ZJU Team Entry for the 2013 AUVSI International Aerial Robotics Competition

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ABSTRACT

This paper introduces the autonomous quadrotor aircraft of the *Wing of Yuquan* Team of Zhejiang University in detail. Our quadrotor aircraft system is capable of exploring and operating autonomously in unknown indoor environment, moreover seeking out the USB flash disk and replacing it. Firstly, an overview of our quadrotor aircraft system is shown, including the problem statement and our team's conceptual solutions. Secondly, the basic hardware system of our quadrotor aircraft consists of the air frame, propulsion and lift system, navigation and control boards and various onboard sensors. Thirdly, the most important part of our aircraft — the software system is detailed, including indoor navigation, vision algorithm, control system, path planning algorithm and so on. In the end, the risk reduction measures are also told.

1 INTRODUCTION

1.1 Overview

Recently, Unmanned Air Aircraft (UAV) 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.

While many UAV applications are in outdoor environment, its navigation technology is not enough for covering the overall applications. Navigation in the indoor environment is obviously different from that in the outdoor environment. The Global Positioning System (GPS) signal, as the most important localization data source in outdoor navigation, could not be available within the buildings. Alternatively, the UAV could rely on the Simultaneous Localization and Mapping (SLAM) algorithm to build the map and estimate its position in the indoor environment.

Due to the IARC 2013 indoor environment and GPS signals denied, our team — the *Wing of Yuquan* Team of Zhejiang University designed a quadrotor aircraft capable of carrying out the task autonomously.

1.2 Problem Statement

The International Aerial Robotics Competition (IARC) maintained its military background in Mission 6. This mission requires the teams to apply completely autonomous aircraft. The takeoff weight cannot be over 1.5 kg. The aircraft should enter and explore an unknown military building autonomously, then seek out a specific USB flash disk and replace it secretly. The whole task must be finished within 10 minutes. If the aircraft don't withdraw from the building at a set time, it must land and turn off the propulsion system, then launch its self-destroy device to destroy the flash disk (through the start-up of beep imitation).

In short, the 6th Mission consists of five steps: 1) Enter the building through an opening window; 2) Search the building for a flash disk; 3) Retrieve the USB flash disk; 4) Replace it with a duplicate flash disk; 5) Withdraw from the building.

1.3 Conceptual Solution

Our team uses the quadrotor aircraft that we designed by ourselves. The quadrotor aircraft is equipped with two CMOS cameras, one laser range finder, one ultrasonic altimeter and the foam rubber on the bottom used for attaching the USB flash disk. The front camera of the aircraft is used to judge the on and off status of blue LED, doorplate signs and laser trip wire identification with target recognition algorithm. Another camera on the bottom is mainly applied for velocity measurement and the search and recognition of USB flash disk. Laser range finder is used for SLAM algorithm. The ultrasonic altimeter is for height estimation. When the aircraft detects the USB flash disk, our aircraft will try to attach the flash disk and put down the fake one. And then our aircraft will withdraw from the building. The quadrotor control system architecture can be seen in Figure 1.

