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Quadrotor UAV Guidence For Ground Moving Target Tracking

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Abstract — **The studies in aerial vehicles modeling and control have been increased rapidly recently. In this paper, a coordination of two types of heterogeneous robots, namely unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV) is considered. The UAV plays the role of a virtual leader for the UGVs. The system consists of a vision- based target detection algorithm that uses the color and image moment of a given target. The modeling of the VTOL vehicle will be described by using Euler-Newton equations. Flight controller commands are directly generated based on the offset of the target from the image frame. The image processing and intelligent control algorithms have been implemented on a latest computer. Matlab Simulink has been used to test, analyze and compare the performance of the controllers in simulations .**

***Index Terms* - UAV, Intelligent control, Modeling, Target tracking**

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I. INTRODUCTION

Multi agent systems have received considerable attention in recent years. It is due to their advantages in accomplishing complex missions such as discoveries, surveillance, disaster monitoring and so on. One of the attractive scenarios for multi agent systems is formation. Indeed formation control can be considered as controlling relative position and orientation of robots in a team [1]. Formation control has been investigated in three main approaches in the literature, namely: Leader-Follower, behavioral and virtual structures. In the leader-follower approach, one agent, designed as a leader, moves along a predefined trajectory, and the other ones should maintain a desired distance and orientation to the leader [1].

Helicopter design has been the center of attention since the beginning of the 20th century. First full-scale four rotor helicopter (quadrotor) was built by Debothezat in 1921 [2]. Other examples are Breguet Richet helicopter, Oemnichen helicopter, Convertawings Model A and Curtis Wright VZ-7 [3, 4]. At those early times due to the lacking control and sensing technologies, it was not possible to build an unmanned vehicle. Advances in sensors, control technology and electronics enable the possibility of that. Currently, there are various commercial and experimental autonomous unmanned VTOL vehicles are being developed at universities, research centers, and by hobbits [5-8].

UAV hovering over a desired position requires information coming from varied sensors, more precisely, it requires data coming from UAV environment. A sensor capable to obtain abundant information of UAV environment is a vision system. Many results related to this topic have been presented in the last few years. Most of them are related to identification and classification of multiple targets [9-15]. A circular pattern navigation algorithm for autonomous target tracking has been studied in [16] and [17] showing a good performance supported by numerical simulations.

Other work trajectory acquisition from video includes particle filters for moving cameras without any stabilization [18] and the Joint Probabilistic Data Association Filter (JPDAF) for tracking multiple targets with unreliable target identification [19]. If a model for the object's motion is known, an observer can be used to estimate the object's velocity [20]. In [21], an observer for estimating the object velocity was utilized; however, a description of the object's kinematics must be known. In [22] an autoregressive discrete time model is used to predict the location of features of a moving object. In [23], trajectory filtering and prediction techniques are utilized to track a moving object. In [24], object-centered models are utilized to estimate the translation and the center of rotation of the object. Several interesting works have been presented concerning visual tracking of targets using UAVs. In [25] a color based tracker is proposed to estimate the target position, while in [26] thermal images are correlated with a geographical information system (GIS) towards the same goal. In [27] a vision-based control algorithm for stabilizing a UAV equipped with two cameras is presented. The same system has been used in [28] to track a line painted in a wall, using a vanishing points technique. Some methods for designing UAV trajectories that increase the amount of information available are presented in [29].

The description of this paper is about using a vision system to observe a visual target over a ground vehicle and tracking it by using an UAV quadrotor. The main challenge involved in target localization include maintaining the target inside the camera's field of view. In order to achieve this requirement, a control schema have been proposed that develops a quadrotor tracking, such the target localization estimation error is minimized. To successfully perform this task, a control strategy which will be explained, have been developed.

This paper will be presented a new system for controlling and tracking in the quadrotor. The performances of this method are compared to other methods in the literature, Matlab simulations have been used for this.

The paper is structured as followings: In section 2 the mathematical model of the quadrotor is described. The controllers are presented in section 3. The simulations supporting the objectives of the paper are presented in section 4. And finally concluding remarks are presented in section 5.

II. MATEMATHICAL MODEL OF THE QUADROTOR

Generally, the quadrotor can be modeled with a four rotors in cross configuration. The throttle movement is provided by increasing (or decreasing) all the rotor speeds by the same amount. It leads a vertical force u1 (N) with respect to body-fixed frame which raises or lowers the quadrotor.

