Micro Air Vehicles' Motion Estimation and Autonomous Navigation in Indoor Environment without GPS

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ABSTRACT

This paper presents a solution of MAV autonomous navigation in unknown indoor environments without GPS signals. We have designed a quad-rotor aircraft. The quad-rotor aircraft's motion is estimated by a variety of on-board sensors, and environments are sensing by fusing measurement data of visual sensors and laser scanning radar. The architecture of whole solution is detailed, and related algorithms are introduced. The experiment results show that our quad-rotor aircraft can autonomously navigate in unknown indoor environment without GPS signals, and finish the appointed tasks.

1. INTRODUTION

Due to occlusion, noise and other reasons, GPS signals in indoor environment are very unstable, which can't provide accurate location information. IMU sensors often have large accumulated errors. Because of MAVs' small size and light weight, load capacity is limited. The limitation forces MAVs to rely on micro sensors.

We describe a solution on quad-rotor platform for indoor tasks. The quad-rotor aircraft's motion is estimated by on-board sensors and stabilized by itself. When the aircraft flies into indoor space, environments are sensing by visual sensors and laser scanning radar. Videos captured by on-board camera are transmitted to ground station. After finished the appointed tasks, the aircraft autonomously navigate to entry point according to a map which is build throughout flight.

1.1 Conceptual solution

Our system mainly consists of two parts: on-board processing part and ground control station processing part.

MAV on-board hardware contains flight control processor DSP, image processor DSP, 3-axis gyro, 3-aixs accelerometer, magnetometer, forward looking camera, downward looking camera, ultrasonic sensor, laser scanning radar. Gyros, accelerometer and magnetometer are mainly used for measuring the attitude of the aircraft, including roll angle, yaw angle, pitch angle. Forward looking camera auxiliary measures the attitude by computer vision methods. An Extended Kalman Filter(EKF) combines these date measured to estimate accurate attitude of the aircraft. Ultrasonic sensor provides altitude estimation. Downward looking camera and laser scanning radar are used for estimating the aircraft's location. Attitude stabilization algorithms and intelligent control algorithms are implemented in flight control processor. Image processor is running for Video capturing, image preprocessing algorithm, data compression. After the aircraft's pose is determined, the data and image frames are packed and send to ground control station by wireless transmission module.

A ground control station consists of the following several major software modules: map building module, object localization module, obstacle avoidance module and path planning module. After the ground control station receives image data, the aircraft's pose data, laser scanning radar measurement, all of data are processed in software modules. Then commands are send back to airborne platform in order to implement the aircraft autonomously navigation and finishing related tasks.