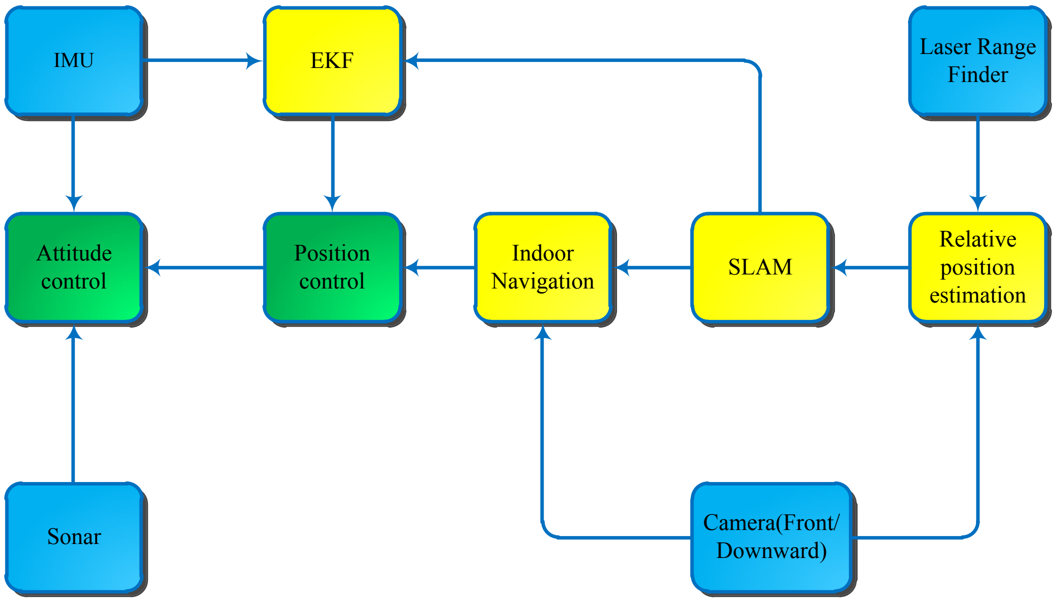


Figure 1. The quadrotor control system architecture

2 HARDWARE STRUCTURE

Concerning the features of the indoor environment and the competition task (retrieving and picking up a flash drive), our quadrotor aircraft capable of Vertical Take-Off and Landing (VTOL) is a desirable flight platform. The hardware structure of the platform is detailed as follows.

2.1 Air Frame

The air frame of quadrotor is quite important, while the payload of the electronic boards and various sensors are mounted on it. A quadrotor aircraft has four propellers, as all the axes of the propellers are parallel and fixed. The physical construction is relatively simple and more robust than many other structures because there is a suitable place to set onboard electronic system on the geometrical center of the quadrotor. Thus the air frame should be very solid and robust, our team chose carbon fibers, which perform better on strength and weight, as our air frame. The air frame is shown in Figure 2.