The roll movement is provided by increasing (or decreasing) the left rotor's speed and at the same time decreasing (or increasing) the right rotor's speed. The pitch movement is provided by a same way but with other two motors. The front and rear motors rotate counter-clockwise while other two motors rotate clockwise, so yaw command is derived by increasing (or decreasing) counter-clockwise motors speed and at the same time decreasing (or increasing) clockwise motor speeds.

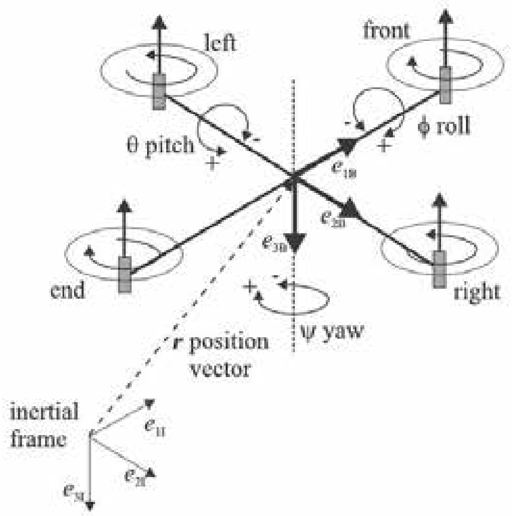

Fig. 1. Configuration, inertial and body fixed frame [30].

In order to model the quadrotor dynamics, two frames have to be defined as showed in figure 1. The orientation of the quadrotor is given by the three Euler angles, which are roll angle φ, pitch angle θ and yaw angle ψ .

These three Euler angles form the vector $\Omega^T = (\varphi, \theta, \psi)$. The position of the vehicle in the inertial frame is given by the vector $r^T = (x.y.z)$. The transformation of vectors from the body fixed frame to the inertial frame is given by the rotation matrix R where cθ for example denotes cosθ and sθ denotes sinθ .

$$R = \begin{pmatrix} c\psi.c\theta & c\psi.s\theta.s\varphi - s\psi.c\varphi & c\psi.s\theta.c\varphi + s\psi.s\varphi \\ s\psi.c\theta & s\psi.s\theta.s\varphi + c\psi.c\varphi & s\psi.s\theta.c\varphi - c\psi.s\varphi \\ -s\theta & c\theta.s\varphi & c\theta.c\varphi \end{pmatrix} \quad (1)$$

The thrust force generated by rotor *i*, *i*=1,2,3,4 is $F_i = b.w_i^2$, where *b* is the thrust factor and $w_i(rad/s)$ is the rotational speed of rotor *i*. Then the thrust force applied to the airframe from the four rotors is given by

$$T = \sum_{i=1}^{4} |F_i| = b.\sum_{i=1}^{4} \omega_i^2 \quad (2)$$

Now the first set of differential equation that describes the acceleration of the quadrotor can be written as:

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = g.\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} - R\frac{T}{m}.\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (3)$$

With inertia matrix *I* (which is diagonal matrix with the inertias I_x,I_y and I_z on the main diagonal), the rotor inertia I_R , the vector *M* that describes the torque applied to the vehicle's body and the vector M_G of the gyroscopic torques we obtain a second set of differential equations:

$$I.\ddot{\Omega} = -(\dot{\Omega} \times I.\dot{\Omega}) - M_G + M \quad (4)$$

The vector *M* is defined as:

$$M = \begin{pmatrix} Lb(\omega_3^2 - \omega_4^2) \\ Lb(\omega_1^2 - \omega_2^2) \\ d(\omega_1^2 + \omega_2^2 - \omega_3^2 - \omega_4^2) \end{pmatrix} \quad (5)$$

The four rotational velocities of the rotors are the input variables w_i of the real vehicle, but with regard to the obtained model a transformation of the input is suitable. Therefore, the artificial input variables can be defined as follows:

$$u_1 = b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \quad (6)$$

$$u_2 = b(\omega_3^2 - \omega_4^2) \quad (7)$$

$$u_3 = b(\omega_1^2 - \omega_2^2) \quad (8)$$

$$u_4 = d(\omega_1^2 + \omega_2^2 - \omega_3^2 - \omega_4^2) \quad (9)$$

Where $u_i = T$ (6) denotes the thrust force applied to the quadrotor airframe; u_2 denotes the force which leads to the roll torque; u_3 for the pitch torque and u_4 for the yaw torque.

