Proceeding of the 2015 IEEE
International Conference on Information and Automation
Lijiang, China, August 2015

Obstacle Avoidance for Quadrotor Using Improved Method Based on Optical flow

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***Abstract*—In this paper, we proposed an improved method based on optical flow to help a low-cost quadrotor avoid obstacles. The method is consist of improved balanced strategy and fast Time-to-Collision (TTC). The improved balanced strategy is designed for the quadrotor to achieve 6 degree of freedom movement. We use a learning method based on optical flow data when the vehicle can avoid the obstacle successfully. The fast TTC method helps extract the relative depth information of the environment. We also introduced a monitoring strategies to supervise our method in real time. All these information is combined to avoid the obstacle. Our method has been demonstrated to work well in corridor environment.**

***Index Terms*—Obstacle Avoidance, Optical Flow, Balanced Theory, TTC**

I. Introduction

Nowadays increasing amount of research has been focused on the Unmanned Aerial Vehicle(UAV). The UAV, also called drone or unpiloted aerial vehicle, has been widely used not only in military fields but also in civilian areas such as aerial surveillance, agriculture area, etc. Quadrotor is one kind of UAV that can perform vertical taking off and landing (VTOL) and other acrobatic maneuvers. A great amount of efforts have been put on this platform to make it an autonomous vehicle.

Navigation is the key problem to tell the robot how to get to right place fast and accurately [1]. The robot gets data from the sensors and extract useful information so as to build a model of its surrounding environment. Then they can take use of these models to help them arrive at the right place. Sensors are powerful to provide the data of the environment in real-time and various of sensors such as the global position system (GPS), the laser range finder,inertial measurement unit(IMU) and camera, can be equipped on the quadrotor. Usually one or more sensors are employed to make the quadrotor an autonomous vehicle.For example, in [2],they used the laser range finder as the main sensor to provide information for their path planning algorithms. And cameras that can provide depth information (e.g. the Microsoft Kinect and stereo camera) are also very popular among researchers [3] [4] [5]. Sometimes different sensors can be combined to give a whole image of the environment [6].

While vision-based navigation has becoming more and more important in recent years [7]. Various of cameras can be taken by the quadrotor, such as the kinect [4], binocular camera [8] and monocular camera [9]. In [10], they built an navigation system based on visual odometry algorithm using an RGB-D camera. There are also many researchers try to extract the information of the environment simply relies on monocular camera [11] [12] [13].

Obstacle avoidance is one basic problem for quadrotor to be an autonomous vehicle. Avoiding the obstacle based on the range sensors such as the LIDAR, laser ranger even the stereo camera system which can provide the absolute distance information of the environment may not be a complex mission. However, there is no standard way to avoid the obstacle simply relies on an monocular camera. Tomoyuki Mori et al. [14] provided a method by detecting the size changes of the image patches. While their method is mainly designed for obstacles (e.g. the tree in the forest) that have much features, which is constrained when the quadrotor flying in featureless environments. The team of Lee [15] used multi-scale-oriented patches and scale-invariant feature transform algorithm to extract the three-dimensional information of the obstacle so as to avoid the obstacle, much features are also required.

Optical flow is a bio-inspired method that has been developing for many years. Nowadays it is an important tool for vision-based navigation [16]. Optical method has been employed to avoid the obstacle, however, since this method is sensitivity to the noise, it is mainly used on mobile robot [17]. Eresen et al. [18] presented a vision-based autonomous flight and demonstrate the ability of optical flow in determining the yaw angle. While it is test in the virtual environment and didn't consider the interference factor of the environment. Here we proposed a method based on optical flow. And Kalman Filter is employed to provide the velocity of the vehicle and stabilize the vehicle. An stable platform is needed in order to use the optical flow method. And we proposed an improved balanced method to reduce the computational complexity and improve the robustness of obstacle avoidance method. The image plane of the video of the quadrotor was developed into nine regions. We collect the optical

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flow data of the nine regions when the quadrotor moving forward or need to make a turn. These data were used to train the quadrotor to judge the condition it is in and determine whether it need to change its movement. What's more,other clues are also involved in our method so as to handle different environment. The TTC method is base on the motion parallax theory which can give the depth information of the environment. Although these information is relatively qualitative, it can still be used as a reference.

This paper is organized as follows. In section II, we will describe our research platform and the sensors that we mainly cares about. The method we proposed will be described in detail in section III. Next we would like to introduce the experiment that we did to demonstrate the feasibility of our method. The final part is the summarize of our work.