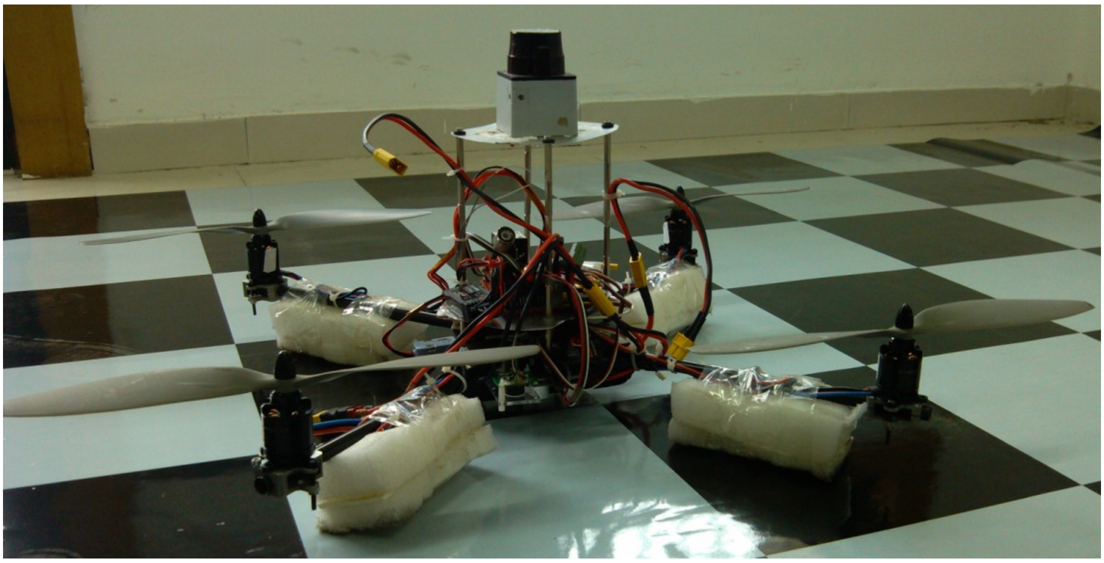


Figure 2. The "Wing of Yuquan" quadrotor platform

2.2 Propulsion and Lift System

Our quadrotor aircraft equipped with four brushless DC motors and four propellers, which distribute symmetrically at the end of four arms. Two pairs of propellers spin clockwise and counter-clockwise respectively, such that the sum of their reaction torques is zero during hovering. A quadrotor is an aircraft that becomes airborne due to the lift force provided by four rotors usually mounted in cross configuration. It is an entirely different aircraft when compared to a helicopter, mainly in the manner of dynamics and control. Classical helicopters are able to shift the angle of attack of its blades periodically to adjust its flight attitude, while a quadrotor has all the blades fixed to the axles, and achieves flight control via collaboration of the propellers.

We change the rotational speed of the four motors, thus creating a relative thrust offset between the propellers. Therefore, the attitude control is achieved, in order that we can achieve velocity and position control. Our air frame is of "X" type and the body coordinate axis is shown in Figure 3.

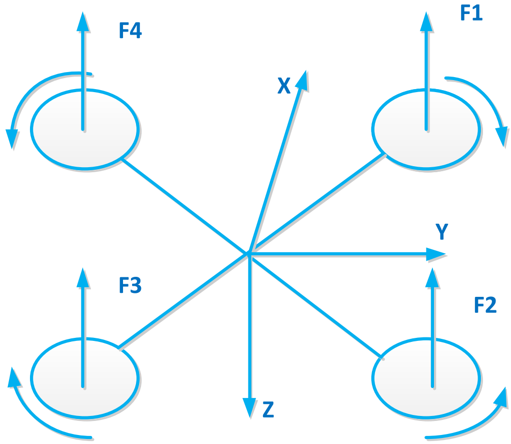


Figure 3. Propulsion and lift system with body coordinate

2.3 Hardware Architecture

The hardware platform of our UAV consists of four parts: 1) flight control board, 2) ARM board 3) ground control station, 4) onboard sensors. The hardware architecture is shown in Figure 4.

