \tag{7}$$

The angular momentum of the vehicle is:

$$H = I\omega = \begin{bmatrix} I_x p \\ I_y q \\ I_z r \end{bmatrix} \tag{8}$$

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

$$
\begin{cases}
\dot{p} = (\frac{I_y - I_z}{I_x})qr + \frac{l_1}{I_x}U_2 \\
\dot{q} = (\frac{I_z - I_x}{I_y})pr + \frac{l_1}{I_y}U_3 \\
\dot{r} = (\frac{I_x - I_y}{I_z})pq + \frac{1}{I_z}U_4 \\
\dot{\theta} = p + (\sin\phi \tan\theta)q + (\cos\phi \tan\theta)r \\
\dot{\phi} = q\cos\phi - r\sin\phi \\
\dot{\varphi} = (q\sin\phi + r\cos\phi)/\cos\theta
\end{cases}
,
\begin{cases}
U_2 = b(\Omega_1^{\ 2} - \Omega_3^{\ 2}) \\
U_3 = b(\Omega_4^{\ 2} - \Omega_2^{\ 2}) \\
U_4 = d(-\Omega_1^{\ 2} + \Omega_2^{\ 2} - \Omega_3^{\ 2} + \Omega_4^{\ 2})
\end{cases}
\quad (9)
$$

The mathematical model of the vehicle is composed of (4) and (9).

Testing

Before the navigation system is completely done, we test our position control based on GPS, we set five waypoint, the result is as *Figure 6* shows The X axis is longitude, the Y axis is latitude, both the unit are second; Considering the accuracy of our GPS is about 2m, the testing result is well.:

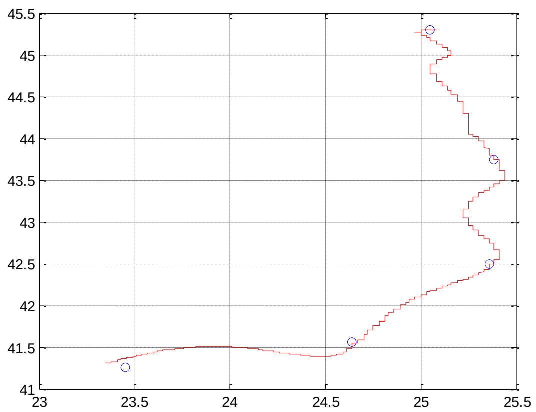


Figure 6 Position control based on GPS

We test the effect of horizontal position and orientation estimation in a $4 \times 7m$ room. As *Figure 7*show, the result of scan matching is very well.

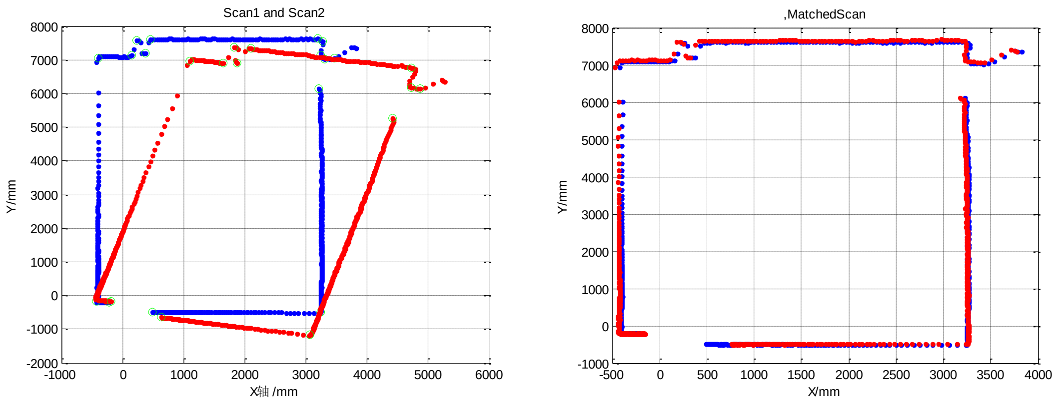


Figure 7 horizontal position and orientation estimation

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. The next aim is to fuse binocular vision sensors together with laser range finder to research 3D SLAM, and accomplish more difficult mission under the more complicated indoor environment.

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