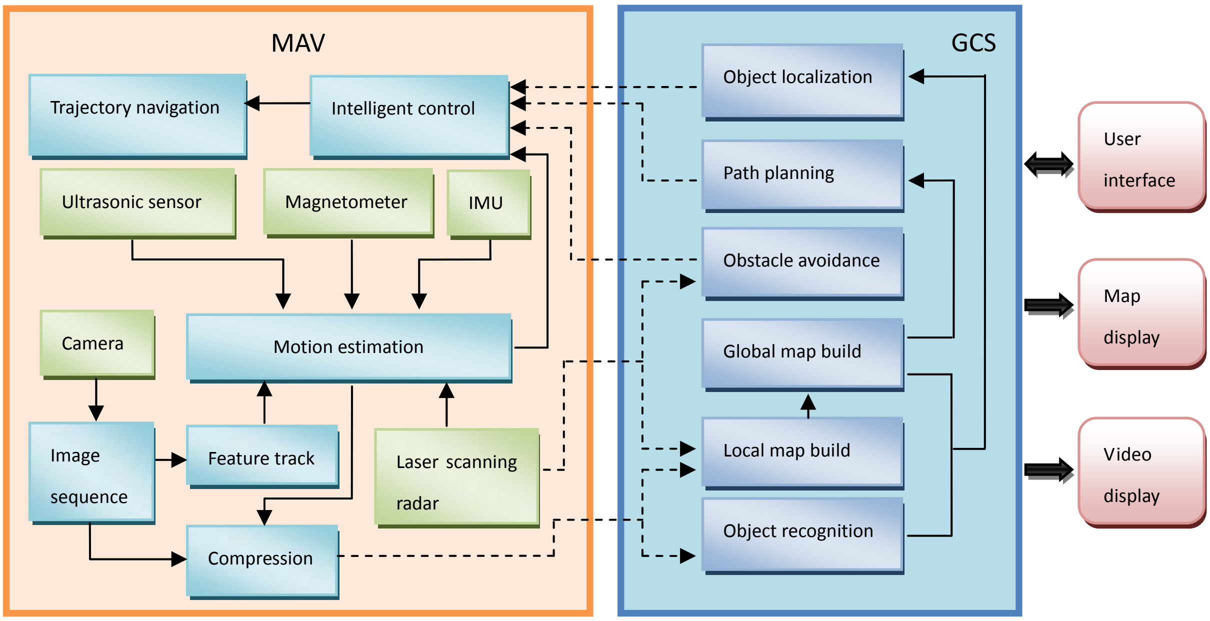

Figure 1. Our system architecture

2. AIR VEHICLE

2.1 Propulsion and Lift system

The MAV we have used is a quad-rotor aircraft. Miniature brushless torque motor and high sensitivity electronic governors are mounted on the platform. Through the tiny brushless motors and miniature propellers matching tests, the propellers and motors have been best matched. The aircraft can take off and land vertically, hover and maneuver. We use multi-disciplinary optimization methods to optimize design with weight and size constraints. The configuration layout, structure, power, energy, system, sensor, all of them are optimized in order to ensure carrying capacity. We use carbon fiber composite materials to design and develop the structure which has light quality, enough strength and stiffness. Figure 2 shows the model of a quad-rotor aircraft.

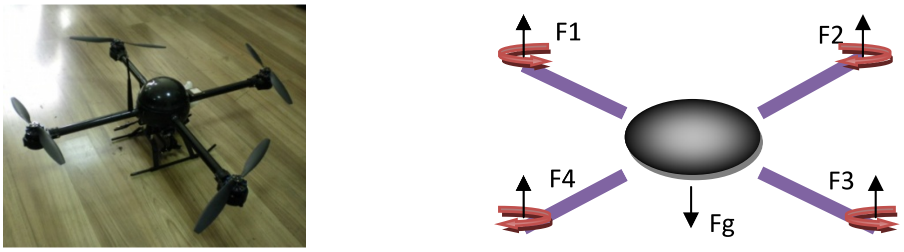

Figure 2. Model of a quad-rotor aircraft

2.2 Control System

Due to the size and weight miniaturization, the measurement error of low cost sensors directly used may be large. Therefore, the error analysis and modeling are adopted in order to improve the precision of the devices used, including random disturbance torque, TFG disturbed torque influence, open loop sensitivity effect, temperature influence, MEMS error compensation et al. An EKF is used for estimating error parameters, feeding back to navigation system, compensating corresponding errors, and correcting feeding back which is closed loop correction. Figure3 shows the control system hardware.