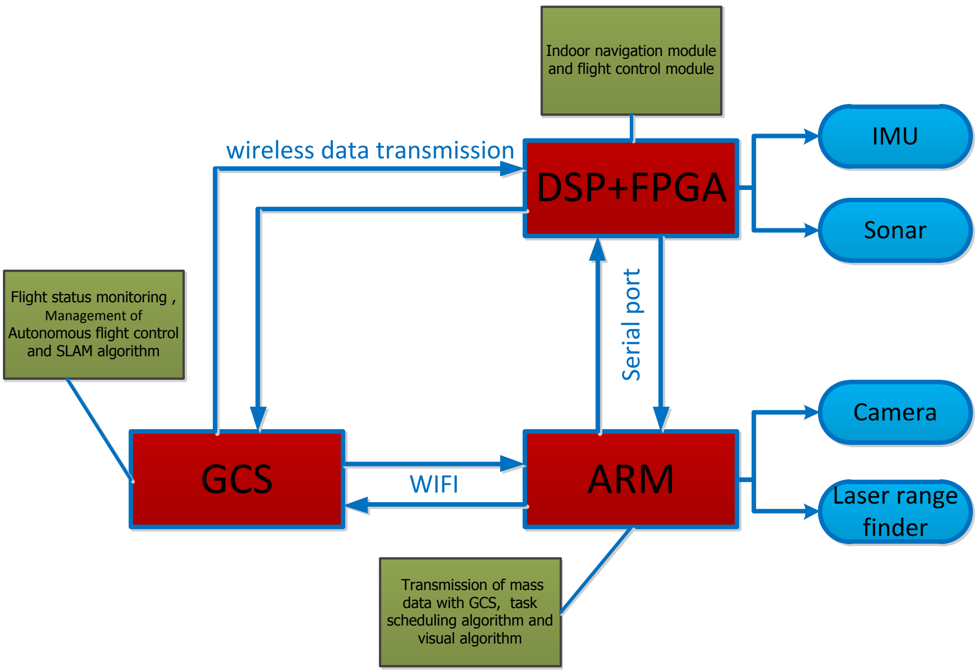


Figure 4. The hardware architecture of UAV system

The fight control board is the core part of the whole system, which is responsible for the implementation of the inertial navigation system (INS), indoor navigation algorithm and flight control algorithm. Considering the calculating speed and the number of external interfaces, we choose the Digital Signal Processor (DSP) with Field Programmable Gate Array (FPGA) hardware architecture as the CPU of flight control board. Compared with Advanced RISC Machines (ARM), DSP is more efficient, and is suitable as the computing CPU. But DSP has not enough external interfaces, so we choose FPGA to extend DSP external interfaces specifically. Thus inertial measurement unit (IMU) and ultrasonic sensor could be mounted on the FPGA. The DPS with FPGA hardware architecture makes the flight control board of high speed, rich interfaces, and easy to realize modularization.

We use a Beagleboard with Ubuntu operating system to operate the upper software including the management of WIFI device, task scheduling algorithm and vision algorithm.

Ground control station (GCS) is responsible for flight status monitoring, management of flight control and SLAM algorithm.

Sensors are also important, and various sensors are mounted on the hardware platform, including laser range finder, IMU, vision light cameras and ultrasonic altimeter. The IMU and ultrasonic altimeter sensors are connected to the flight control board. IMU is for the realization of the inertial navigation system (INS) and ultrasonic altimeter is used for height estimation. Two CMOS cameras and the laser range finder are connected to the Beagleboard. Cameras are used to recognize the specific doorplate signs and the USB flash disk, as well as velocity measurement. Laser range finder is used for Simultaneous Localization and Mapping (SLAM) algorithm. The sensors we used are shown in Figure 5.

(a)CMOS camera *(b) Laser range finder* *(c) Ultrasonic altimeter*

Figure 5. The onboard sensors

2 SOFTWARE SYSTEM

2.1 Flight Control

Corresponding to Hierarchical structure[1]: organization level, coordination level, and execution level, we divide the control task into three layers: 1) motion control layer, 2) action plan layer, 3) flight scheduling layer. From the bottom to the top, it is more and more intelligent. The fight control task architecture is detailed in Figure 6.

1) Motion control layer (execution level): We divide a complex control task into several simple control modes including hovering, forward flight and so on. Each atomic control mode in a different controller under different control algorithms executes in accordance with the corresponding function. This layer will be the basic action library packaged into a single module, respectively, so that by simply adding or modifying the controller, it is efficient to complete the single-mode operation and maintain the library expansion.

2) Motion planning layer (coordination level): Firstly, to detail switching-out conditions of the

current task, which is used to determine if it can be switched to the task modal; Secondly, to generate the next task modal reference trajectory as the set value in a single-mode control; Thirdly, to achieve undisturbed switching among task modals. For example, Hovering: to determine a region (hovering circle, setting the region of space — the horizontal distance x m and, vertical distance y m from the hovering point), if the quadrotor at a low speed stabilizes in the hovering circle, when hanging over one second, then operate switching-out.; If the four rotor speeds fall over a small but stable loop, when the time reach eight seconds, then operate switching-out.

3) Flight scheduling layer (organizational level):

(A) Cope with the conventional route tasks, be able to plan single-mode task execution sequences independently.

(B) Cope with the real-time airline routes changing process of task scheduled through the ground station, allow artificially adding, deleting, and editing waypoints not executed.

(C) Cope with switching routes in the mission of route tasks, can be switched to manual mode or perform other tasks, still require the quadrotor capable of executing tasks from a route waypoint until the task is completed.

(D) Cope with the emergency treatment in the event of failure and in the case of emergency situations, can abort the current task and execute the appropriate emergency response mechanism.

