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Simple Autonomous Flight Control of a UAV Flying Above a UGV Using Onboard Camera Vision*

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***Abstract*— An autonomous flight control method of UAV(: Unmanned Aerial Vehicle) which flying just above the UGV(: Unmanned Ground Vehicle) using only the information of the onboard camera of UAV is proposed in this paper. In the conventional research, motion capture system, GPS, and laser range finder are often used to measure the position and posture of UAV. Although the conventional measurement system is effective in certain conditions and limited environments, it is not always applicable outdoors. There have also been researched about the cooperation of UAV and UVG, but much previous research, its effectiveness was shown in by numerical simulation or experiments using many sensors. By using our proposed system, it is possible to select a feature point on the UGV placed on the ground by using only a UAV onboard camera, and to fly the UAV just above the UGV. Besides, if the UGV moves along a trajectory, UAV can fly above the UGV. In our experiment, we use ROS for an image processing and calculation of control inputs. To operate the UAV automatically, we apply a simple PID control method and its gains are individually adjusted. The effectiveness of our proposed method is shown by experiment.**

I. Introduction

In April 2016, a series of major earthquakes had hit the Kumamoto area of Japan, and a lot of landslides had occurred. The Photo (Fig. 1) was taken by the camera which mounted on the four rotor type helicopter (i.e., “multicopter”). It was the first time in Japan that multicopter was used to observe the state of the landslide. Since then, many floods have occurred in Japan, because of river flooding, then to surveillant such area, UAV monitoring activities have been expanding.

To observe the state of the landslide and disaster site, we should watch that area, continuously. It is thought about observing the area by a manned helicopter, but it is realistic to utilize a multicopter for the consideration of cost, safety, and continuity. However, a multicopter was operated by a human operator in Kumamoto landslide observation. If we can automatically fly the multicopter near the landslide area, we can observe the area for long time by using the video camera which mounted on the multicopter. But, in general, however, the power source of multicopter is a battery, and its flight time is limited to about 40 minutes. In order to solve a short time flight problem, it is nice solution that the power is supplied from a generator installed on the ground to a multicopter by a cable. Moreover, if the generator is put on the UGV, and multicopter can fly just above the UGV automatically, then the UAV (multicopter)/UGV system becomes very effective for the practical applications. In such a situation, we can automatically fly the multicopter by using GPS system. But, GPS may not be always available in a good state at places such as the disaster spot. Therefore, it is necessary that we should make an autonomous flight control system of multicopter without using GPS.

Fig. 1. Landslide area inspected by multicopter (Photo from Geospatial Information Authority of Japan, `http://www.gsi.go.jp`)

To utilize the multicopter at outdoors, we should develop a simple autonomous flight control system of multicopter. It is natural that we derive a dynamic model of multicopter to design an autonomous flight control system for a multicopter. There have been widely developed dynamic models of multicopter for autonomous flight control[1], [2], [3], [4], [5], [6]. The model of multicopter is described by a nonlinear dynamics, therefore, its construction is quite complicated. The effectiveness of dynamic model based control system design method is well known, but it is difficult to apply in the practical applications. To solve this problem, based on a precise analysis of aerodynamics forces and moments, a simple first order delay with time constant model was derived and PID controller was also designed[7]. The actual flight control results were also given, but, the position of multicopter is measured by GPS, ultrasonic rangefinder, and integrated carrier phase measurements are used[8]. To measure the position and posture of mulilticopter, using OptiTrack (https://www.optitrack.com) method was also shown[7], [9]. Using the OptiTrack system, position and posture of multicopter can be measured precisely, then amazing autonomous flight control was also given. But, the flight area of multicopter is limited to the domain surrounded by the OptiTrack systems, therefore, the use of this system is difficult at outdoors.

As another autonomous flight control system, image–based visual servo method was proposed[10]. Position and posture measuring, and control method of multicopter was

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given, but its effectiveness was only shown by numerical simulations. Applying an onboard optical flow sensor, the translational velocity and position estimation method of multicopter were also proposed[12].