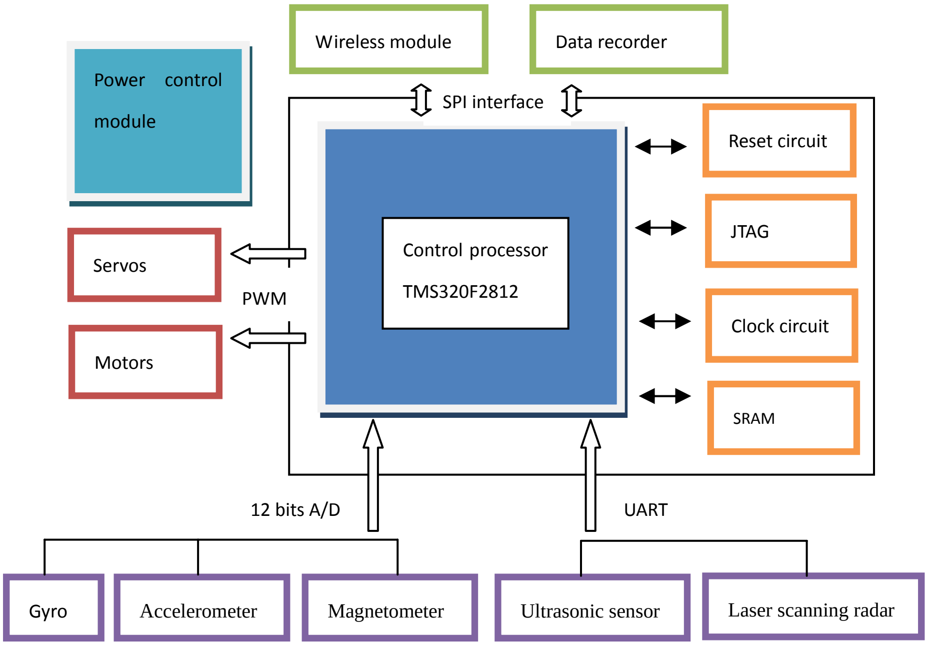

Figure 3. Control system hardware

We have designed an expert system based on fuzzy control procedures. A proper fuzzy parameter rules are determined by studying MAV’s nonlinear model, different control parameters for the system efficiency and stability. The fuzzy control design is include fuzzed processing, formulating fuzzy rule sets, getting corresponding fuzzy relations, generating fuzzy operators, getting the corresponding fuzzy control values. According to removing fuzzy rules, the fuzzy control values are converted to accurate control signals. The expert system is used for attitude control, trajectory control and speed control.

The flight dynamics of quad-rotor is nonlinear and unsteady because of its small size, low speed, special aerodynamic configuration and complex flight environment. The traditional control methods are incompatible with the development of quad-rotor aircrafts. The dynamic inversions to slow states and fast states are designed using the theory of time-scale separation. On-line neural networks are introduced to compensate the dynamic inversion errors, and pseudo control compensations are used to cancel the interaction between the actuators and the adaptive factors. The adaptive flight control system of quad-rotor aircraft is studied based on the theories above and compared with the flight control system using dynamic inversion-PID. The simulation results demonstrate that the flight control system based on adaptive dynamic inversion is robust and capable of following commands. Compared with the dynamic inversion-PID control system, the adaptive control system is more suited to quad-rotor aircraft. Figure4 shows the adaptive dynamic inversion based control architecture.

2.3 Flight Termination System

When accident happens, the aircraft can be switched to manual control model form autonomous control mode. If the aircraft can receive RC controller's command signals, the onboard control system starts autonomous landing procedure and shut down motors.

3. PAYLOAD

3.1 Sensors

Our quad-rotor aircraft sensors contain a forward looking camera, a downward looking camera, a laser scanning radar and an ultrasonic sensor.

