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Vision-aided Tracking of a Moving Ground Vehicle with a Hybrid UAV

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***Abstract*— In this work, we present the development of a target tracking and following system using a self-customized hybrid UAV, KH-Lion. KH-Lion is a small and autonomous tail-sitter UAV stabilized and controlled by two vectored propulsion systems. A target tracking system was developed on this platform for autonomous target following on a predetermined moving object on the ground. A customized AprilTag marker was attached on a radio-controlled car, and the target tracking algorithm was verified in actual flight experiment in which the moving car is tracked. Experiments were conducted in the environment of VICON motion tracking system, which provides us with a ground truth to evaluate the performance of the tracking. The system was verified and tested with a moving speed of approximately 0.5 m/s.**

I. INTRODUCTION

In the recent years, we see an increase in applications involving unmanned aerial vehicles (UAVs) or drones in the market, due to the advancement of autonomous UAV technologies. At the same time, hybrid UAVs, benefiting from both the advantages of a fixed-wing UAV and a rotorcraft, have attracted great interest from both the academia and the industry. Such hybrid UAVs with vertically take-off and landing (VTOL) ability as well as long distance cruise operation have significantly increased their potential applications in both military and civilian operations in hard-to-access environments.

Specifically, two typical hybrid UAV models, the quad-plane type and the tail-sitter type (see Fig. 1 for tail-sitter type), are intensively studied and reported in the literature. The quad-plane hybrids have multiple rotors on a fixed-wing body, able to take-off and land vertically like a rotorcraft, and to perform cruising flight like a fixed-wing plane. Due to the two separate propulsion systems, this type of hybrid aircraft is less desired as its efficiency drops. On the other hand, a tail-sitter hybrid utilizes only a single propulsion structure, where both the VTOL and cruising flight share the same power source. It is more efficient, but difficult to be automated due the a complex transition which involves the change in its angle of attack.

Target tracking is one of the ideal applications to be done using UAVs [1]. Autonomous tracking of object with UAV is a challenge especially if the object is moving during the operation. One of the most crucial keys in autonomous tracking of moving object is the relative proximity information of

Fig. 1. KH-Lion, the tail-sitter hybrid UAV

the target to the UAV. In literature, global positioning system (GPS), LiDAR and radar sensors have been widely used for relative pose estimation between the aircraft and the ground object [2]. Aircrafts adopting GPS information for precise guidance and landing are well presented in [3], [4].

Recently, vision-aided autonomous vehicles are becoming popular due to rich information provided by the images [5]. Due to its usefulness, many monocular vision and stereo vision based algorithms are developed for tracking of markers with UAVs [6], [7]. These algorithms work with a customized known marker attached on the object to be tracked. Many works has been documented where the UAVs are able to hover above the marker, to track the marker, and even to land on the marker while it is moving [8], [9]. Most of these successful example of autonomous tracking of moving objects were done on multi-rotor or fixed-wing UAVs, where not much of such system in the literature were in a hybrid platform [10], [11].

As the hybrid platforms are able to undertake long distance missions, while capable to land vertically in a confined space, it would further expand its potential if the hybrid aircraft is able to track and follow a ground moving target. This ability can be further elaborated to allow the hybrid UAV to take-off from the moving platform, and to land on it after the mission. Motivated by this, an autonomous tracking of a moving platform with hybrid UAV is proposed. A monocular vision camera is primarily used to estimate the relative position of the reference target, while a GPS sensor is used to provide position measurement to the hybrid UAV. It is noted that for more accurate data comparison, the experiment explained in

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this paper was done in the presence of a VICON motion tracking system to replace the use of GPS measurement.

The outline of this paper is as follows: Section II briefly presents hardware components and sensors used in this work. Section III focuses on the mathematics modelling and flight control of the hybrid UAV, whereas Section IV is on the on-board vision-aided tracking algorithm. The actual flight experiment results are given in Section V. Lastly, we draw some concluding remarks in Section VI.

