Tsinghua Team Entry for the 2012 AUVSI International Aerial Robotics Competition

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ABSTRACT

This paper describes the technical details of a Quadrotor system capable of exploring unstructured indoor environment, detecting and replacing a specific USB flash disk, without relying on any external navigation aids. A Gmapping Simultaneous Localization and Mapping (SLAM) algorithm fused with various onboard sensor data is used to provide relative position, velocity and altitude of the vehicle. Two visible light cameras are mounted on the vehicle, the frontward one is used to detect the target room, and the downward one is responsible for USB disk identification with a simple manipulator to replace it. A DH-Bug path planning algorithm is introduced to help the vehicle implementing obstacle avoidance. Moreover, we design elaborate control architecture to ensure the stability and mitigation of vehicle uncertainties. This Quadrotor is designed to be Tsinghua Aerial Robotic Team's entry for the 2012 International Aerial Robotics Competition.

I. INTRODUCTION

Miniature Air Vehicle (MAV) has been widely used in indoor reconnaissance and surveillance, due to the features of flexible deployment and small size. Therefore, the corresponding application technologies have attracted lots of attentions from many governments, universities and research institutes in recent years.

The unstructured and complex indoor environment gives a tremendous challenge to the safety of MAV, which can be divided to external and internal factors. Firstly, during most mission implementation, MAV needs GPS signals[1] and control commands from ground station to "know" its location and executive flight, which are subject to external electromagnetic interference (EMI) and unstable communication link. Secondly, unknown indoor flight environment, complex illumination condition and uncertain obstacles, etc. compose the unstructured internal area, threat the safety of MAV directly. Moreover, specific mission require MAV to perform corresponding operation, such as replacing USB flash disk in Mission 6 with the help of controllable mechanical equipment. Rapid development of control theories, data processing algorithms and high performance infrastructures make it possible that MAV can implement a mission "autonomously".

This paper describes technological details of our Quadrotor system, which is designed to be Tsinghua Aerial Robotic Team's entry for the 2012 International Aerial Robotics Competition.

With the help of various onboard sensors, the MAV are expected to sense the cluttered indoor flight environment, implement obstacle avoidance flight, communicate with ground station, and replace the specific USB flash disk.

A. Statement of the problem

The 6th Mission of IARC requires a MAV weighing less than 1.5kg have the ability to enter and self-navigate within an unknown indoor environment, search a specific USB flash disk and replace it, then exit without being detected.

B. Conceptual solution to solve the problem

The THUDrone Team has developed a MAV system capable of exploring unknown indoor environment and implementing specific operation without any external navigation aids such as GPS. The overall MAV system consists of an off-the-shell Quadrotor base platform, various kinds of avionics and onboard sensors. An elaborate navigation algorithm is designed to provide attitude, altitude, velocity and relative position estimations of MAV within indoor area, by fusing information from laser range finder, inertial measurement unit and ultrasonic altimeter. We design a navigation strategy based on the DH-Bug algorithm which can lead the MAV to explore the unknown environment for a reasonable time-consuming and avoid the obstacles in an appropriate way. We also design target detection algorithm to locate the "Chief of security" room and search the flash disk, using vision light images from frontward and downward cameras, respectively. Finally, a controllable mechanism is responsible for the specific USB flash disk pickup. The overall system architecture is as shown in fig.1.

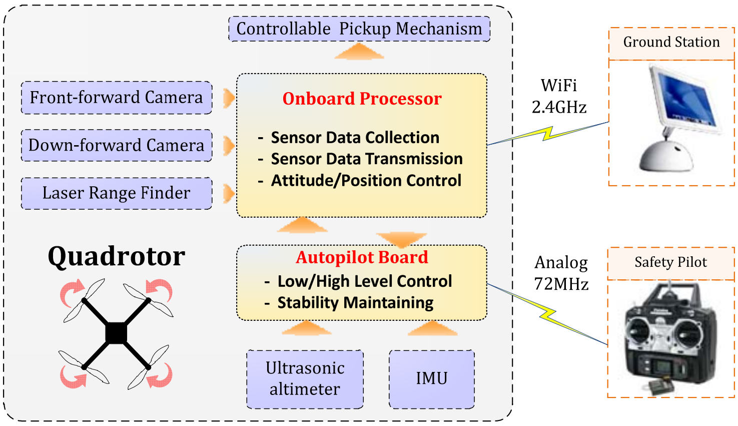

Figure 1. Overall system architecture.