However, also the gyroscopic torques depend on the rotational velocities of the rotors and hence on the vector $u^T = (u_1, u_2, u_3, u_4)$ of the transformed input variables. We assume that:

$$g(u) = \omega_1 + \omega_2 - \omega_3 - \omega_4 \quad (10)$$

And then evaluation of (4) and (5) yields the overall dynamic model in the following form:

$$\ddot{x} = -(cos\varphi.sin\theta.cos\psi + sin\varphi.sin\psi).\frac{u_1}{m} \quad (11)$$

$$\ddot{y} = -(cos\varphi.sin\theta.sin\psi - sin\varphi.cos\psi).\frac{u_1}{m} \quad (12)$$

$$\ddot{z} = g - (cos\varphi.cos\theta).\frac{u_1}{m} \quad (13)$$

$$\ddot{\varphi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) - \frac{I_R}{I_x}\dot{\theta}g(u) + \frac{L}{I_x}u_2 \quad (14)$$

$$\ddot{\theta} = \dot{\phi}\dot{\psi}\left(\frac{I_z - I_x}{I_y}\right) + \frac{I_R}{I_y}\dot{\varphi}g(u) + \frac{L}{I_y}u_3 \quad (15)$$

$$\ddot{\psi} = \dot{\theta}\dot{\varphi}\left(\frac{I_x - I_y}{I_z}\right) + \frac{1}{I_z}u_4 \quad (16)$$

Equations (11) to (16) represent the full mathematical model of the quadrotor.

III. CONTROL ALGORITHMS DESIGN

In this section, a new algorithms for controlling the attitude and position of the quadrotor will be presented; that the proportional Integral Derivative (PID) controllers is assumed to perform this tasks.

As mentioned before the inputs chose like equations (6) to (9). Where u_i controls the motion along the z-axis, u_2 controls rotation along the x-axis (roll angle), u_3 controls the rotation along the y-axis (pitch angle) and u_4 controls rotation along the z-axis (yaw angle). Two other controllers which control the position of the quadrotor (x and y) use some equations that comes in follow paragraphs. The designed controllers should set values to u_i parameters which determines the four rotor speed parameters w_i by (6) to (9).

First of all, an overview of the algorithms used in the simulation will be shown. The aim of this paper is hunted down a moving target by a quadrotor UAV. Thus a specific algorithm must be able to identify and follow the target by getting the position of the target and predicting desired path of the target by using a certain algorithm. An overview of the work come in the figure 2.

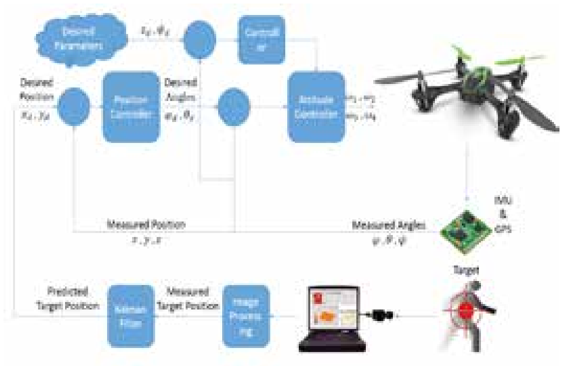

Fig. 2. Overview of the work

Now the system in figure 2 must be simulated to ensure of performances of the applied systems and algorithms. In this paper the MATLAB and Simulink have been used to simulate the system. Now the details of each block in the algorithm, must be explained.

1. Image processing and target detection algorithm

Video tracking use in many applications such as traffic monitoring, detection and identification of unusual behavior in the scene, navigation and human-computer communication such as gestures recognition and other applications.

This project is intended to detect a red moving target by using a digital camera that is fixed on the top of a laboratory environment and estimate path of the object for identifying and tracking by using Kalman filter algorithm. This path will be sent to the quadrotor processing system to follow the moving target. A test sample was carried out for this project is came in figure 3.