II. Hardware Platform

The tail-sitter hybrid UAV, KH-Lion was constructed according to the following requirements:

1) Able to take-off and land vertically (vertical mode), and to cruise flying like a fixed-wing aircraft (cruise mode);
2) Able to carry essential sensors and electronics for autonomous flight;
3) Propulsion system works on both vertical mode and cruise mode; and
4) Enough payload to install a gimbal controlled camera on-board.

Prior to the final design as shown in this paper, the KH-Lion was designed upon the two existing hybrid UAVs, the J-Lion and U-Lion. U-Lion has a single contra-rotating motor with expandable wings for cruise flight [12], while J-Lion is a hybrid UAV with two tilt motors [13]. The KH-Lion was designed more closely to J-Lion, with similar flying wing configuration and two vector-thrust propulsion systems. The vector-thrust propulsion systems as well as the two control fins in the wings provide three axes torques in full flight envelope.

Sensors, actuators and avionics to be installed on KH-Lion will be discussed in the following subsections.

A. Flight Controller

Pixhawk flight controller was used as the main flight controller for UAV stability and movement control. Customized autopilot system was implemented with advanced control algorithm to realize both vertical mode and cruise mode autonomous flight including the transition between the modes. A GPS receiver can be attached to Pixhawk easily, to provide GPS coordinate of the UAV for autonomous position and velocity control.

B. Gimbal Controlled Camera System

Monocular camera is employed for visual image capturing for the tracking of ground objects. In this implementation, a PointGrey BlackFly camera is used. This camera is required to face vertically downwards at all time during flight.

In order to achieve a stabilized visual image capturing, a 2-axis gimbal system is considered. Arris Zhaoyun 2-axis Brushless Gimbal is adopted to mount and stabilize the camera. The camera is controlled in both pitching and rolling directions. To accommodate the choice of camera, minor modification is carried out on the mounting plate of the gimbal.

C. On-board Computer

In general, image processing is computationally intensive. The current on-board ARM-based processor for flight controller alone will not be able to take up the task. Hence, an UP-board with Intel Atom Quad Core processor is utilized to run the algorithm using images captured by the on-board camera. UP-board is small and light, which weighs approximate 100 g.

III. Mathematics Model and Control

To achieve good performance in the hybrid UAV stabilization and object tracking, a mathematics model of the hybrid UAV was first developed. Inner-loop and outer-loop controllers were then designed upon the identified dynamical model, to stabilize and to control the position of the UAV in both vertical mode and cruise mode. In this section, a brief overview of the mathematics model of KH-Lion will be presented, followed by the controllers design. Readers are encouraged to read [14] for a detail model identification of a similar hybrid UAV, J-Lion.

A. Mathematics Model

Three coordinate systems were first defined as the operating space of the UAV. They are

1) Global frame x_n, y_n, z_n is set to be a coordinate system located on the ground where the UAV takes-off. The x_n, y_n, z_n directions are pointed towards North, East, and down respectively;
2) Body frame x_b, y_b, z_b is defined with its origin located at the CG of the UAV, where y_b pointing towards wingtip on the right, and z_b pointing towards its tail; and
3) Rotor frame x_r, y_r, z_r is defined to describe the vectoring thrust direction. It is aligned with the body frame when no thrust angle is applied. The origin of the rotor frame is located at the center of each motor. Note that the direction of thrust will remain the same for both the motors, and thus a single rotor frame will be sufficient.

1) Kinematics: Kinematics equations are well known. It can be represented in many forms: Euler angle, rotation matrix or quaternion forms. Here we adopt the rotation matrix representative:

$$\dot{\mathbf{P}}_{\mathrm{n}} = \mathbf{R}_{\mathrm{n/b}}\mathbf{V}_{\mathrm{b}}, \tag{1}$$

$$\dot{\mathbf{R}}_{\mathrm{n/b}} = \mathbf{W}\mathbf{R}_{\mathrm{n/b}}, \tag{2}$$

where $\mathbf{R_{n/b}}$ represents the transformation matrix and $\mathbf{W}$ is the angular velocity tensor. These are trivial and will not be discussed further.