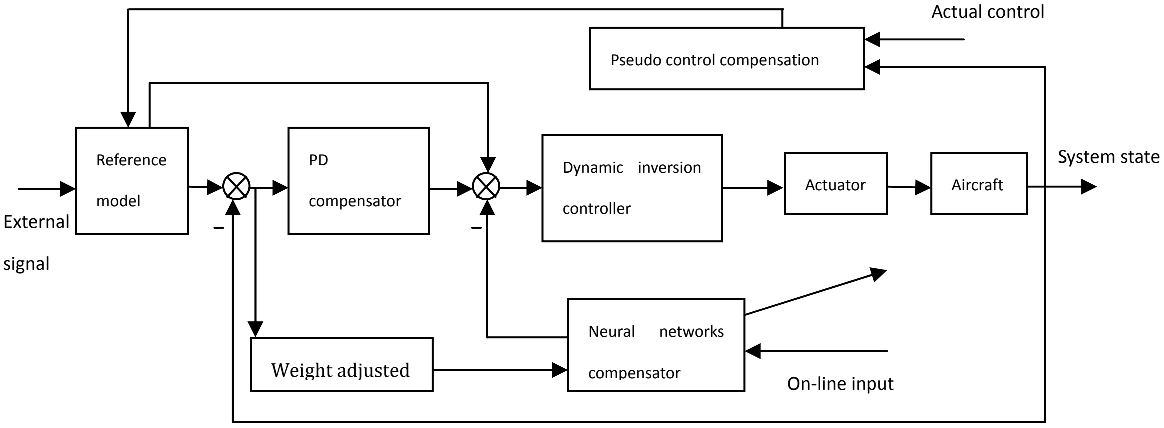

Figure 4. Adaptive dynamic inversion based control architecture

URG-04LX laser range-finder offers both serial (RS-232) and USB interfaces to provide extremely accurate laser scans. The field-of-view for this detector is 240° at 10Hz. Distances are reported from 20 mm to 4 m (0.79 in to 13.12 ft). This sensor comes with diagnostic software and detailed information on the simple serial protocol used to manipulate the readings, turn on/off the laser, and interact with this rich sensor. This sensor is used for environment perception and map building.

Our ultrasonic sensor provides altitude measurement for quad-rotor aircraft navigation in indoor environment. The field-of view for this sensor is smaller than 15°. The accuracy can reach 3mm, and its distances are reported from 0.02m to 5m.

3.2 Vision sensors

We have designed a vision system consist of a downward looking camera, a forward looking camera and an image processing DSP TMS320DM642.

The downward looking camera captures ground images. Optical flow algorithm calculates the aircraft's velocity. The Harris corners[1] is a well known detector that is widely used in large amount of applications. It extracts many corners very quickly based on the magnitude of the eigenvalues of the autocorrelation matrix.

Optical flow method as an important motion detection method is firstly proposed by Horm and Schunck[2]. $I(x, y, t)$ is an intensity image at instant t. At a small increment $\triangle t$, intensity image is $I(x+\triangle x, y+\triangle y, t+\triangle t)$, assuming that

$$I(x+\triangle x, y+\triangle y, t+\triangle t)= I(x, y, t) \tag{1}$$

For a small displacement $(\triangle x, \triangle y)$, Eqn. 1 can be approximated by the linear terms of its Taylor series. The second and higher order terms of the Taylor series expansion are negligible.

$$I_x u + I_y v + I_t = 0 \tag{2}$$

$$I_x = \frac{\partial I}{\partial x},\quad I_y = \frac{\partial I}{\partial y},\quad I_t = \frac{\partial I}{\partial t},\quad u(x,y,t) = \frac{dx}{dt} = \frac{\Delta x}{\Delta t},\quad v(x,y,t) = \frac{dy}{dt} = \frac{\Delta y}{\Delta t}.$$

$$(\nabla I)^T U + I_t = 0 \tag{3}$$

Lucas and Kanade[3] assume that motion vectors are constant in a small image window. Optical flow estimation error is defined as

$$\sum_{(x,y)\in\Omega} W^2(x)(I_x u + I_y v + I_t)^2 \tag{4}$$

Where $W^2(x)$ is window weight function. The solution of Eqn. 4 is

$$U = (A^T W^2 A)^{-1} A^T W^2 B \tag{5}$$

$$X_i \in \Omega,\quad A = [\nabla I(X_1),...,\nabla I(X_n)]^T,\quad W = diag[W(X_1),...,W(X_n)],\quad B = -[I_t(X_1),....,I_t(X_n)]^T.$$

As displacement of $(\triangle x, \triangle y)$ in image coordinate outputs, we divide it by time T. Then we can get image movement speed. After that, the image speed multiplies a coefficient which is equal to the ratio of H and h. H is the distance between lens and ground plane, h is the distance between lens and image plane. The aircraft's speed can be calculated in X direction and Y direction. Figure5 is the optical flow result.