II. Research Platform

A. Dynamic model of Quadrotor

As we mentioned above, the quadrotor is an inherently an unstable system. It is vital to build the dynamic model of this vehicle so as to develop appropriate control strategy.

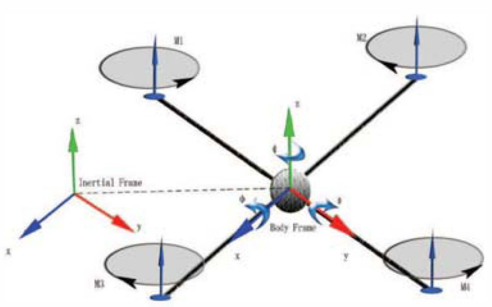

Fig. 1. Coordinate system of quadrotor

let $E_q = \{e_x, e_y, e_z\}$ be the coordinates of the inertial frame, and the $B_q = \{b_x, b_y, b_z\}$ be the body system which is fixed on the quadrotor. The term $\upsilon = (\upsilon_x, \upsilon_y, \upsilon_z)^T$ denotes the linear velocity of the quadrotor with respect to the inertial frame. And the Euler angle with respect to body system is $\varpi = (\phi, \theta, \psi)^T$. Here we would like to build a model of the imput momentum M and the output angular velocity $\omega = (\omega_x, \omega_y, \omega_z)^T$.

According to the Newton-Euler's formula,we can get the equations below:

$$F = m\ddot{x} \tag{1}$$

$$M = I\dot{\omega} + \omega \times (I\omega) \tag{2}$$

Here I it the inertial matrix. $M = (M_x, M_y, M_z)^T$denotes the total momentum on the quadrotor. Assume the quadrotor's rigid body is symmetric with one mass point on the center and four mass points on the four corner, we can get:

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{3}$$

Let R denote the rotation matrix between the body frame and the inertial frame. In the inertial frame,the movement of the quadrotor is determined by the thrust T with respect to the body frame,the gravity and the force of friction f. Then the linear movement in the inertial system can be written as:

$$m\ddot{x} = RT + \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + f \tag{4}$$

and we can formulate the motion equation based on Euler's equations. By the equation (2) and the simplified I, we can finally get the model:

$$\begin{bmatrix} \dot{\omega_x} \\ \dot{\omega_y} \\ \dot{\omega_z} \end{bmatrix} = \begin{bmatrix} \frac{M_x}{I_{xx}} \\ \frac{M_y}{I_{yy}} \\ \frac{M_z}{I_{zz}} \end{bmatrix} - \begin{bmatrix} \frac{I_{yy} - I_{zz}}{I_{xx}} w_y w_z \\ \frac{I_{zz} - I_{xx}}{I_{yy}} w_x w_z \\ \frac{I_{xx} - I_{yy}}{I_{zz}} w_x w_y \end{bmatrix} \tag{5}$$

This is exact the equation that we used to control the quadrotor.

B. Ar-drone

Fig. 2. Ardrone platform

Ar-drone is a low-cost quadrotor platform developed by Parrot,Ltd. It is designed for children as a toy originally but it is widely used in research areas [19]. As the Fig.2. shows, it is propelled by four brush-less motors with carbon fiber structure. Two cameras are equipped on the platform with one looking forward and another looking downside. The front-facing camera has $75° \times 60°$ field of view and can provides the color image with 640×480 pixel in real time with WiFi network. Others sensors such as high-precision inertial measurement unit (IMU) and ultrasound are also available. The ARM9 processor running at 468 MHz provides a powerful processing capacity. These firmwares can fully satisfied our required in our experiment.

This platform is relatively an stabilized platform with complex vision and control algorithm has been employed [20]. A driver of ar-drone for robot operation system (ROS) is available and the video stream from camera and data from sensors are transmit as various ROS topic, which reduces our development complexity and help us focus more on the vision algorithm.