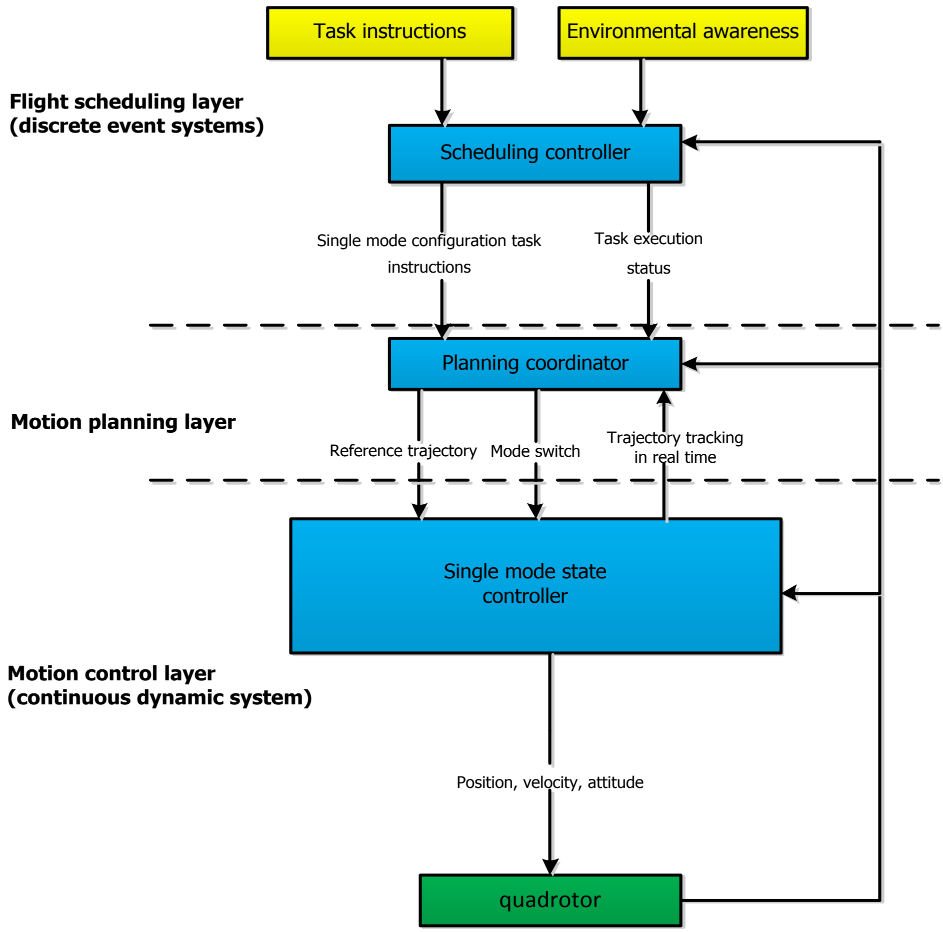


Figure 6. The fight control task architecture

The motion control layer is the most important because it manages all the basic controllers. So we use four-channel cascade control strategy which is applied in the four channels of roll, pitch, yaw, and vertical. PID controller is used for attitude loop. The differential D is actually a damper, which can be used to improve the damping characteristic of the object. Velocity loop and position loop are PI controllers. The cascade control schematic of the quadrotor is shown in Figure 7.

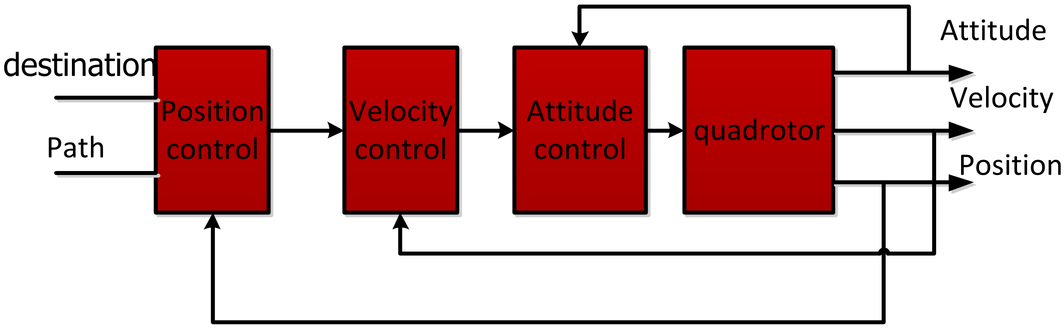


Figure 7. The cascade control schematic of quadrotor

3.2 Indoor Navigation

Indoor navigations is used to estimate the whole state of the aircraft. There is no GPS signal in the indoor environment, so we cannot use integrated GPS and INS navigation algorithms to provide the state estimation. Fortunately, SLAM algorithm is very suitable for the aircraft indoor navigation. SLAM is used to build the map around the aircraft and estimate its position simultaneously, so it can provide the global position and velocity information precisely. We fuse the SLAM results with INS process via EKF algorithm to provide correct and convergent state estimation. In fact, SLAM is used to correct the drift of state estimation caused by IMU bias. In order to process SLAM at a high frequency, we decide to choose D&C SLAM[2] which can provide a balance performance between speed and precision.