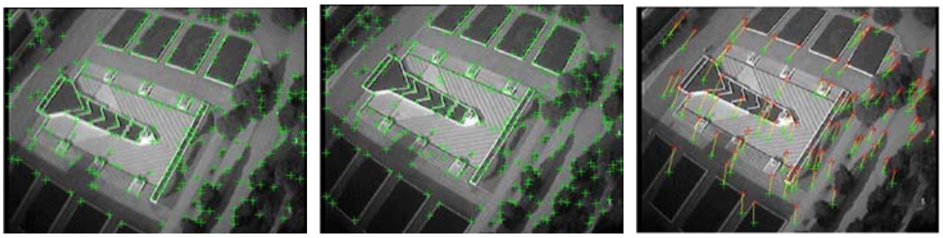

Figure 5. Optical flow result

The forward looking camera provides measurement of attitude and position for quad-rotor aircraft. The aircraft need reliable attitude and position information in indoor environment. The measurement of onboard IMU sensors such as gyros and accelerometers are corrupted by large accumulated errors, and GPS signal is unavailable in such situation. A vision based indoor MAV motion estimation and structure recovery method is presented. Firstly, Features were tracked by biological vision based matching algorithm through the image sequence, and the camera's motion was estimated by a five point algorithm. In indoor environment, the planar relationship was used to reduce feature points' dimension from three into two. Then, these parameters were optimized by a local strategy to improve motion estimation and structure recovery accuracy. The measurements of IMU sensors and vision module were fused with EKF. MAVs' attitude and position information were estimated.

Point p and p' are the corresponding points on two frames, the relationship between the two points as:

$$\mathbf{p}'^{\mathrm{T}}\,\mathbf{E}\mathbf{p} = 0 \tag{6}$$

E is essential matrix. Nister uses Gauss-Jordan elimination method to solve the polynomial equations for all possible solutions[4]. Combined with RANSAC algorithm, feature points re-projection errors are calculated and the only one solution of essential matrix is got with eliminating the mismatch. After that, camera's relative motion can be estimated.

In order to reduce computer burden, we presents a dimension reduction method. Many planes exist in indoor environment, and a lot of feature points are located on these planes. Using the relationship between feature points and planes can reduce the redundant information. There are seven parameters for describing a plane $\boldsymbol{\pi}_i=[\boldsymbol{\mu}_i,\alpha_{1i},\beta_{1i},\alpha_{2i},\beta_{2i}]$. $\boldsymbol{\mu}_i$为is mean value of these feature points on the plane. The direction of the plane are two base vectors $\mathbf{v}(\alpha_{1i},\beta_{1i})$, $\mathbf{v}(\alpha_{2i},\beta_{2i})$.

$$\mathbf{v}(\alpha,\beta) = [\cos\alpha\sin\beta, -\sin\alpha, \cos\alpha\cos\beta]^{\mathrm{T}} \tag{7}$$

Now, the feature points on the plane can be described as:

$$\mathbf{P}_j^{new} = [(\mathbf{P}_j - \boldsymbol{\mu}_i)\cdot\mathbf{v}(\alpha_{1i},\beta_{1i}), (\mathbf{P}_j - \boldsymbol{\mu}_i)\cdot\mathbf{v}(\alpha_{2i},\beta_{2i})]^{\mathrm{T}} \tag{8}$$

The number of m feature points' position parameters is reduced from $3m$ to $2m+7$. We use k-means method for all of these feature points [5].