C. Yearly Milestones

This is our first competition in the IARC. the THUDrone Team aims to develop a stable, robust MAV capable of exploring unknown indoor environment and implementing specific mission. In 2011, some vehicles can implement self-navigating within indoor environment and detecting the USB disk. The subsequent yearly milestones include exploring the indoor environment without being detected, picking-up specific USB disk and bringing it back within allocated time.

II. AIR VEHICLE

Quadrotor is a good choice for MAV due to their relatively high flexibility and maneuverability. In 2012 IARC, the THUDrone Team selected the AscTec Pelican Quadrotor produced by Ascending Technologies GmbH as the base platform (see Fig.2a), to meet the 6th mission payload requirements. The base vehicle structure, motors and rotors of the Pelican Quadrotor were used without any modification.

(a) AscTec Pelican Platform *(b) Quadrotor Propulsion and Lift System*

Figure 2. THUDrone Team use the AscTec Pelican as base aerial platform.

A. Propulsion and Lift System

The propulsion system of Pelican consists of four brushless DC motors (BLDM) and propellers, which distribute symmetrically at the end of four arms (see Fig. 2b). When the four BLDMs rotate at the same speed, they provide lifting force for the Quadrotor. Different rotational speed of the two motors on the diagonal will produce moment in the direction of pitch or roll. When the rotational speed of two motors on one diagonal increase, meanwhile, the rotational speed decrease on the other diagonal, it will produce moment in the direction of yaw. In short, we can control the attitude of the Pelican by changing the rotational speed of the four motors in order that we can achieve velocity and attitude control.

B. Guidance, Nav., and Control

b1) Stability Augmentation System

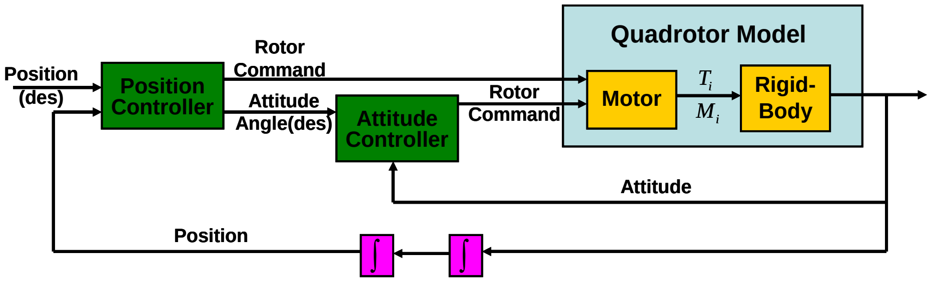

Figure 3. The inner-outer control schematic of Quadrotor

The inner-outer loop control structure is designed since the attitude loop of the Quadrotor is a statically unstable system. The inner control loop is used for the attitude stability augmentation, and the outer one is used for position control. The purpose of stability augmentation control loop is to make the three attitude angles, namely pitch, roll, yaw, as close to the order as possible. For this purpose, attitude feedback is needed to achieve attitude closed-loop control, in which the simple and robust PID control method is used. All of the PID control parameters will be optimized based on actual flight test.

b2) Navigation

Navigation is intended to finish SLAM and path planning.

SLAM (Simultaneous Localization and Mapping) module is used to build the 3D map of the indoor environment and estimate the location of the vehicle. In the 6th mission, we use Gmapping SLAM algorithm[2], an efficient Rao-Blackwellized particle filter, can rebuild 3D map by fusing 2D planes scanned by laser range finder. Using the algorithm, we send the vehicle global location periodically to the data fusion EKF to correct the drift of the position estimation caused by IMU bias. The position estimates should be re-computed from the corrected position consider of the time delay between the position estimation module and the SLAM module. The overall SLAM module outputs a probability grid map, indicating the possibility of the grid occupied.