2) Rigid Body Dynamics: Based on Newton-Euler formalism describing the translational and rotational dynamics of a rigid body, the dynamic equations can be written into the following input-output form:

$$m\dot{\mathbf{V}}_{\mathbf{b}} + \omega \times (m\mathbf{V}_{\mathbf{b}}) = \mathbf{F}, \tag{3}$$

$$\mathbf{J}\dot{\omega} + \omega \times (\mathbf{J}\omega) = \mathbf{M}, \tag{4}$$

where $\mathbf{F}$ and $\mathbf{M}$ are the force and moment vectors in body frame, m is the mass of aircraft, and $\mathbf{J}$ is the moment of inertia matrix. A full model on both vertical mode and cruise mode was introduced in [14], here we focus mainly on forces and moments acting on the UAV body in vertical mode. They are

$$\mathbf{F} = \mathbf{F}_{\text{grav}} + \mathbf{F}_{\text{prop}}, \quad (5)$$

$$\mathbf{M} = \mathbf{M}_{\text{prop}} + \mathbf{M}_{\text{fin}}, \quad (6)$$

where $\mathbf{F}_{\text{grav}}$ is the gravity force, $\mathbf{F}_{\text{prop}}$ is the total thrust vector generated by the 2 motors, $\mathbf{M}_{\text{prop}}$ is a combination of torque induced when motors point towards off-main axis and the reaction torque of the motors, which can be easily obtained by the physical relationship between the rotor frame and the body frame. $\mathbf{M}_{\text{fin}}$ is the torque produced by the control fins on the wings and it is estimated based on the flat plate theory as presented in [14].

B. Inner-loop Control

The UAV control problem is separated into the attitude stabilization layer and the position tracking layer. The attitude stabilization layer involves the design of an inner-loop controller which ensures the UAV roll, pitch and yaw dynamics are robustly stable. Moreover, the position tracking layer involves the design of an outer-loop controller which enables the UAV to track any smooth 3D trajectory in a responsive and precise way.

As the hybrid UAV will transit between vertical mode and cruise mode, two separate control systems are needed. In this paper, we focus only on vertical mode as the UAV will track and follow a ground moving vehicle only in this mode. Interested readers may refer to [15] for full envelope controllers design.

In vertical mode, an augmented linear system can be obtained by integrating the angular error $e = (\phi_e, \theta_e, \psi_e)^{\mathrm{T}}$. For simplicity, these 3 control channels are assumed to be decoupled, and thus individual controllers can be applied to each of them. For illustration purpose, only pitch channel of the system is shown here:

$$\dot{\mathbf{x}}_{\text{aug}} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \mathbf{x}_{\text{aug}} + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} u, \quad (7)$$

where $\mathbf{x}_{\text{aug}} = [\theta_e, q, \int_{(\theta_e)}]^{\mathrm{T}}$, $\int_{(\theta_e)}$ is the integration of the pitch angular error, i.e. $\int \theta_e \mathrm{d}t$.

With the derived state-space equation where u is the virtual angular acceleration input, an linear quadratic regulator (LQR) controller was implemented as

$$u = \mathbf{F}\mathbf{x}_{\text{aug}}, \quad (8)$$

with $\mathbf{F}$ is designed by minimizing the cost function

$$J = \int (\mathbf{x}^{\mathbf{T}}\mathbf{Q}\mathbf{x} + ru^2)\mathrm{d}t. \quad (9)$$

As documented in [13], the desired angular acceleration is then mapped to the desired tilting angle of the vectoring thrust δ, following the relationship

$$u = \frac{T r_{\text{pz}} \sin\delta}{J_y}, \quad (10)$$

where T is the total thrust, r_{pz} is the distance between the motor to the CG of the UAV in z-direction, δ is the motor tilting angle and J_y is the moment of inertia of the UAV in pitch direction. As the servos are able to provide sufficiently fast response, the dynamics of the tilting is ignored. The controller design of the other two channels are similar to this but with different actuation mappings.

C. Outer-loop Control

The design of the outer-loop controller is much more critical for this application due to the requirements to track and follow moving objects. The relative position of the reference marker to the UAV at every instance is estimated by our vision algorithm which will be discussed in the next section. The robust and perfect tracking (RPT) control concept from [16] perfectly fits this requirement.