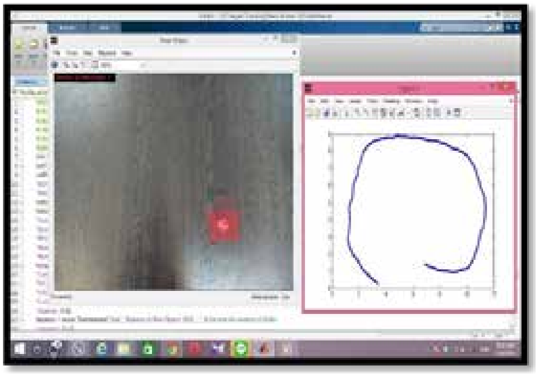

Fig. 3. Track the red moving target and path estimation

2. Kalman filter

The Kalman filter is a linear recursive estimator that predicts the next state based on dynamics model and update this result agrees with the measurements obtained.

In this paper for estimating the position of the moving target in a two-dimensional space of a series of noisy inputs and past positions, the Kalman filter have been used.

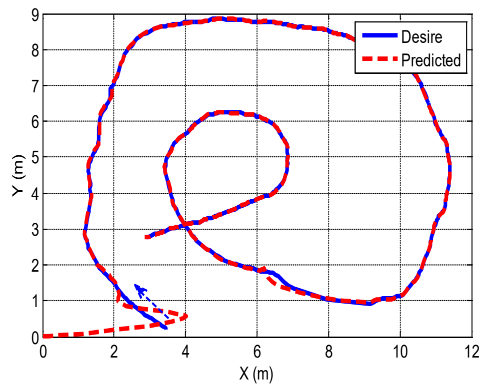

Fig. 4. Estimation of the path of the moving target using Kalman filter

With this algorithm, in order to estimate the path of the moving target, image processing have been used and data sent to the control center of the quadrotor to pass this estimated path. Figure 4 shows actual path of the moving target achieved by using image processing and the Kalman filter estimated path to have a compare between both of them.

3. Classical PID controller

Due to their simple structure and robust performance, proportional-integral-derivative (PID) controllers are the most commonly used controllers in industrial process control. The equation of a PID controller has the following form:

$$u(t) = K_p e(t) + K_I \int_0^t e(t)d\tau + K_D \frac{d}{dt} e(t) \quad (17)$$

Where K_p , K_I and are called the propositional, integral and derivative gains, respectively.

For adjusting the controller parameters the Ziegler-Nichols method will be used and response of the system with this adjusting will be showed in the result section.

In the simulations were performed, to control the position or following the path of a moving target, six different controllers is used. In the figure 5 overview of the control system of the quadrotor can be seen which two different control systems have been used for position control (internal and external control system).

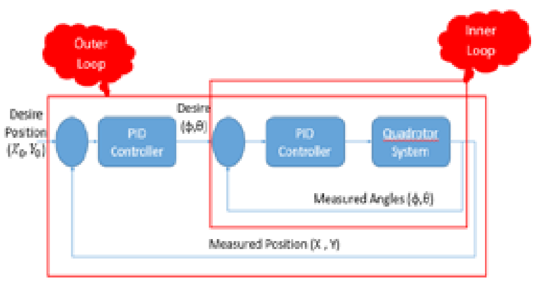

Fig. 5. Overview of the position control system of the quadrotor

Internal control system is attitude control and external control system is position controller. In the following some equations for position control of the quadrotor can be seen.

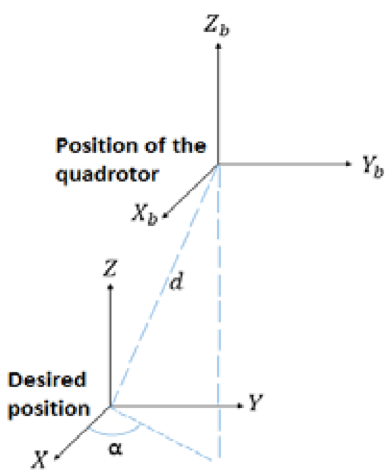

Fig. 6. A view of the current position and desired position of the quadrotor

$$d = \sqrt{(x - x_0)^2 + (y - y_0)^2} \quad (18)$$

x_0 and y_0 are desired coordinates are obtained from Kalman filter algorithm.