This paper proposes a simple autonomous flight control method for multicopter (UAV) which is based on visual information of camera. Especially, we give a flight control system that the UAV can fly just above the feature point which can choose the camera image. The feature point is selected from a camera image, and its image is provided by a camera attached on the UAV. In this case, it is not necessary for us to prepare a marker (e.g., AR marker) as a feature point, we only choose the feature point such as the corner of an object which is shown in the camera image. If we choose the UGV as the feature point, then UAV can fly just above the UGV, in addition, UAV can fly in cooperation with the motion of UGV. Recently, there have been researched about the cooperation of UAV and UVG[11], [13], [15], [16], [17], however, the effectiveness of the proposed methods are shown only by numerical simulations. In one of those researches, using a spherical camera is considered[11], but its method quite complicate and it only gives numerical simulations. UAV/UGV collaborative control method was also proposed[14], but, in the experimental results, this method uses GPS for hovering and attitude control.

To begin with, as for the position control of UAV, such exact positioning control is not possible, because UAV does not fly along a guide lane. Therefore, it is inevitable that some error is caused by the positioning control of UAV. In this paper, our proposed method uses only onboard camera and sensors, a relative position between UAV and UGV are measured by very simple and cheap way. Moreover, simple and easy equipment component of our flight control system is effective in emergency situations, because the adjustment of control system and equipment is easy to understand. Besides, it is desirable that the number of sensors for an autonomous flight control of multicopter is minimum in emergency situations. The effectiveness of our proposed method is presented by some experimental flight control results. Our proposed system does not use GPS information in the experiment.

II. Actual Manipulation and Previous Control Method of UAV

For an autonomous flight control, needless to say, it is very important to know a dynamics of UAV. In the past decade, a lot of dynamic models and autonomous flight control method for UAV has been proposed[1], [2], [3], [4], [5], [6]. Fig. 2 shows a coordinate system of UAV which employed almost previous researches. Corresponding to roll, yaw, pitch from dynamics of UAV, appropriate torques τ_θ, τ_ψ, τ_ϕ are given by the controller.

In actual UAV, appropriate control signals are transmitted from radio controller to the flight controller which mounted on UAV. Then, flight controller calculates an appropriate rotation speed of each rotor and control signals supply to motors. As we can see Fig. 3, if the signals for the

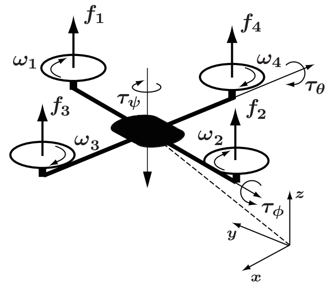

Fig. 2. A coordinate of the UAV

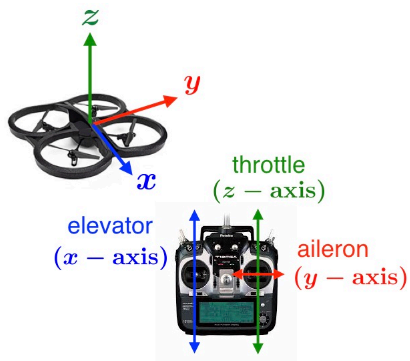

Fig. 3. Axis of UAV and relationship between stick operation and motion direction

elevator, aileron, and throttle are appropriately given from the radio control transmitter, then we can manipulate the UAV. In short, we do not transmit the values of torque corresponding to roll, yaw, and pitch to each rotor from the radio controller in the practical situations. After all, if the appropriate elevator, aileron, and throttle values can be calculated, then the position and posture of UAV are controlled by the flight controller. As we can see Fig. 3, these manipulations correspond to the x, y, and z axial directions[1]. In conclusion, when we want to control the position and posture of UAV, we should make an appropriate values of elevator, aileron, and throttle, corresponding to the position of x, y, and z axes of the UAV, respectively.

Based on these considerations, we have already confirmed the effectiveness of autonomous flight control for UAV[18], [19]. In the previous our researches, the position and posture of UAV were measured by the external single camera, then three–dimensional autonomous flight control of UAV was carried out. We have also given some experimental results to show the effectiveness of our proposed method. In the next sections, we will propose a simple and effective method for an autonomous flight control method of UAV which can fly over UGV using an only onboard camera of UAV.