Path planning module is used to navigate the vehicle to target room with obstacle avoidance base on 3D environment map. In the 6th mission, we choose Distance Histogram Bug (DH-Bug) algorithm[3], which has redefined motion modes and new switching criteria to achieve more efficient path. Considering the fact that we have no idea of USB disk location, we set a virtual goal, which could be in front of the Quadrotor with a given direction and distance range. If the Quadrotor can't detect the final goal identification or reach the virtual goal along the path computed by the algorithm, we will mark this region and set another virtual goal to go on searching and constructing the map[4]. When meeting with obstacle, the vehicle will first check whether there is a hole to go through, otherwise the algorithm will sample different plots randomly in real-time map built by SLAM module and calculate a collision-free path for the vehicle.

b3) Figure of control system architecture

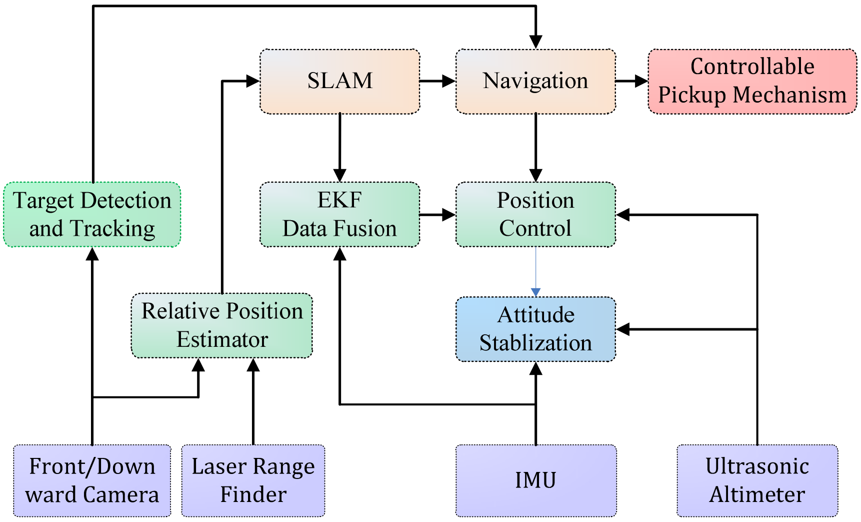

Figure 4. The control system architecture.

C. Flight Termination System

There's a RC controller connected to the low-level control chip on the autopilot. When the high-level control commands make any error, leading to a threat to people's safety, the operator can always take over the flying Quadrotor through one channel of the RC controller, then make an emergency landing.

III. PAYLOAD

A. Sensor Suite

THUDrone is designed based on the Pelican Quadrotor produced by Ascending Technologies GmBH, which is an extremely robust, stable, and safe platform. The onboard sensors include laser range finder, inertial measurement unit, vision light cameras and ultrasonic altimeter. The inertial measurement unit and ultrasonic altimeter are connected to the autopilot board, laser range finder and cameras are connected to the onboard computer, which is x86 architecture, standard operating systems. The onboard computer has dimensions of only 58×65mm, weighs 26g, but includes a 1.6Ghz Atom processor, corresponding chipset, and 1GB RAM.

a1) GNC Sensors

(a) Hokuyo Laser Range Finder *(b) Vision light camera* *(c) Ultrasonic altimeter*

Figure 5. Various onboard sensors.

Hokuyo UTM-30LX Laser Range Finder: A laser range-finder returns a point cloud of 1080 points in a 270 degree, 30 meter range surrounding the vehicle at 40Hz, as shown in fig.5a. High speed vision light cameras can provide 752×480 colored images as a speed of 87fps, used for target detection and tracking, as shown in fig.5b. And an off-the-shell ultrasonic altimeter is used for attitude stability and position control, as shown in fig.5c.

a2) Mission Sensors

The THUDrone will use a simple manipulator to grab the USB disk by magnetic force, as shown in fig.6.