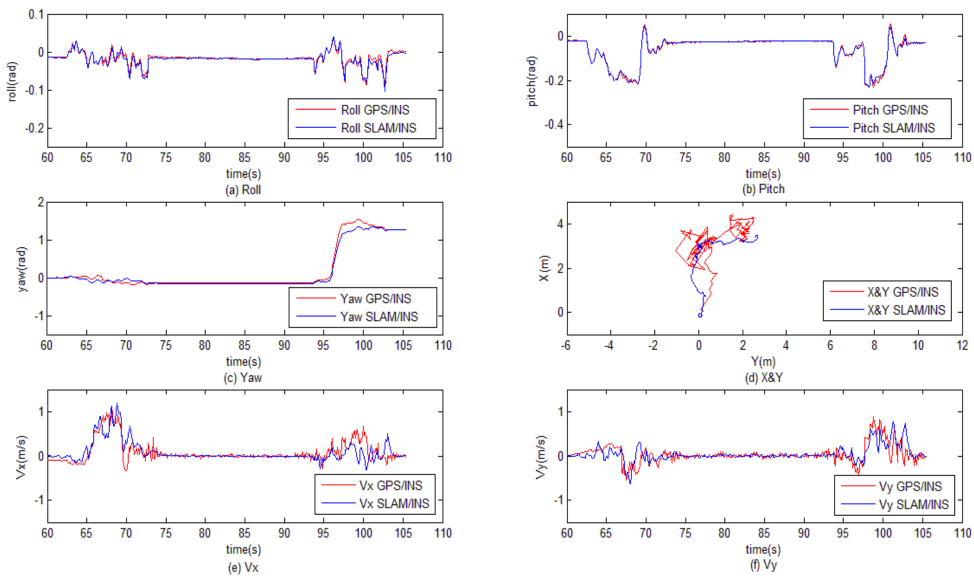


Figure 8. State curves estimated by GPS/INS and SLAM/INS navigation systems

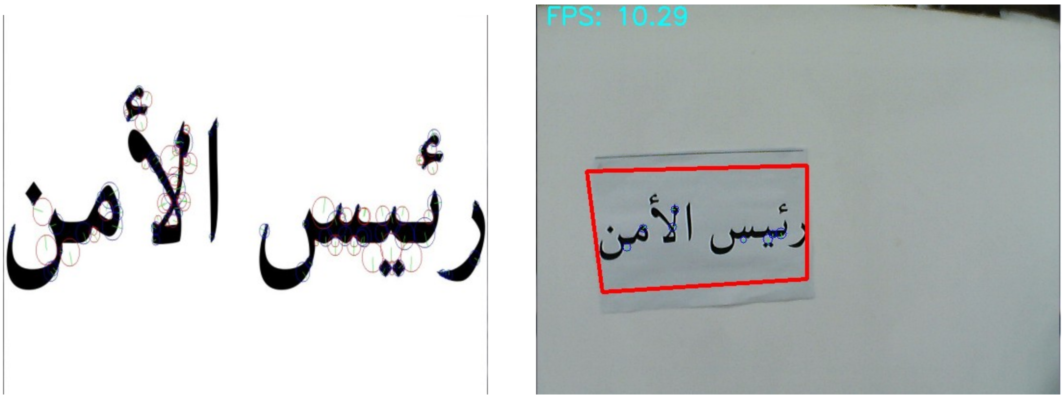
The state curves estimated by GPS/INS and SLAM/INS navigation systems are our experiments' results, shown in Figure 8. In general, the attitude estimations are almost the same. The velocity estimation of GPS/INS is better than that of SLAM/INS, and the position estimation of SLAM/INS is better than that of GPS/INS.