The outer dynamics of the UAV can be assumed differentially flat, which means that all its state variables and inputs can be expressed in terms of algebraic functions of flat outputs and their derivatives. A good and intuitive choice of flat output for the hybrid UAV in vertical mode is

$$\sigma = [x, y, z, \psi]^{\mathrm{T}}. \quad (11)$$

It is observed that the first three outputs, x, y, z, are totally independent. In other words, when designing its outer-loop control law and generating the position references, the UAV can be considered as a mass point with constrained velocity, acceleration and its higher derivatives in the individual axis of the 3-D global frame. Hence, a stand-alone RPT controller based on multi-layer integrator model in each axis can be designed to track the corresponding reference in that axis. Similar to the inner-loop, to achieve a good tracking performance, it is common to include an error integral to ensure zero steady-state error. This requires an augmented system to be formulated as

$$\begin{cases} \dot{\mathbf{x}}_{\text{aug}} = \begin{bmatrix} 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \mathbf{x}_{\text{aug}} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u \\ \mathbf{y} = \mathbf{x}_{\text{aug}} \end{cases}, \quad (12)$$

where $\mathbf{x}_{\text{aug}} = \left[\int(\mathbf{p}_{\text{e}}) \quad \mathbf{p}_{\text{r}} \quad \mathbf{v}_{\text{r}} \quad \mathbf{a}_{\text{r}} \quad \mathbf{p} \quad \mathbf{v}\right]^{\mathrm{T}}$, $\mathbf{p}_{\text{r}}$, $\mathbf{v}_{\text{r}}$, $\mathbf{a}_{\text{r}}$ are the position, velocity and acceleration references in the controlled axis, $\mathbf{p}$, $\mathbf{v}$ are the actual position and velocity and $\mathbf{p}_{\text{e}} = \mathbf{p}_{\text{r}} - \mathbf{p}$ is the tracking error of the position. Following the procedures in [16], a linear feedback control law of the following form can be acquired as:

$$u = \mathbf{F}\mathbf{x}_{\text{aug}}, \quad (13)$$

where

$$\mathbf{F} = \begin{bmatrix} \frac{k_i\omega_n^2}{\varepsilon^3} & \frac{\omega_n^2+2\zeta\omega_n k_i}{\varepsilon^2} & \frac{2\zeta\omega_n+k_i}{\varepsilon} & 1 & -\frac{\omega_n^2+2\zeta\omega_n k_i}{\varepsilon^2} & -\frac{2\zeta\omega_n+k_i}{\varepsilon} \end{bmatrix}.$$

Here, ε is a design parameter to adjust the settling time of the closed-loop system. ω_n, ζ, k_i are the parameters that determine the desired pole locations of the infinite zero structure of (12) through

$$p_i(s) = (s+k_i)(s^2+2\zeta\omega_n s+\omega_n^2). \tag{14}$$

Theoretically, when the design parameter ε is small enough, the RPT controller can give arbitrarily fast responses. Nevertheless, it is safer practically to limit the bandwidth of the outer loop to be much smaller than that of the inner-loop dynamics, because of the constraints of the UAV physical dynamics and its inner-loop bandwidth.

IV. Vision-based tracking algorithm

In this work, we adopt the AprilTag visual fiducial system to provide the relative position estimation of the visual target. The AprilTag visual fiducial system [17] uses a 2D bar code styled tag, allowing full 6 DOF localization of features from a single image. The AprilTag visual detection algorithm is fast and robust, which provide an detection accuracy up to ± 3 cm and detection speed of 10 Hz running on the onboard computer.

As the hybrid UAV's dynamics is slower than the moving target vehicle, the relative position could not be directly fed into the position control of KH-Lion which might led to unexpected oscillation around the visual target. As a result, a target tracking algorithm is proposed as follows:

1) Estimate the relative position $\mathbf{P}_\mathrm{c}$ and relative velocity $\mathbf{V}_\mathrm{c}$ in the camera frame using Kalman filter
2) Calculate the position and velocity of the target in the local NED frame as $\mathbf{P}_\mathrm{n}$, $\mathbf{V}_\mathrm{n}$
3) Input the $\mathbf{P}_\mathrm{n}$ and $\mathbf{V}_\mathrm{n}$ to the Reflexxes trajectory generation algorithm to generate the feasible trajectory for the UAV