Assuming that a given image sequence, feature points' position information and camera motion parameters are treated as initial estimation. Maximum likelihood estimation method is used for optimization. In order to meet the real-time need, we present a local optimization strategy to optimize the camera's movement parameters and indoor environment structure. Local optimization method uses Levenberg Marquardt algorithm[6] to minimize cost function $\boldsymbol{\varepsilon}^i(\boldsymbol{\zeta}^i,\boldsymbol{\eta}^i)$. The cost function is described as:

$$\varepsilon^i(\boldsymbol{\varsigma}^i,\boldsymbol{\eta}^i) = \sum_{C^k\in\{\mathbf{C}^{i-N+1}\ldots\mathbf{C}^i\}}\ \sum_{\mathbf{P}_j\in\boldsymbol{\eta}^i}\left\|\mathrm{d}^2(\mathbf{p}_j^k,\mathbf{C}^k\mathbf{P}_j)\right\|^2 \tag{9}$$

N (number of optimized cameras at each stage) and M (number of images taken into account in the re-projection function) are the two main parameters involved in the optimization process. The given value can influence both quality of results and speed of execution. Our strategy is:

$$\begin{cases} n=3, N=5 & if(\mathbf{v}_{mav}\le\mathbf{v}_{thresh}) \\ n=5, N=M & if(\mathbf{v}_{mav}>\mathbf{v}_{thresh})AND(M\le 10) \\ n=5, N=10 & if(\mathbf{v}_{mav}>\mathbf{v}_{thresh})AND(M>10) \end{cases} \tag{10}$$

3.3 EKF Data Fusion

Because of the noise influence, IMU measurement will produce accumulative error. We use EKF fuse measurement of IMU sensor and visual module to improve aircraft's attitude and position estimation accuracy. The state equation is:

$$\mathbf{x}(k+1)=\begin{bmatrix}\mathbf{r}^n(k)+\mathbf{v}^n(k+1)\Delta t\\ \mathbf{v}^n(k)+[\mathbf{C}_b^n(k)(\mathbf{a}^b(k)+\delta\mathbf{a}^b(k))+g^n]\Delta t\\ \mathbf{\Psi}^n(k)+\mathbf{E}_b^n(k)[\boldsymbol{\omega}^b(k)+\delta\boldsymbol{\omega}^b(k)]\Delta t\end{bmatrix} \tag{11}$$

And the update equation is:

$$\mathbf{r}^c=\mathbf{C}_b^c\mathbf{C}_n^b\mathbf{r}^n+\mathbf{v}_{\mathbf{r}}$$

$$\mathbf{\Psi}^c=\mathbf{E}_b^c\mathbf{E}_n^b\mathbf{\Psi}^n+\mathbf{v}_{\mathbf{\Psi}} \tag{12}$$

$\mathbf{r}^c$ and $\mathbf{\Psi}^c$ are the camera’s position and attitude. The measurement of visual sensors updates above equation(12). Figure6 shows the experiment EKF fusion result. In order to provide the reference, we design two ways to verify attitude and position estimation accuracy. First of all, the aircraft is fixed on a three axis turntable, rotated around three axis respectively. The aircraft’s roll angle, pitch angle and yaw angle curve are obtained. The second method is fixing the aircraft on a wheeled ground vehicle. The vehicle has an odometer which is used to provide the reference curve of north and east position. The frequency of visual module updating is 1 Hz, and the frequency of IMU module updating is 50 Hz. Figure7 shows the environment perception result.