III. Experimental System of Proposed Autonomous Flight control for UAV

A. Experimental system and Control method

Proposed experimental system is shown in Fig. 4. In our experiment, we use Parrot AR.Drone 2.0 (AR.Drone 2.0:

[1] http://uavcoach.com

Fig. 4. Experimental system

TABLE I
AR.DRONE 2.0 SPECIFICATIONS

dimensions	0.517 m × 0.517 m × 0.115 m
total weight	0.420 kg
OS	Linux 2.6.32
CPU	1GHz 32bit ARM Cortex A8 Processor, 8 MIPS AVR CPU
protocol	Wi-Fi b,g,n
sensors	• 3 axis gyroscope: 2000° /second precision • 3 axis accelerometer: ± 50mg • Pressure sensor: ± 10 Pa • Ultrasound sensors for ground altitude measurement • 60 FPS vertical QVGA camera for ground speed measurement
Front view camera	HD Camera (720p 30FPS)
motors	4 brushless "inrunner" motors 14.5 W, 28,500 RPM
battery	LiPo Battery (11.1 V, 1000 mAh)

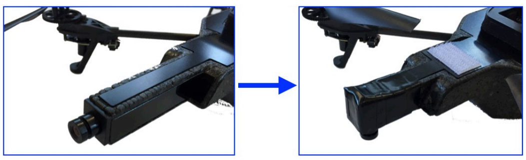

Fig. 5. Remodeling of front view camera

http://ardrone2.parrot.com) as an UAV. Technical specifications of AR.Drone 2.0 are given in Table I. To capture the object on the ground, we remodeled the front view camera (onboard camera) of AR.Drone as shown in Fig. 5. Then, using this onboard camera of the UAV, we can get an image of the object which is placed on a floor. This camera image is transmitted from UAV to ROS by WiFi. On the ROS, we use the package `ardrone_autonomy`[20]. `ardrone_autonomy` includes the ROS topic about data communication for takeoff, landing, hovering, navigation, and so forth. This package can also manage the data about velocity and acceleration of each direction, rotation angle of each axis, the number of revolutions of each motor, information of battery, and camera image.

ROS processes the received camera image and uses OpenCV to recognize the feature point of the object. Fig. 6

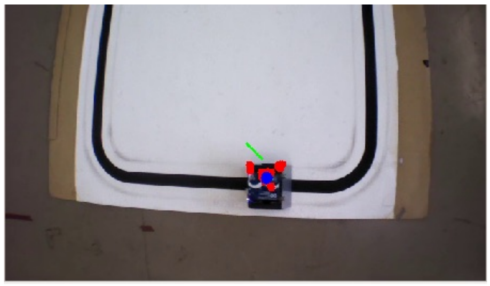

Fig. 6. Captured image on ROS

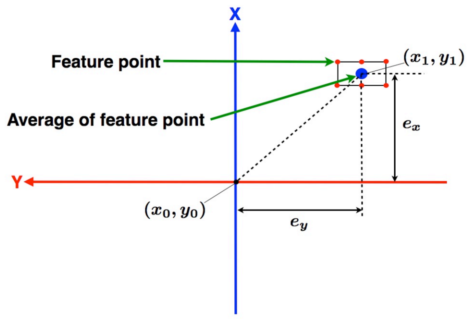

Fig. 7. Coordinates of captured image of x and y direction

shows the camera image which captured ROS. This camera image corrected the distortion by using the OpenCV function (`cvCalibrateCamera2`). As we can see Fig. 6, the red points are feature point and the blue point is the average point of red points. Then, we can detect a position of feature point as pixel coordinates on the camera image. The positional relationship of a camera image and the feature point is shown in Fig. 7. Based on the definition of the axis in Fig. 3 and the captured image as Fig. 6, we can give the x–axis as vertical direction and y–axis as horizontal direction on camera image. As shown in Fig. 7, coordinates of average point of feature point and the center of image are defined as (x_1, y_1) and (x_0, y_0), respectively. Then, we define the errors of each direction as follows.

$$e_x = x_0 - x_1 \tag{1}$$

$$e_y = y_0 - y_1 \tag{2}$$

The altitude of UAV is measured by onboard ultrasound sensors. As shown in Fig. 8, we define the reference altitude as r_z and the measured altitude as z_1, then the error of altitude is defined as follows.

$$e_z = r_z - z_1 \tag{3}$$

Then, if we can control that each error signal becomes zero, then UAV can fly just above the average point of the feature point.