In order to achieve good tracking result, the velocity of the visual target has to be estimated. Denote $\mathbf{x}_\mathrm{c} = [\mathbf{P}_\mathrm{c} \quad \mathbf{V}_\mathrm{c}]^\mathrm{T}$, then the dynamics of $\mathbf{x}_\mathrm{c}$ is

$$\begin{aligned} \dot{\mathbf{x}}_\mathrm{c} &= \begin{bmatrix} 0 & \mathbf{I} \\ 0 & 0 \end{bmatrix} \mathbf{x}_\mathrm{c} + \begin{bmatrix} 0 \\ \mathbf{I} \end{bmatrix} \mathbf{a}_\mathrm{c} + \mathbf{w}(t), \\ \mathbf{y}_\mathrm{c} &= \begin{bmatrix} \mathbf{I} & 0 \end{bmatrix} \mathbf{x}_\mathrm{c} + \mathbf{v}(t), \end{aligned} \tag{15}$$

where $\mathbf{I}$ is the 3×3 identity matrix, $\mathbf{a}_\mathrm{c}$ is the relative acceleration of the visual target in camera frame and $\mathbf{y}_\mathrm{c}$ is the measurement from the AprilTag visual fiducial system. However, since the acceleration of the vehicle could not be measured, but within a range between ± 4 m/s^2, the $\mathbf{a}_\mathrm{r}$ is treated as zero and $\mathbf{w}(t)$ is Gaussian white noise with zero mean and a large covariance of $\sigma_w^2 = 4$. The measurement noise is obtained from the AprilTag measurement data and is $\sigma_v^2 = 0.01$. Then the typical Kalman filter design procedure is applied for the estimation of the $\mathbf{x}_\mathrm{c}$.

After obtaining $\mathbf{x}_\mathrm{c}$, the position and velocity of the target in local NED frame $\mathbf{x}_\mathrm{n} = [\mathbf{P}_\mathrm{n} \quad \mathbf{V}_\mathrm{n}]^\mathrm{T}$ could be obtained as

$$\begin{aligned} \mathbf{x}_\mathrm{n} &= \begin{bmatrix} \mathbf{R}_\mathrm{n/c} & 0 \\ 0 & \mathbf{R}_\mathrm{n/c} \end{bmatrix} \mathbf{x}_\mathrm{c} + \mathbf{x}, \\ \mathbf{R}_\mathrm{n/c} &= \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \end{aligned}$$

When we obtain the $\mathbf{x}_\mathrm{n}$, the last step is to generate a feasible trajectory $\mathbf{x}^*(t)$ such that the reference is approaching $\mathbf{x}_\mathrm{n}$ while also fulfilling the dynamic constrain of KH-Lion. The Reflexxes algorithm [18] solves the two point boundary value problem for a third-order integrator with constraints on the input and the states. The problem is solved using switching control based method with a closed form solution thus fast response and real-time performance is easily achieved. As a result, it can solve the acceleration smooth trajectory from current state $\mathbf{x}$ to the target state $\mathbf{x}_\mathrm{n}$ with constrains on jerk, acceleration and velocity. The generated trajectory reference is then fed to the outer-loop control for the position tracking of the target.

V. Flight Test Results

The hybrid UAV, KH-Lion, implemented with the above-mentioned tracking algorithm was tested in an indoor flight test, with the aim of tracking a moving vehicle attached with the designed marker. In the flight experiment, the UAV took-off autonomously from the ground, then hovered above the moving vehicle. Lastly, it was commanded to track and follow the vehicle while it was moving. The setup of the experiment is shown in Fig. 2.

A sample image captured by the on-board camera is shown in Fig. 3. With the AprilTag attached on the ground vehicle, the hybrid UAV was commanded to track the AprilTag while it is moving. For comparison purpose, the experiment was carried out in the presence of VICON motion tracking system, where the positions of the UAV and the moving marker were both obtained by the VICON system to be used as ground truth.

