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An indirect adaptive neural control of a visual-based quadrotor robot for pursuing a moving target

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ABSTRACT

This paper aims to use a visual-based control mechanism to control a quadrotor type aerial robot which is in pursuit of a moving target. The nonlinear nature of a quadrotor, on the one hand, and the difficulty of obtaining an exact model for it, on the other hand, constitute two serious challenges in designing a controller for this UAV. A potential solution for such problems is the use of intelligent control methods such as those that rely on artificial neural networks and other similar approaches. In addition to the two mentioned problems, another problem that emerges due to the moving nature of a target is the uncertainty that exists in the target image. By employing an artificial neural network with a Radial Basis Function (RBF) an indirect adaptive neural controller has been designed for a quadrotor robot in search of a moving target. The results of the simulation for different paths show that the quadrotor has efficiently tracked the moving target.

1. Introduction

In general, the use of a visual sensor in the control loop of a robot is called a Visual Servoing (VS) control. This control technique, irrespective of camera position and orientation, and based on the manner of using the visual information, is classified into Image Based Visual Servoing (IBVS) and Position Based Visual Servoing (PBVS) control methods [1,2]. In the first type, the control law is calculated from the 3D Cartesian information reconstructed from the 2D camera information. Since, in practice, the reconstructing of 3D information from the image of a scene may be very difficult or even impossible, most of the PBVS approaches use an estimation technique which assumes that there is an initial knowledge about the geometrical model of an observed object. Basically, the PBVS schemes are quite sensitive to the initial conditions and are ineffective in the presence of image noise [3]. In the second type of control mechanism (i.e., IBVS), the control law is computed only through the visual features. Since the IBVS approach does not need to thoroughly reconstruct the 3D information, it requires less computations and, thus, it is leaner and more robust than PBVS. Nevertheless, the depth of the observed image is needed; in fact, as has been demonstrated in [4], an incorrect depth estimation of image features could create problems for the IBVS system.

In [5], the PBVS system has been employed for controlling a helicopter that uses an installed camera to estimate its position. A bi-camera vision system has been used in [6] for extracting the 3D position information from the viewpoint of a helicopter used for following the electrical power lines. The first work regarding the control of an aerial quadrotor by the PBVS method has been reported in 2002 by Altug et al. [7]. A special camera combination has been used in [8] to estimate the position of a quadrotor helicopter; and based on these estimations, two different nonlinear controllers have been developed for quadrotor robot dynamics. The position-based approach has also been employed in [9] for the automatic landing of a quadrotor helicopter. A classical IBVS control mechanism for quadrotor helicopter has been developed in [10]. An image-based quadrotor control method with an adaptive mechanism has also been reported in [11] for keeping the image features in the visual field of the camera. In [12], the IBVS system has been used for landing a quadrotor helicopter on a moving platform. However, in all these works, the controller for robot dynamics has been designed separate from that for image feature dynamics; and the uncertainties related to the information of image depth and target movement have not been considered in the system dynamics. In designing an IBVS control method in [13], the authors have pointed out that for robots with relatively high speeds, especially those with under-actuated dynamics, the robot's dynamics must be considered in designing a controller.

In a cascade nonlinear control method designed in [14], it has been shown that the dynamics of image features destroy the triangular structure of a robot's dynamics, and that the passivity of these

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dynamics is preserved only when image features obtained from spherical imaging are used. The proposed control law with the described image features has been practically implemented in [15] on an under-actuated quadrotor helicopter, and the obtained results indicate unfavorable behaviors along the vertical axes, in view of the large changes in the sensitivity of visual characteristics in three directions of motion. The main problem with the use of spherical imaging is the improper response of a system in the cartesian space; so that, due to the particular characteristic of this type of imaging, uniform convergence is not achieved in controlling the translational motion of a flying robot. This specific problem has been investigated in [16] in which the authors have used new image features to improve the response and to achieve a uniform convergence of a robot's position in its operating space. Of course, the definitions put forth for image features require some initial information; and they have also resulted in some restrictions, including the requirement of a not-so-large distance between a robot and its final situation. To resolve this issue, a method based on a virtual spring has been proposed in [17] for designing a dynamic IBVS controller for a quadrotor by using perspective image moments.

A visual-based control problem regarding the liftoff and landing of a vertical-flight unmanned aerial vehicle (UAV) has been investigated in [18]. The design scheme enables the UAV to follow a moving target. It has been shown in [19] that the image equations that are obtained from perspective image moments have a passivity property in the oriented image plane, which is called the virtual image plane.

In order to control a UAV, the back stepping method has been used in [20] along with neural networks (NNs) to deal with the modeling errors and nonlinear dynamics. The back stepping technique has also been employed in [21] for controlling a quadrotor. In this work, the aerodynamic forces and moments have been estimated by means of a NN. A nonlinear adaptive controller for a quadrotor has been proposed in [22]. The functioning of this controller is based on the combination of the back stepping technique and NN.