III. Approach

We mainly employ the optical flow method to achieve the obstacle avoidance mission. The quadrotor is an unstable system, which is uneasy to use the optical flow method since it is sensitive to vibration. In our work, problem was solved in two ways. Firstly, an data filter approach using kalman filter is adopted so as to stabilize the quadrotor [21]. This is the corner stone to smooth optical flow data. Then we improved the conventional optical flow method. We use a novel optical flow balanced strategy for optical flow and the so called time to contact (TTC) to estimate the distance to the obstacles. The final command will be determined by the following equation:

$$Cmd = \alpha * Cmd_{IBS} + \beta * Cmd_{TTC} \tag{6}$$

Where Cmd_{IBS},Cmd_{TTC} represent the command signal by the improved balanced strategy and the TTC method respectively.And α,β are the parameters of how much you rely on this command.

A. Optical Flow

Optical flow is a method that can help us track the motion of the pixel or a patch. We can get the motion vectors of the interest objects. If we consider the object is static, then we can estimate the motion of the camera correspondingly. What's more, the closer the object, the bigger the optical flow vector [22]. Thus we can perceive the depth information simply relies on a monocular camera. This two properties above is the basic principle using the optical flow. If we take all the optical flows vectors into account, this method is called dense optical flow, while if we only choose some feature points to track, this method is called sparse optical flow. The former is more accurate but it needs large computation, and the latter one doesn't need much computational resource but it is very unstable in featureless environments. Here we aim to combine the advantages of those two methods by using an improved balanced method.So we compute the dense optical flow vector in the cross regions in the image plane, while computing the sparse optical flow in the left regions for reference, which will be introduced in detail in next section.

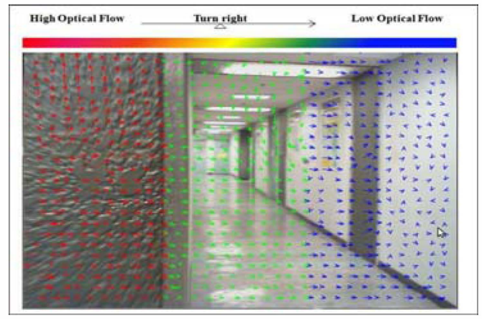

Fig. 3. Traditional Optical Flow Balanced Strategy

B. Improved Balanced Strategy

According to the motion parallax theory, the closer the objects, the bigger the corresponding optical flow vector. This property often help us deal with the obstacle avoidance problems by monocular camera. From Fig.3, the optical flow on the left is bigger than the center and right region. The control command is given by the equation below:

$$\triangle F = \frac{\sum \mid F_{left} \mid - \sum \mid F_{right} \mid}{\sum \mid F \mid} \tag{7}$$

where F_{left}, F_{right}, F represent the optical flow on the left region, on the right region and all the optical flow vectors in the image respectively. If $\triangle F$ is bigger than zero, it means the optical flow on the left is bigger than the right, and vice versa. And consequently, the corresponding control command will be send to the vehicle to tell it where to go.

However, the traditional way above is often used on the ground mobile robots which are relatively stable when they moving. The quadrotor platform, by contrast, is more easier to introduced noise. Here we proposed an improved balanced strategy which is design for aerial vehicles. As the Fig.4 shows, instead of dividing every image plane in the video flow into three regions, we divide the image into nine, this strategy is in consideration of the 6 DOF of the quadrotor. What's more, we only compute the optical flow in the cross regions of the image plane. While in the remaining regions, the sparse optical flow is calculated so as to give a reference to reduce quadrotor vibration.

The control command $\triangle F_{ver}$ and $\triangle F_{hor}$ are given according to equation (6), which are corresponding thrust toward vertical direction and horizontal direction respectively. In addition, the sparse optical flow of four corner regions are also used for reference. In Fig.4, we denote (0.5,0.5) to represent the top left corner of the image plane, therefore the bottom right corner is represented by (2.5,2.5). So the control command is calculated by:

$$\triangle F_{ver} = \triangle F_{verCross} + \triangle F_{verSparse} \tag{8}$$

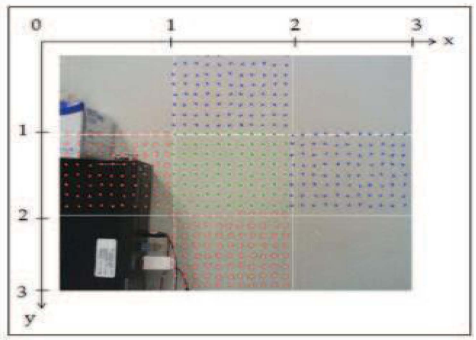

Fig. 4. Improved balanced strategy

$$\triangle F_{hor} = \triangle F_{horCross} + \triangle F_{horSparse} \tag{9}$$

Where $\triangle F$ is calculated by equation (7) and $\triangle F_{verCross}$ is the result of the regions (0.5,1.5),(1.5,1.5),(2.5,1.5),the $\triangle F_{verSparse}$ is the difference of the sparse optical flow of (0.5,0.5),(2.5,0.5) and (0.5,2.5),(2.5,2.5), so the parameters are defined in equation (9).