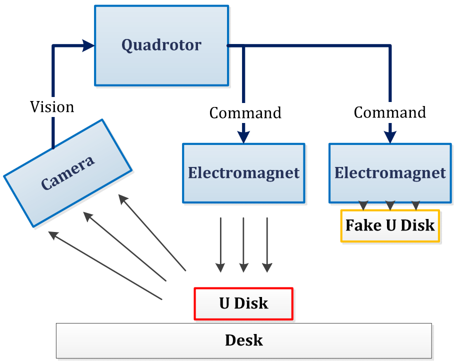

Figure 6. The manipulator operation framework.

After the Quadrotor flies into the target room and finds the USB disk, it will adjust its position until it reaches just above the disk. Then, the device powers on the electromagnet to grab the disk. After that, the device powers off another electromagnet to drop the fake USB disk. We use a micro electro holding magnet which weighs only 15g. The driving circuit uses a MOSFET to achieve the voltage-controlled power supply.

a21) Target Identification

USB identification: The THUDrone uses downward camera to extract disk features, such as optical characterization, geometry topological characteristic, points and lines. Compared with features from training images, we will know the exact location of the USB disk.

Target Room identification: The THUDrone uses frontward camera to detect the target room. Region-based method and texture-based method are two candidate approaches. The difference between the text region and the background is used to segment the texts from background, and also, Gabor filter, wavelet filter, FFT and space variance method are introduced in texture analyzing to improve robustness and adaptability.

B. Communications

The onboard computer can communicate via 802.11abg and XBee wireless links. In the 6th mission, the onboard computer will communicate with a ground station using a Wireless Local Area Network (WLAN) link.

C. Power Management System

The Quadrotor is powered by a three-cell-Lithium-Polymer-Ion battery whose voltage is about 12V. The battery is connected to a power board, which has four 12V interfaces to power the BLDCs. Meanwhile, a voltage adapter is used to turn the voltage into 5V for powering the processors onboard. The SCM onboard will measure the voltage of the battery continuously during the flight and raise the alarm once under voltage happens so that we can ensure safety of fight and battery.

IV. OPERATION

A. Flight Preparations

a1) Checklist(s)

1. Make sure the power of battery is full;
2. Check the status of Quadrotor and the connection of avionics;
3. Get on power, check the switch of control rights;
4. Check the software;
5. Make a simple test flight to make sure the data link and the sensors work fine.

B. Man/Machine Interface

There are two man/machine interfaces in the entire system. One is the ground station, and the other is the RC controller. The ground station is used for real-time display of Quadrotor flight status, including attitude, position and ambient environment and so on, which is used to judge whether the flight is normal. The RC controller is used to take over the Quadrotor when there’s an abnormal flight, so as to ensure the safety of people and vehicle.

V. RISK REDUCTION

A. Vehicle Status

THUDrone will transfer its flight status continuously to the ground station via wifi connection during the flight. The ground station will display the status and save them for further analysis, including attitude, height, ambient environment, camera images and so on.

a1) Shock/Vibration Isolation

The shock is from the rotation of motors, which will interfere the accelerometer and the ultrasonic sensor. For the ultrasonic sensor, we can paste a layer of sponge to absorb the shock. As for the accelerometer, we can’t use sponge that has great elasticity because the accelerometer needed to be closely integrated with the body to reflect the acceleration accurately. So we use rubber washers to retard shock, and at the same time filter should be used in the software to reduce the effects of the shock on the attitude estimation.

a2) EMI/RFI Solutions

EMI will interfere the 3D-MAG, from the rotation of motors and the current in the electric wires. So we placed the 3D-MAG on the top of the body, where is farthest to the motors and the wires. Moreover, we merge the accelerometer data and 3D-MAGs data to reduce the estimation error of the yaw angle. For RFI, there are only two wireless modules in our system, that is the RC controller and the wifi link, which are not working on the same frequency. So the system itself does not produce RFI.