According to the error signals (1), (2), and (3), control inputs for the elevator, aileron, and throttle are given by P–

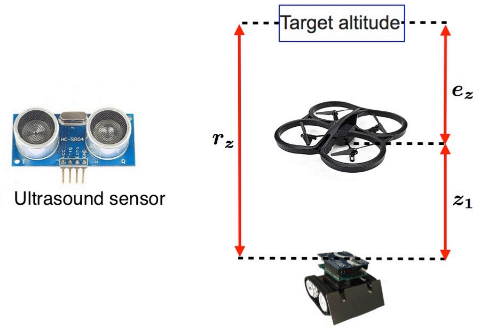

Fig. 8. Error definition for altitude

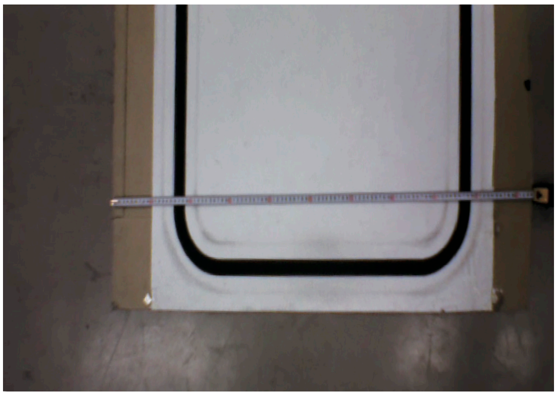

Fig. 9. Captured camera image with ruler

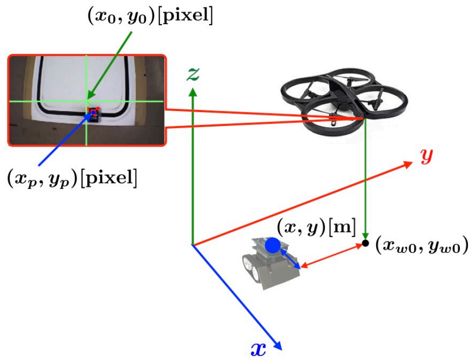

Fig. 10. The concept of conversion

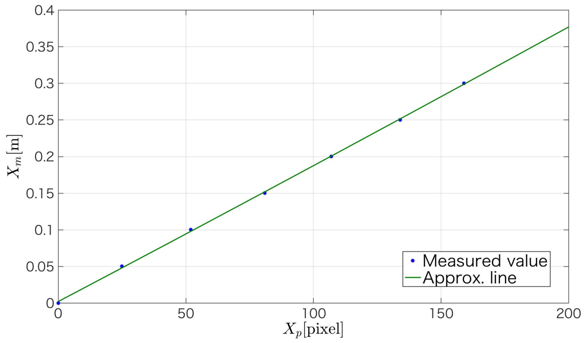

Fig. 11. From pixel coordinates to metric unit for x axis

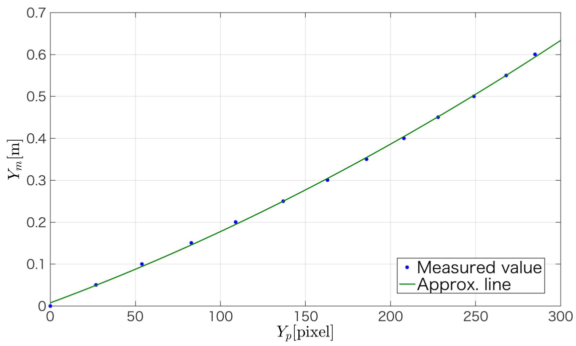

Fig. 12. From pixel coordinates to metric unit for y axis

D and P control as follows:

$$u_{\text{elevator}}(t) = k_{P_x} e_x(t) - k_{D_x} \frac{\mathrm{d}x_1(t)}{\mathrm{d}t} \tag{4}$$

$$u_{\text{aileron}}(t) = k_{P_y} e_y(t) - k_{D_y} \frac{\mathrm{d}y_1(t)}{\mathrm{d}t} \tag{5}$$

$$u_{\text{throttle}}(t) = k_{P_z} e_z(t) \tag{6}$$

Based on the control inputs which are given by Eqs. (4), (5), and (6), those control inputs are transformed to the appropriate values by a ROS and their signals are transmitted to UAV. In this experiment, the yaw angle which corresponding to input τ_ψ, is controlled by the onboard flight controller to keep the direction at the time of the takeoff, automatically.