Not only did we compute the optical flow in two directions so as to fit with the motion of aerial vehicle, but we also proposed a learning method based on the prior optical flow information when the quadrotor avoid the obstacle. Firstly we let the quadrotor flying toward an obstacle and the quadrotor achieve the obstacle avoided mission by manual control. And record the optical flow data when the vehicle flying toward or turn around in this process. This is the data set that we use to generalize the regulation that the quadrotor follows. Then the quadrotor can fly independently simply by matching the optical flow with our prior information. The final command of this strategy is determined by the result in equation (8),(9) and the result of the learning method.

C. Time to Contact

The term "Focus of expansion (FOE)" depicts the projection center of the environment. It is the source of optical flow hence any two optical flow vector can determine the FOE. Sometimes the FOE indicates the center which the quadrotor is pointing. When the quadrotor is moving toward the FOE, we can get the relative depth according to the relationship of certain pixel and the FOE.The depth information is called TTC, which can be calculated by:

$$\tau = \frac{y}{y'} \tag{10}$$

where y represents the distance between the pixel and the FOE, y' represents the norm of the optical flow vector in the pixel location. Then we can get τ, which is the depth information of that pixel.

However, when the quadrotor is flying, the FOE is relatively unstable, which is uneasy for us to calculate the TTC. In order to fullfill the stability. We make use of the moving mean (MM) method to reduce the high-frequency noise.

$$L_{point} = \frac{L_{p\_new} + L_{p\_odd1} + L_{p\_odd2} + \ldots + L_{p\_oddn}}{N} \tag{11}$$

Here $L_{p\_new} + L_{p\_odd1} \ldots L_{p\_oddn}$ represent the location of N FOE at a certain time, when new location of FOE is calculated, the last location point will be dropped which guarantees there are N points involved.

The overall system is depicted like the block diagram below:

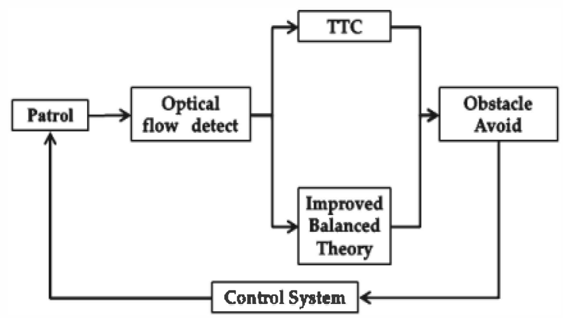

Fig. 5. The block diagram of the overall system

IV. Experiment and Result

A. Improved Balanced Theory

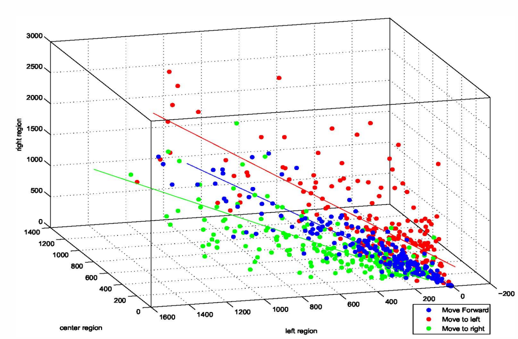

Fig. 6. Optical flow of three conditions

In Fig.4., we divide the image plane into nine regions, in our experiment, we found this method is useful to improved the stability of the optical flow method and uneasy to be disturbed by the noise on the corner region. We also noticed that the sparse optical flow on the corner region, which we use to monitor the system in real-time, are good reference for making decisions.

In our experiment, we collect the optical flow data of the nine regions when the quadrotor is moving forward or making turns in order to find the relationship between the optical flow and obstacle avoidance. To simplify, take the regions (0.5,1.5), (1.5,1.5),(2.5,1.5) in Fig.4. into consideration. We need to consider the optical flow vector in three conditions: no obstacle and move forward (markerd $condition1$ and the next two follows), there is an obstacle on the right and need to turn left, there is an obstacle on the left and need to turn right. At first, we control the quadrotor manually and collect the optical flow vector in three conditions mentioned above. In order to observe the obstacle flow easily, we build a 3D graph, which the three coordinates represent the three regions respectively. As Fig.6. shows, different color indicate the condition 1, 2 and 3 separately. The three lines represent the main direction of the three conditions, which tells us that the difference between the order moving forward and turn left or right is big so as to rely on to avoid the obstacle. And we can also use these data to train the quadrotor to learn how to avoid obstacles.