B. Safety

To ensure the safety of people and the vehicle, a series of tests should be taken before the flight, as mentioned in checklist. We have already taken safety into account when designing the system. Firstly, we use small prop protection. Then we designed two emergency schemes. One is that we can stop the propellers via the data link between the ground station and Quadrotor. The other one is that we can take over the Quadrotor through one channel of RC controller. These two schemes uses different data link, improving the system security redundancy.

C. Modeling and Simulation

Modeling

As shown in fig.7, E(X,Y,Z) is the world frame, B(X,Y,Z) is the body frame.

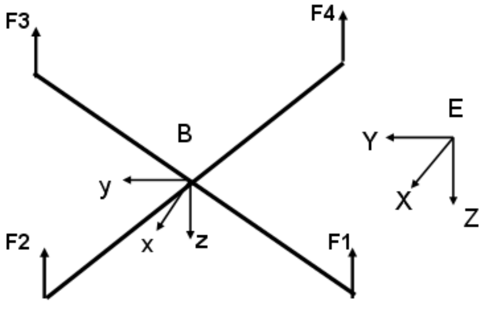

Figure 7. World frame and body frame.

World frame is related to the ground, and the body frame is fixed to the Quadrotor. Therefore, the Quadrotor's maneuver can be represented by the relative motion of B around E. And the relative motion can be divided into parallel motion and rotary motion. The parallel motion corresponds to Quadrotor's position change, which is relatively simple. The rotary motion corresponds to Quadrotor's attitude change which should be represented by rotation matrix.

Then we define the representation of attitude angles. We use x-y-z Euler angle to represent Quadrotor's attitude, as shown in fig.8.

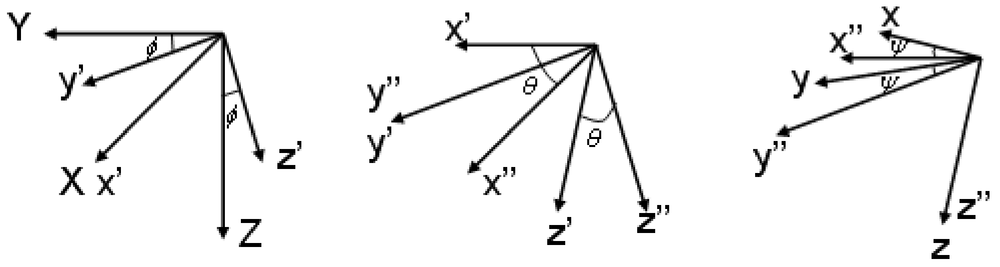

Figure 8. Sketches of pitch roll and yaw.

We can get the rotation matrix of B around E through computation.

$$ {}_B^E R_{xyz} = $$

$$\begin{pmatrix} \cos\psi\cos\theta & -\sin\psi\cos\theta & \sin\theta \\ \cos\psi\sin\theta\sin\phi+\sin\psi\cos\phi & -\sin\psi\sin\theta\sin\phi+\cos\psi\cos\phi & -\cos\theta\sin\phi \\ -\cos\psi\sin\theta\cos\phi+\sin\psi\sin\phi & \sin\psi\sin\theta\cos\phi+\sin\phi\cos\psi & \cos\theta\cos\phi \end{pmatrix} \tag{1}$$

Vectors in B frame can be transformed into E frame with the matrix (1).

The source of the Quadrotor's propulsion is very simple, which is the lift force and the moment generated by the four propellers' rotation. We can find that the force analysis of the Quadrotor in the body frame has a very simple representation:

$$\vec{F}_B = \begin{pmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} F_i \end{pmatrix} \tag{2}$$

F_i is the lift force generated by the i-th propeller. With the help of the previous matrix, we can transform the force into the world frame:

$$\vec{F}_E = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = {}_B^E R \vec{F}_B = \left(\sum_{i=1}^{4} F_i \right) \begin{pmatrix} \sin\theta \\ -\cos\theta\sin\phi \\ \cos\theta\cos\phi \end{pmatrix} \tag{3}$$

Ignoring the air resistance, we can get the parallel motion equations of the Quadrotor by the Newton's second law.