B. Conversion from pixel to metric units

In our proposed method, the coordinates of feature points in camera images are given by many pixel information. For the convenience of understanding, we want to know the relative distance between the center of image and feature point in metric units. In the following, we give the conversion method from pixel to metric units. First of all, it is assumed that UAV stably flies on the $x-y$ plane. Fig. 9 is the camera image that UAV flies at 1 m height, and we can see that a ruler puts on the floor. We also assume that the center of camera image (its coordinates (x_0, y_0) in Fig. 7) gives the coordinates (x_{wo}, y_{wo}) in the world coordinate (i.e., floor coordinate). The concept of this conversion can be depicted in Fig. 10. Then, we can know the feature point of object which put on the floor as the coordinates (x_1, y_1) in the camera image, at the same time, we can also know the distance from (x_{wo}, y_{wo}) to (x_1, y_1) in metric units by the ruler. In this way, we moved feature points at 0.05 m intervals along the ruler and recorded x and y pixel coordinates at each location. Based on the recorded data, we can depict the relationship between pixel coordinates values and its metric unit as Figs. 11 and 12. The lines on Figs. 11 and 12 are approximated lines which given by least squares method, and their equations are given as follows:

$$x = 2 \times 10^{-7} {x_p}^2 + 1.8 \times 10^{-3} x_p + 1.9 \times 10^{-3} \tag{7}$$

$$y = 2 \times 10^{-6} {y_p}^2 + 1.5 \times 10^{-3} y_p + 7.2 \times 10^{-3} \tag{8}$$

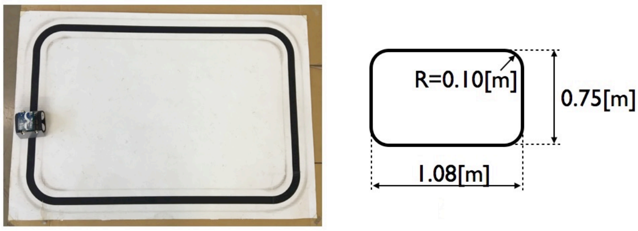

Fig. 13. Tracking path of UGV

where x and y are the distance from the center of the camera image to feature point in metric units. x_p and y_p are the pixel coordinates when the feature points put on x and y, respectively. Then, if we get the pixel coordinates of the feature point on the camera image, then we can know the relative distance between the feature point and (x_{wo}, y_{wo}). In our experimental system, the accuracy of these results is sufficient.

IV. Experimental results

To confirm the effectiveness of our proposed system, the system is applied to the UAV. The experimental environment is shown in Fig. 4. The experimental ROS PC is composed by Intel Core i5–6500, NVIDIA GeForce GTX1060 6GB, etc., and video image capture and control method are programmed by Open CV and Python 2.7.12, respectively. The control flow of the proposed control system is as; capturing a video image, feature point detection, getting the positional information by pixel on the camera image, calculating the control inputs which are based on Eqs. (4), (5), and (6), and transmitting control signal to the UAV using `ardrone_autonomy`.

In the following figures of experimental results, we show UAV positions in metric units. We give the reference altitude of UAV as 1.0 m, and we put the UAV near the object. In this paper, the following two experiments were carried out:

- Ex. 1: hovering control with altitude 1.0 m
- Ex. 2: tracking control (fly over the UGV and UGV moves along the tracking path)

In Ex. 2, the UGV moves along a predefined trajectory as shown in Fig. 13 and its control method is given, appropriately. All experiments, we adjusted the design parameters of P-D and P controller (4), (5), and (6) with repeating experiments as follows:

$$k_{P_x} = 2.7 \times 10^{-4}, k_{D_x} = 4.8 \times 10^{-3},$$

$$k_{P_y} = 3.15 \times 10^{-4}, k_{D_y} = 2.8 \times 10^{-3},$$

$$k_{P_z} = 3.0 \times 10^{-4}$$

The above design parameters are depended on the experimental equipment, therefore, we should adjust again the design parameters when we fly another UAV. Eqs. (4), (5), and (6) are discretized at sampling intervals of 0.033 s.