The ground vehicle was commanded to travel in a rectangular path of about 3 m by 3 m, with a speed of approximately 0.5 m/s. Fig. 4 shows the trajectory of the moving marker, together with the trajectory of the hybrid UAV while tracking the moving marker autonomously. Fig. 5 shows the comparison between the vision-estimated moving marker position with the actual position of the vehicle. It shows a promising result that the tracking performance is consistent throughout the whole experiment.

Fig. 6, Fig. 7 and Fig. 8 show the orientation, position, and velocity performances of the hybrid UAV in the mentioned flight test. It is observed that the response of the system matches rather closely to the reference generated by our tracking algorithm. It also shows that the RPT controller implementation on the outer-loop is indeed suitable for tracking and following tasks.

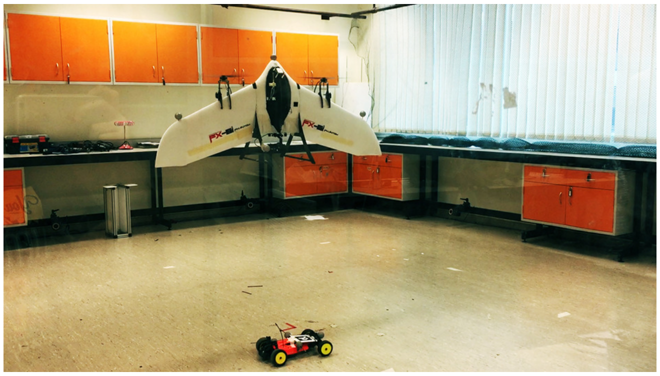

Fig. 2. Experiment setup with a hybrid UAV and a remote control car

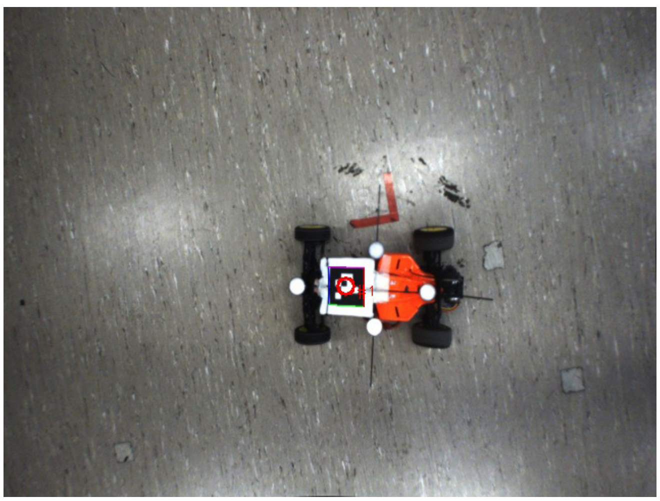

Fig. 3. Image captured by on-board camera

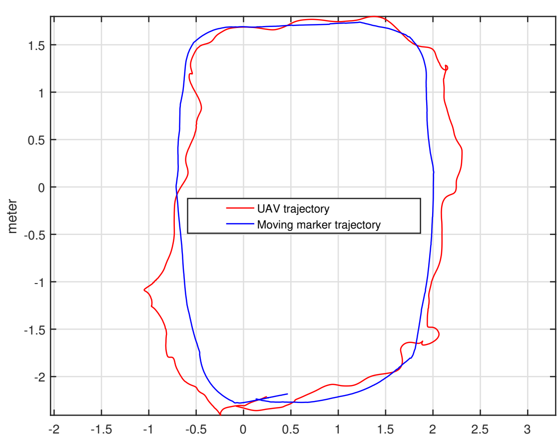

Fig. 4. Trajectory of moving marker and UAV measured by VICON system