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = \frac{1}{m} \begin{pmatrix} F_x \\ F_y \\ F_z - mg \end{pmatrix} = \begin{pmatrix} \dfrac{\sin\theta}{m} \displaystyle\sum_{i=1}^{4} F_i \\ \dfrac{-\cos\theta \sin\phi}{m} \left(\displaystyle\sum_{i=1}^{4} F_i \right) \\ \dfrac{\cos\theta \cos\phi}{m} \left(\displaystyle\sum_{i=1}^{4} F_i \right) - g \end{pmatrix} \tag{4}$$

Then we can get the rotary motion equations of the Quadrotor according to moment balance:

$$\begin{cases} \ddot{\phi} = l\left(F_1 - F_2 - F_3 - F_4\right)/I_x \\ \ddot{\theta} = l\left(F_1 + F_2 - F_3 - F_4\right)/I_y \\ \ddot{\psi} = \left(M_1 - M_2 + M_3 - M_4\right)/I_z \\ \quad = \left(F_1 - F_2 + F_3 - F_4\right)/I_z' \end{cases} \tag{5}$$

l is the distance from the motor to the center of body, M_i is the reverse moment generated by motor rotation, $I_z^{'}$ is an equal physical quantity used to replace M_i with F_i. (4) and (5) comprise the quadrotor's models.

Simulation

Fig.9 shows that how does our algorithm that used for crossing hole in the obstacle realizes.

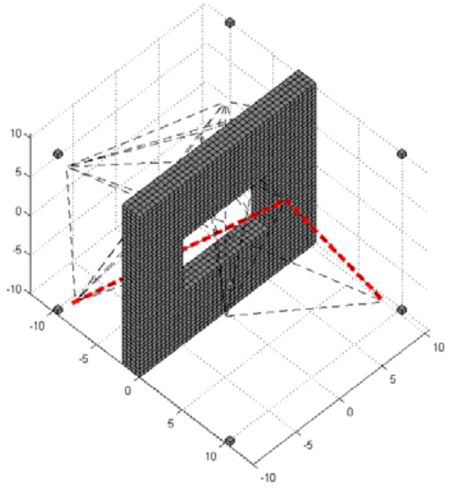

Figure 9. Path planning simulation result.

D. Testing

The test on Quadrotor consists of following parts:

1. Check every component and make sure that they all work fine. Meanwhile, test the link between them;
2. Test the inner-loop (attitude loop) by sending attitude and thrust orders to Quadrotor through RC controller, and get the actual flight status to analyze the dynamic performance of attitude loop controller;
3. Test on control logic and make sure that Quadrotor can deal with control information from different sources, and make the control modes switch reliably. The most important part of the switch test is to make sure RC controller can take over Quadrotor at any time;

4. Add a height control loop to Quadrotor, that is, we only have to adjust the attitude angles through RC controller and Quadrotor will achieve height stabilization by programs onboard, so as to make itself stay in air for a long time;
5. Add a position control loop by the airborne equipment so that Quadrotor can hovering by itself and flying according to the position orders from the ground station.

VI. CONCLUSION

In this paper, we presented the technical details of a Quadrotor system capable of exploring unstructured indoor areas, detecting and replacing a specific USB flash disk, without relying on any external navigation aids. The Quadrotor uses an off-the-shell base platform with various sensors onboard. Information provided by laser range finder, inertial measurement unit and ultrasonic altimeter are fused to form a self-navigation solution using Gmapping SLAM algorithm. Two visible light cameras are mounted on the vehicle, the frontward one is used to detect the target room, and the downward one is responsible for USB disk identification with a simple manipulator to replace it. A DH-Bug path planning algorithm is introduced to help the vehicle implementing obstacle avoidance. Moreover, we design elaborate control architecture to ensure the stability and mitigation of vehicle uncertainties.

So far, we have already finished SLAM and control architecture development, corresponding test and simulation are currently in progress. The Tsinghua Aerial Robotic Team intends to compete in the 2012 IARC competition with this vehicle.

VII. REFERENCES

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