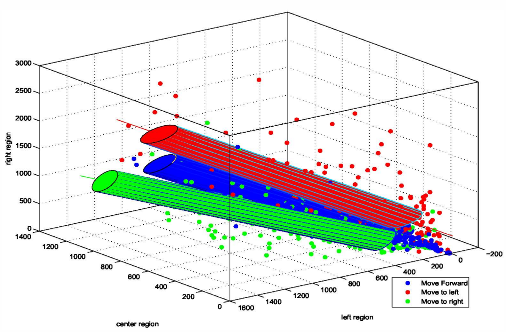

Fig. 7. Three cylinders that comtains most optical flow data.

In Fig.7, we get the three which contains the most three optical flow data separately. When the quadrotor flying, it will collect the optical flow data in real-time. Then it will give moving order according to which cylinder the optical flow point is falling to. If the optical flow point belongs to no cylinder or belongs to more than one cylinder, no order will be given.

B. Time to Contact

The time to contact method is proposed to improve the performance of improved balanced theory. One key step for calculating TTC is to get the accurate location of FOE.

Fig.8 shows the performance of MM filter method. We can see the raw data of the location of FOE contains much noise which can make the TTC result not available. But the fliter data curve, which is the pink one from the Fig.8, is more smooth than the blue curve below, this demonstrate our method is useful and the location of FOE can be used to get the TTC.

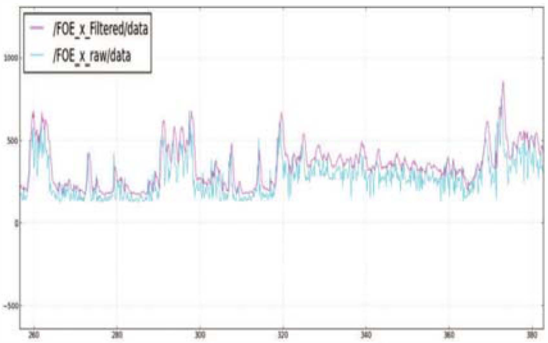

Fig. 8. The position of FOE is smoothed by MM method.

We did some experiment by the TTC method. As the Fig.9 shows, two similar objects were placed on the table with different distance away from the slowly moving camera. The color indicates the distance. We can see from the figure that the more closer the object, the lighter the color, which means that we can get the relative distance by the TTC method.

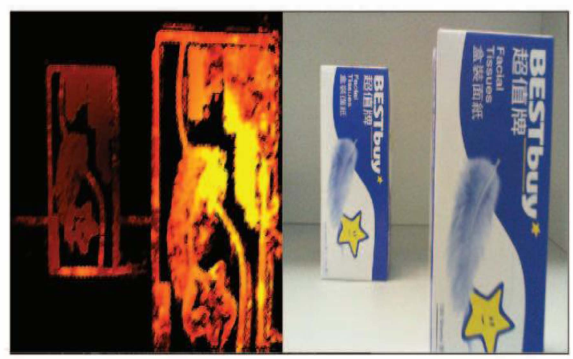

Fig. 9. The result of TTC method

C. Flying Performance

Fig. 10. Flying Test

The improved balanced method and the TTC reference give the control order to the quadrotor. In order to test the performance of our method, we did the experiment using the Ar-drone in typical indoor environment as the Fig.10 shows. In our 20 experiments, the quadrotor can avoid the obstacle for 15 times,the success rate is 75%. The result show that our method can avoid the obstacle successfully in most cases.

V. Conclusion and Future Work

In this paper, we proposed a method to avoid the obstacle using optical flow by monocular camera. Our contribution is proposing a new balanced strategy and relatively stable TTC method in finishing the optical flow mission. A method based on learning is introduced in the new balanced strategy. And we combine all these clue to help the quadrotor avoid the obstacle automatically.In the future, we would like to using other clues such as the region extension, projection clue, etc into the area that help the quadrotor avoid the obstacle simply by the monocular camera.

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