3.3 Path Planning and Obstacle Avoidance System

Path planning is used to navigate the aircraft to enter into the target room, with obstacle avoidance capacity based on 3D global map. D&C SLAM can build 2D map at a certain height. So it's easy to build many 2D maps at different heights which can be combined to a 3D global map. The key point of path planning is to decide which way to go and guarantee no repeating. The basic algorithm of path planning is wall following which leads the aircraft to fly forward in a passageway. The upper path planning algorithm is Distance Histogram Bug (DH-Bug) algorithm which is very efficient.

3.4 Vision System

The aircraft is equipped with two CMOS cameras. The front camera is used to judge the on and off status of blue LED in the opening of the compound, the signboard of the office of the "Chief of Security" and laser trip wire identification; another camera on the bottom is applied for the recognition of flash drive and velocity measurement in the indoor environment where GPS signal denied. The detection of the blue LED is performed using a simple blob detection mechanism, and we use the HSI color model to deal with the effects of illumination and hue respectively. We do doorplate sign recognition via SURF[3] (Speeded Up Robust Features), and matching these descriptors with those found in the target sign board via the RANSAC brute forcing method. The sign recognition result can be seen from Figure 9. The recognition of the USB flash disk is also done with SURF algorithm.



(a)The origin sign *(b)The recognition result*

Figure 9. Sign recognition using SURF

3.5 Communication

The Beagleboard receives the data sent by the laser range finder, and transmits them to the GCS via WIFI. At the same time, in order to implement the path planning and the flight control after image processing, the DSP and Beagle Board keep on exchanging data during all the flight. The DSP and GCS communicate with each other by sending the flight status and receiving the orders from the GCS in real time.

3.6 Ground Control Station

As presented above, the GCS is a very important part of the system, the GCS software is built on the PC, and the main functions of GCS consist of flight status monitoring, graphical map displaying, data storing, playback, and the SLAM algorithm calculating. On one hand, we can observe the status of the quadrotor in the visual area of the GCS; on the other hand, the data received from UAV can be saved in the GCS for future data analysis.

3.7 Task Scheduling Mechanism

Due to the complexity of the 6th mission, we divide the mission into several simple tasks and put them into a finite-state machine (FSM). The FSM is designed to schedule all the simple tasks and manage all the sub modules, such as the flight module and the vision module.

4 RISK REDUCTIONS

During the experiments, we also design some measures to reduce risks. The measures cover two aspects: inference mitigation and safety guarantees.

4.1 Interference Mitigation

When the quadrotor is in the flight, the shock or vibration of the motors and propellers will interfere the ultrasonic sensor, the accelerometer and many other sensors, which affects the data that the sensor acquires. On one hand, we use cushions to isolate the shock or vibration; on the other hand, we design filters to mitigate it.

Besides, Electromagnetic interference (EMI) also exits in the system. When experimenting in outdoor environment, we lift the antenna of GPS at the beginning, which could eliminate EMI. Moreover, there are 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 works without radio frequency interference (RFI).

4.2 Safety Guarantees

To ensure the safety of people and the quadrotor aircraft, a series of tests should be taken before the flight. And we have already taken safety into account when designing the system. We designed two emergency schemes. One is that we can stop the propellers via the data link between the GCS and the quadrotor. The other one is that we can take over the quadrotor through one channel of RC controller. These two schemes use different data link, improving the system security redundancy.

5 CONCLUSION

In this paper, our team developed a quadrotor UAV system for the 2013 AUVSI International Aerial Robotics Competition. The technical details of the quadrotor UAV system are presented in the aspects of hardware structure and software system, respectively. Moreover, we design risk reduction measures to ensure the safety and mitigation of aircraft uncertainties.

Before the competition, additional tests are still needed to make the quadrotor UAV system become robust and accurate enough. Our team—the *Wing of Yuquan* Team of Zhejiang

University, intends to participate in the 2013 AUVSI International Aerial Robotics Competition with this quadrotor UAV.

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