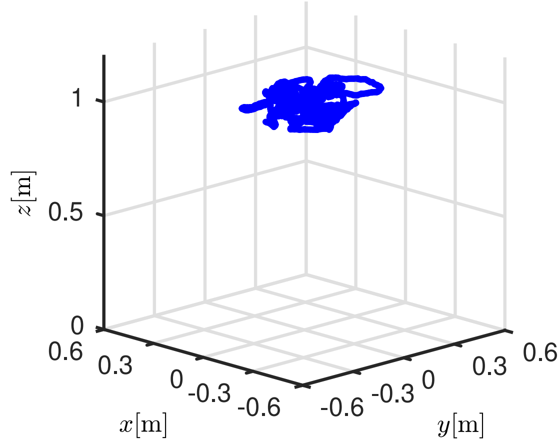

Fig. 14. 3D plot at hovering

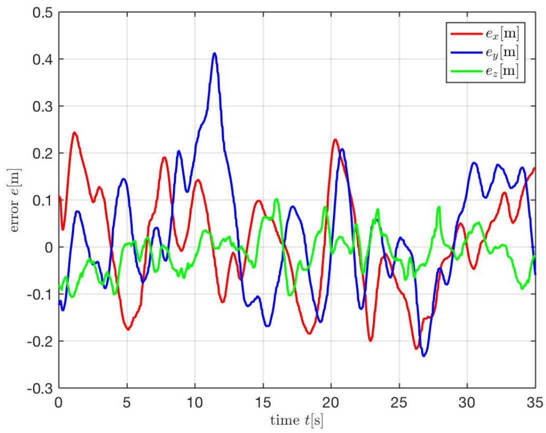

Fig. 15. Errors at hovering

In all the experiments, after flight altitude of UAV almost arrived at 1 m, we recorded the experimental data. Experimental results are shown in Figs. 14, 15, 16, and 17. Those figures depicted the relative distance from feature point to the coordinates (x_{wo}, y_{wo}) which is given by the arguments in subsection III-B. In Figs. 14, 15, 16, and 17, the origin $(x, y, z) = (0, 0, 0)$ means the coordinates of average of feature point on the floor when we began to record the experimental data. As we can see those experimental results, the maximum error of each axis are almost less than 0.3 m which is half of width of UAV. From the point of view of autonomous flight control of UAV, this accuracy is enough for this experiment. Then, we can conclude that the autonomous hovering and flight tracking control are accomplished by using our proposed method.

V. Conclusions and Future work

In this paper, we proposed a simple and simple autonomous flight control method of UAV that can fly directly

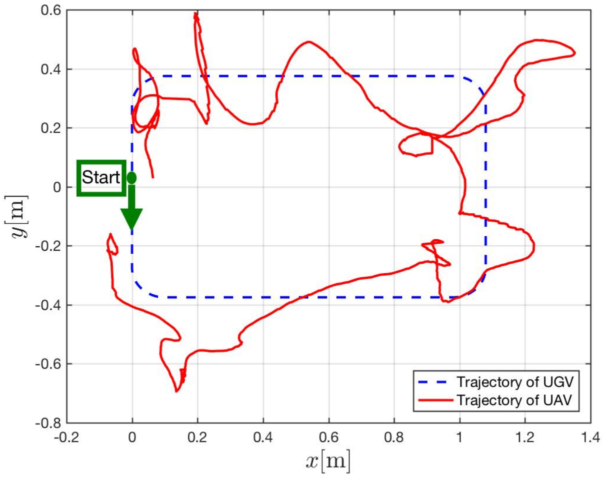

Fig. 16. Trajectory tracking

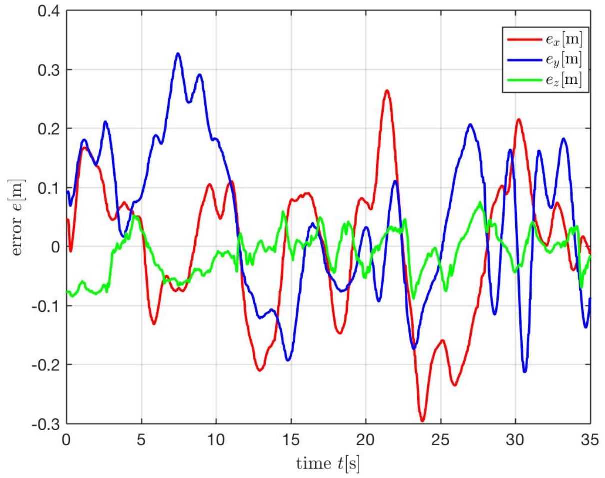

Fig. 17. Errors at tracking

above UGV. The information of position and attitude for the UAV were measured by the onboard camera and ultrasound sensor, respectively. Our experimental system is composed by ROS, therefore, our system can easily expand the image processing and apply another method by using ROS packages. In this experiment, our autonomous flight control system was made by Python programming code and used some packages of ROS. Using our proposed system, UAV can fly autonomously on UGV and its method is very simple. Therefore, the proposed method is very effective in practical flight outdoors.

In this research and experiment, we use the ultrasound sensor to determine the altitude of UAV. But in the practical application, we will use laser rangefinders which mounted on UGV to measure the altitude of UAV. Moreover, our future work will consider the influence of power supply cable for the control of UAV flight.

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