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Research Article

Adaptive vision-based control of an unmanned aerial vehicle without linear velocity measurements

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ABSTRACT

In this paper, an image-based visual servo controller is designed for an unmanned aerial vehicle. The main objective is to use flow of image features as the velocity cue to compensate for the low quality of linear velocity information obtained from accelerometers. Nonlinear observers are designed to estimate this flow. The proposed controller is bounded, which can help to keep the target points in the field of view of the camera. The main advantages over the previous full dynamic observer-based methods are that, the controller is robust with respect to unknown image depth, and also no yaw information is required. The complete stability analysis is presented and asymptotic convergence of the error signals is guaranteed. Simulation results show the effectiveness of the proposed approach.

1. Introduction

Unmanned aerial vehicles (UAVs) have recently received a great attention among researchers and in industry because of their potential applications including traffic monitoring, search and rescue, fire monitoring, etc. [1,2]. Developing new control methods and improving the sensory system are the challenging problems to increase applications of UAVs [3,4]. Although there are reliable sensory systems in the market that can provide significant information for the vehicle stabilization, cost and weight are two important factors that limit using those systems in the small-scale UAVs. These vehicles generally include an inertial measurement unit (IMU) and a global positioning system (GPS). This sensor suite provides reliable information for the angular velocity and attitude, but in contrast the translational position and linear velocity information cannot be effectively estimated by it [5]. On the other hand, GPSs are ineffective when the application of interest involves indoor environment.

Vision sensor is a reliable, light-weight and low-cost system, which in combination with an IMU system can provide useful translational velocity information and also can be effectively used in localization of a vehicle with respect to its environment. In the recent years, many applications have been reported in using the vision system for UAVs including obstacle avoidance [6], pose estimation [7], line tracking [8] and positioning [9].

Direct implementation of visual information in the feedback control is called visual servoing which is mainly classified into two approaches including position-based visual servoing (PBVS), and image-based visual servoing (IBVS). In the first approach, 3D position and orientation information of the target is reconstructed from 2D image data. Estimation approaches are exploited for this purpose, where the algorithms generally require *a priori* information from the geometric model of the observed target. Some works have reported the implementation of this approach on the aerial vehicles; e.g., [10–12]. In the second approach, the controller is designed based on the dynamics of image features in the image plane. This approach is more attractive since it is robust against camera calibration errors and does not require 3D information of the image, and hence it is computationally simple comparing to PBVS. However, this approach still requires the depth information of the image, and the controller design is more challenging.

It is highly recommended to consider the dynamics of the whole system in designing an IBVS approach for UAVs [13]. This is a challenging problem since these vehicles are generally underactuated. In most of the available works, passivity properties of spherical image moments are exploited to design a dynamic IBVS

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controller for UAVs [14–17]. However spherical image features do not generally provide satisfactory behaviour for the robot motion in vertical axis [18]. To overcome this conditioning problem, the authors have proposed a method in [19], which utilizes perspective image moments and the controller is designed for their dynamics in a suitably oriented image plane.

Since the linear velocity is an input for the image dynamics in the IBVS approach, the low quality of this information is another problem in applying this control method for UAVs. Considering the unreliable linear velocity information obtained from an IMU system, optic flow of image features is used in [5] as a cue of the translational velocity and the dynamics of the system are expressed based on the dynamics of spherical optic flow. The approach, however, does not consider the error in estimation of the optic flow, and it also has the conditioning problem mentioned above. An observer-based method has been presented in [20], where the method considers partial dynamics of the system and only a limited basin of attraction is achieved. A method using a nonlinear observer is also presented in [21] which assumes that the image depth is known. The full dynamic IBVS approach, presented in [22], assumes that a geometric model of the object is known in advance, from which the image depth information is not required. All of the mentioned works require magnetic field sensors for estimating the yaw angle of the UAV, where the estimated value is generally unreliable for a control task.

In this paper, considering the full dynamics of the system, an IBVS controller without linear velocity measurements is designed to control the translational motion of a vertical take-off and landing UAV called quadrotor. Image features are selected from appropriate combination of perspective image moments and reprojected on a suitably defined virtual image plane. These features provide efficient trajectories in both image and Cartesian space and also do not require a geometric model of the target. Nonlinear observers are designed to estimate the flow of image features. The controller is robust with respect to parametric uncertainty of the system model associated with depth information of the image. In addition, exploiting passivity properties of the image dynamics in the virtual image plane, the controller does not require the yaw information of the quadrotor. The designed force input for the translational dynamics is bounded, which helps to keep the target points in the field of view of the camera. Stability analysis guarantees that the controller drives the system errors to zero. Simulation results are provided to illustrate the effectiveness of the proposed approach. This work is an extension to the authors' previous works on observer-based IBVS control of the quadrotor [23,24], in which only the translation dynamics of the vehicle are considered. Another improvement of this paper w.r.t. [23,24] is the boundedness of the input of the translational dynamics.