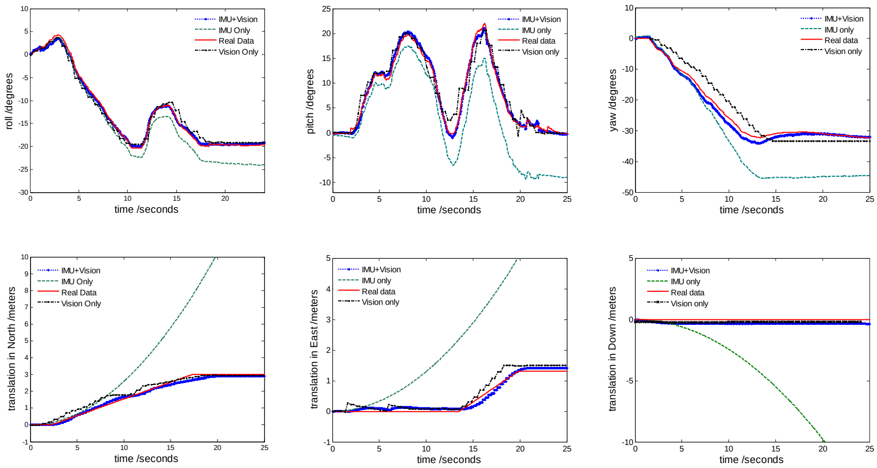

Figure 6. EKF fusion result

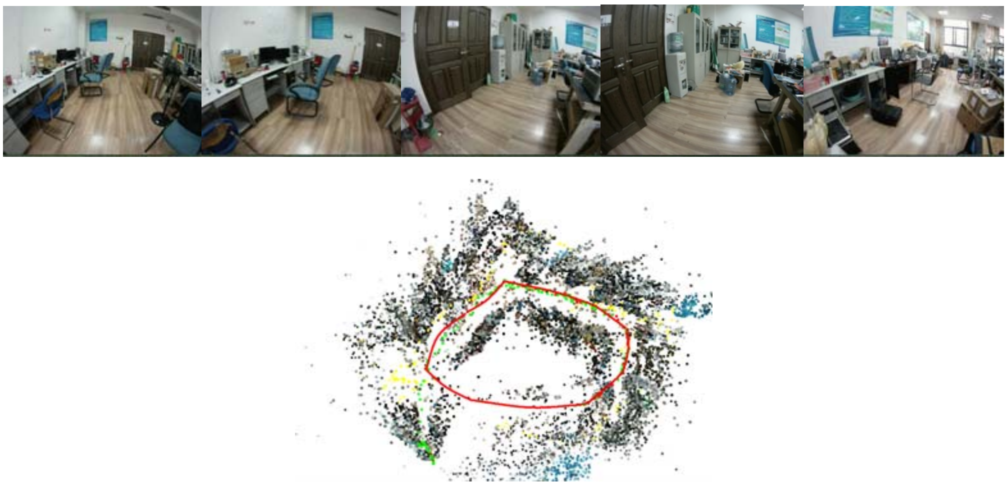

Figure 7. Environment perception result

3.4 Target Identification

We use on-board forward looking camera and downward looking camera to identify target. After the image has been captured, image processing procedure is started. Target is identified by its color, shape, and size. Combined with the aircraft's position and attitude, the image coordinates of the target are used for calculating the location relative to the aircraft.

3.5 Threat Avoidance

Obstacle avoidance procedure keeps the aircraft's safe. The measurements of laser scanning radar and forward looking camera are used in obstacle avoidance module.

4. OPERATION

4.1 Flight Preparations

At the flight preparation stage, on-board system and ground station software should be initialized properly. All of the sensors should be ensured mount well.

4.2 Checklist

a. Check the motors and propellers fixed well.
b. Place the aircraft at take off area.
c. Check the battery power.
d. Power on the aircraft and ground station.
e. Check sensors and wireless transmitter module working status.
f. On-board control system and ground station software initialization.
g. Start planning path and assign tasks.

5. RISK REDUCTION

The aircraft status is monitored by ground station software module and human operators. If risk happens, human operator switches the aircraft autonomous navigation mode to manual control mode. If ground station can't receive signals from on-board wireless module, the control module started autonomous landing procedure for keeping safe.

6. CONCULSION

We present a solution of MAV autonomous navigation in unknown indoor environments without GPS signals. The quad-rotor aircraft's motion is estimated by a variety of on-board sensors, and environments are sensing by fusing measurement data of visual sensors and laser scanning radar. The experiment results show that our quad-rotor aircraft can autonomously navigate in unknown indoor environments without GPS signals, and finish the appointed tasks.

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