In this paper, to overcome the existing uncertainties in image dynamics, and also because of the nonlinear nature of a quadrotor, a NN with Radial Basis Function (RBF) has been used to devise an indirect adaptive controller for the quadrotor, so that it can follow a moving target by applying the IBVS scheme. The equations of motion for the considered quadrotor have been presented in the following section. In Section 3, image dynamics similar to those in [19] are presented. Then, the indirect adaptive controller is designed in Section 4 and the simulation results are given in Section 5. Finally, the conclusion of this work is presented in Section 6.

2. Motion equations for a quadrotor robot

In this section, the dynamic and kinematic equations for a quadrotor robot have been described. These equations are similar to the equations introduced in other papers (e.g., in [23–25]).

This robot has 4 motors which are considered the main drivers of this quadrotor. Each of these motors consists of a rotor installed within a symmetric frame. The shafts of these rotors are parallel to each other and they produce a downward air draft.

To express a quadrotor robot's equations of motion, two coordinate systems are considered: the inertia frame $\mathscr{I} = \{O_i, X_i, Y_i, Z_i\}$ and the body frame $\mathscr{B} = \{O_b, X_b, Y_b, Z_b\}$ which is attached to the robot's center of mass. These frames have been shown in Fig. 1. The robot is equipped with a camera, with its lens pointing downward, and these robot-related equations indicate the motion equations of the camera as well [19]. The center of frame $\mathscr{B}$ is located at position $\zeta = (x, y, z)$ relative to the inertia frame and its orientation is determined by an orthogonal rotation matrix $R : \mathscr{B} \to \mathscr{I}$; these orientations are defined by means of Euler angles φ, θ and ψ as the roll, pitch and yaw angles, respectively.

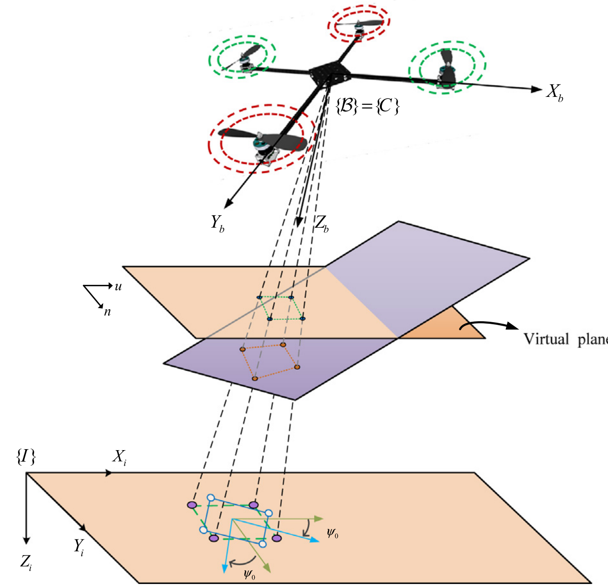

Fig. 1. Projection on a virtual image plane and a camera's coordinates system and a virtual plane.

By considering $V \in \mathfrak{R}^3$ and $\mathbf{\Omega} = \begin{bmatrix} \Omega_1 & \Omega_2 & \Omega_3 \end{bmatrix}^T$ as the respective linear and rotational velocities of a quadrotor robot in the body frame, the kinematics of the quadrotor, as a rigid body with 6 degrees of freedom can be expressed as follows:

$$\dot{\zeta} = RV$$

$$\dot{R} = Rsk(\mathbf{\Omega}) \tag{1}$$

Expression $sk(\mathbf{\Omega})$ indicates a skew-symmetric matrix so that for vector $b \in \mathfrak{R}^3$ we have:$sk(\mathbf{\Omega})b = \mathbf{\Omega} \times b$. The '$\times$' sign symbolizes an external vector multiplication. By using the Newton–Euler method the dynamics of a 6 DOF rigid body with mass m and inertia matrix $J \in \mathfrak{R}^{3\times3}$ about the body's center of mass, and in relation to body frame B, can be expressed as [23]

$$m\dot{V} = -m\mathbf{\Omega} \times V + F + \Delta_F \tag{2}$$

$$J\dot{\mathbf{\Omega}} = -\mathbf{\Omega} \times J\mathbf{\Omega} + \tau + \Delta_\tau \tag{3}$$

where $F \in \mathfrak{R}^3$ and $\tau \in \mathfrak{R}^3$ are the force and moment vectors expressed in frame $\mathscr{B}$, respectively, and they specify the particular dynamics of the system. In this dynamics, when the center of O_b coincides with the inertia axis of robot, the inertia matrix will become diagonal, $J = \mathrm{diag}(J_{xx}, J_{yy}, J_{zz})$. Sometimes, other disturbing forces and moments are also applied to the system, which cannot be overlooked in relation to the major forces and moments.These forces and moments can be expressed as the uncertainties of the system; which Δ_F and Δ_τ are the unknown vectors of force and moment applied to the system, respectively. The robot motors generate the thrust input U_1 and the total torque actuation of the system $\tau = \begin{bmatrix} U_2 & U_3 & U_4 \end{bmatrix}^T$, which specifies the robot's under-actuated dynamics. The equation for the generated force (Eq. (2)) can be expressed as [19]

$$F = -U_1 E_3 + mgR^T e_3. \tag{4}$$

In Eq. (4), $E_3 = e_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$ denote the unit vectors expressed in the body and inertia frames, respectively.