The paper is organized as follows. In Section 2, kinematic and dynamic models of the quadrotor are studied. Section 3 describes the image features and their dynamics in the image plane. The proposed observer-based IBVS controller is given in Section 4. Simulation results are discussed in Section 5, and the conclusions are given in Section 6.

2. Kinematics and dynamics of the robot

In this section, equations of motion of the quadrotor helicopter are described. For this end, two coordinate frames are considered, which are shown in Fig. 1. The frames include an inertial frame $\mathcal{I}=\{O_i, X_i, Y_i, Z_i\}$ and a body-fixed frame $\mathcal{B}=\{O_b, X_b, Y_b, Z_b\}$, which is attached to the center of mass of the robot. Refer to the Appendices for a list of symbols used throughout the paper.

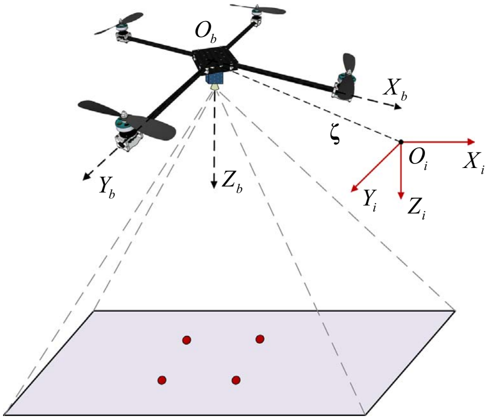

Fig. 1. A quadrotor helicopter and coordinate frames.

The frame $\mathcal{B}$ is located at position $\boldsymbol{\zeta}=[x\ y\ z]^\top$ with respect to the frame $\mathcal{I}$, and its attitude is given by the rotation matrix $\mathbf{R}:\mathcal{B}\to\mathcal{I}$, which describes the successive rotations about the axes of inertial frame with order of rotations specified as $X_i-Y_i-Z_i$. The rotation matrix depends on the three Euler angles ϕ, θ and ψ denoting, respectively, the roll, pitch, and yaw, which is defined as in the following:

$$\mathbf{R}=\begin{bmatrix} c_\psi c_\theta & c_\psi s_\theta s_\phi - s_\psi c_\phi & c_\psi s_\theta c_\phi + s_\psi s_\phi \\ s_\psi c_\theta & s_\psi s_\theta s_\phi + c_\psi c_\phi & s_\psi s_\theta c_\phi - c_\psi s_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{bmatrix} \tag{1}$$

where $s_a \equiv \sin(a)$ and $c_a \equiv \cos(a)$. The following property is satisfied for the rotation matrix [25, p. 107]:

Property 1. *For any vector* $\mathbf{u}\in\Re^3$ *and the rotation matrix* $\mathbf{R}$ *one has*

$\mathbf{Rsk(u)R}^\top = \mathbf{sk(Ru)}$.

The notation $\mathbf{sk}(\cdot)$ in Property 1 is the skew-symmetric matrix such that

$$\mathbf{sk(u)}=\begin{bmatrix} 0 & -u_3 & u_2 \\ u_3 & 0 & -u_1 \\ -u_2 & u_1 & 0 \end{bmatrix}, \quad \forall \mathbf{u}=[u_1\ u_2\ u_3]^\top \in \Re^3,$$

and for any vectors $\mathbf{u}_1, \mathbf{u}_2 \in \Re^3$, $\mathbf{sk}(\mathbf{u}_1)\mathbf{u}_2 = \mathbf{u}_1 \times \mathbf{u}_2$, where $\times$ denotes the vector cross product. A skew-symmetric matrix has the following property:

Property 2. *A skew-symmetric matrix* $\boldsymbol{\Lambda}\in\Re^{n\times n}$ *and a vector* $\mathbf{u}\in\Re^n$ *satisfy the relation* $\mathbf{u}^\top\boldsymbol{\Lambda}\mathbf{u}=0$.

Considering $\mathbf{V}\in\Re^3$ and $\boldsymbol{\Omega}=[\boldsymbol{\Omega}_1\ \boldsymbol{\Omega}_2\ \boldsymbol{\Omega}_3]^\top\in\Re^3$ respectively as the linear and angular velocities of the robot in the body-fixed frame, the kinematics of the quadrotor can be written as follows [26]:

$$\dot{\boldsymbol{\zeta}} = \mathbf{RV}$$
$$\dot{\mathbf{R}} = \mathbf{R}\mathbf{sk}(\boldsymbol{\Omega}).$$

Also, the time derivatives of the Euler angles are given by

$$\begin{bmatrix} \dot\phi \\ \dot\theta \\ \dot\psi \end{bmatrix} = \begin{bmatrix} 1 & s_\phi t_\theta & c_\phi t_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & \frac{s_\phi}{c_\theta} & \frac{c_\phi}{c_\theta} \end{bmatrix} \begin{bmatrix} \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{bmatrix} \tag{2}$$

where $t_\theta \equiv \tan(\theta)$.

The dynamics of a general six degrees of freedom (6DOF) rigid body, with the mass of m and the constant symmetric inertia matrix $\mathbf{J}\in\Re^{3\times3}$ around the center of mass, with respect to the

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