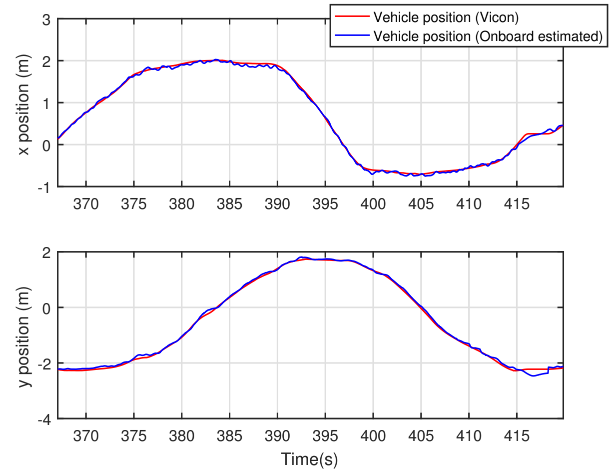

Fig. 5. Estimated moving marker position

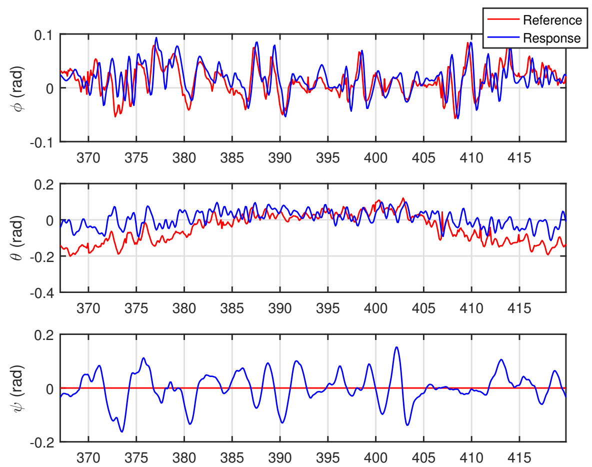

Fig. 6. Orientation performance of the UAV

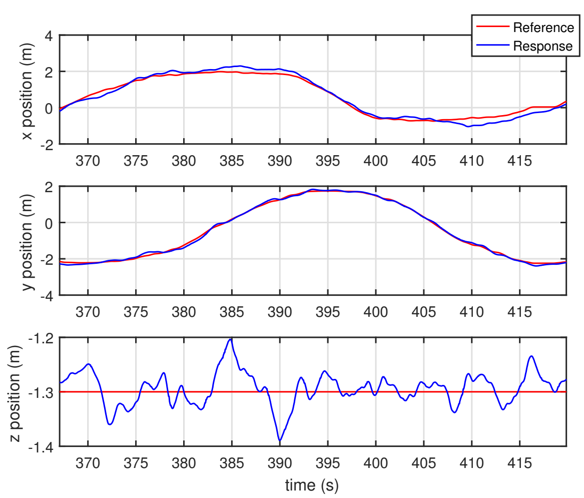

Fig. 7. Position performance of the UAV

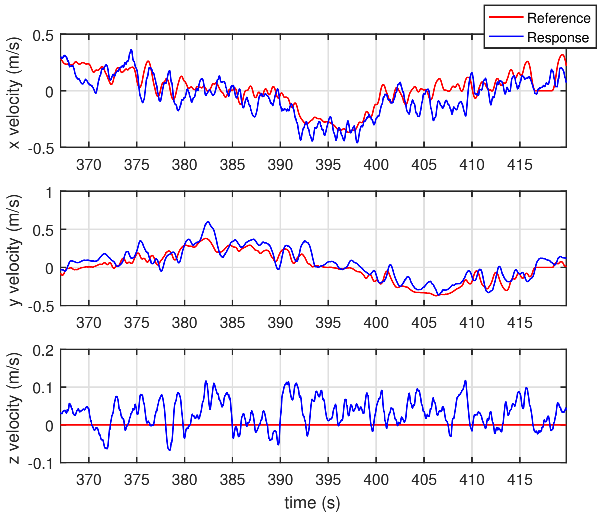

Fig. 8. Velocity performance of the UAV

VI. Conclusions

The proposed vision based tracking algorithm has been implemented on actual hybrid UAV, and flight experiments were carried out to verify the algorithm. The whole system was validated by experiments with result of successful tracking of a moving platform with speed of 0.5 m/s in a VICON environment. However, a few challenges and limitations of the current system need to be solved. Firstly, the flight controller needs to be fine tuned in order to track a vehicle with sudden acceleration or deceleration. Then, the tracking and following speed of the hybrid UAV needs to be increased for a faster operation. Finally, we aim to develop an autonomous landing system to land the hybrid UAV to the moving ground vehicle.

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