$$\alpha = arctan \left({}^{y - y_0}/_{x - x_0} \right) \quad (19)$$

$$\beta = \alpha - yaw \quad (20)$$

The controllers are try to decrease d which is the distance between the current position and desired position. Requirement forces which must be applied into the quadrotor to compensate for the distance created as follows.

$$\begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\varphi \sin\theta & \cos\varphi \cos\theta \\ 0 & \cos\varphi & -\sin\varphi \\ -\sin\theta & \sin\varphi\cos\theta & \cos\varphi\cos\theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix} \quad (21)$$

$$F \cos\varphi \sin\theta = f_x = A\cos\beta \quad (22)$$

$$-F \sin\varphi = f_y = A \sin\beta \quad (23)$$

To revert to the original path and producing the requirement forces from actuators truly, the quadrotor must be in special attitude. Following equations can be used to obtain Euler angles at any moment.

$$\varphi_d = Arcsin \left(-\frac{A}{F} \sin\beta \right) \quad (24)$$

$$\theta_d = Arcsin \left(\frac{A\cos\beta}{F\cos\varphi} \right) \quad (25)$$

Output signal of the position control assumed to be $\frac{A}{F}$. The quadrotor need to another controller to have a constant height above the moving target. this height is assumed to be 5 meters.

IV. RESULTS AND SIMULATION STUDY

The mathematical dynamical model of the quadrotor vehicle as well as the controllers and algorithms have been developed in Matlab Simulink for simulation. The goal of this analysis is to test how well the controllers can make the quadrotor track the ground moving target. The quadrotor starts from position [0, 0, 5] and target starts from position [4, 0.2, 0]. The quadrotor is commanded to follow the target.

The results of simulations are shown in Figure 7 to Figure 12. From Figure 7 response of the quadrotor for the roll angle control can be seen. Figure 8 shows the response for the pitch angle control and Figure 9 shows response of the quadrotor for the yaw angle control.

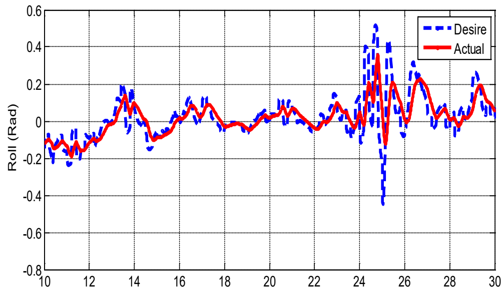

Fig. 7. The roll angle control of the quadrotor (red solid line) and desired angle (blue dashed line)

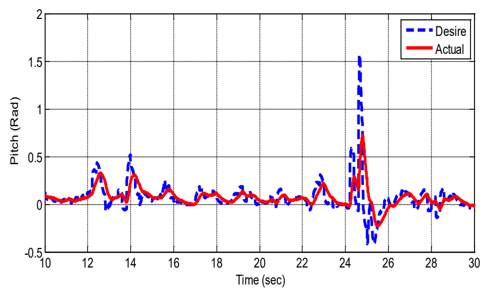

Fig. 8. The Pitch angle control of the quadrotor (red solid line) and desired angle (blue dashed line)

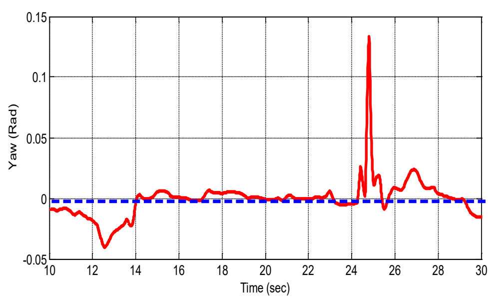

Fig. 9. The yaw angle control of the quadrotor (red solid line) and desired angle (blue dashed line)

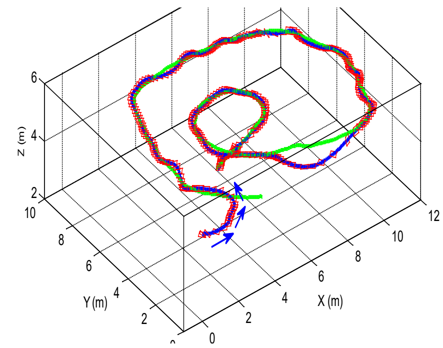

Fig. 10. Target tracking, the position of the moving target (green dashed line) and controlled position of the quadrotor (blue solid line)

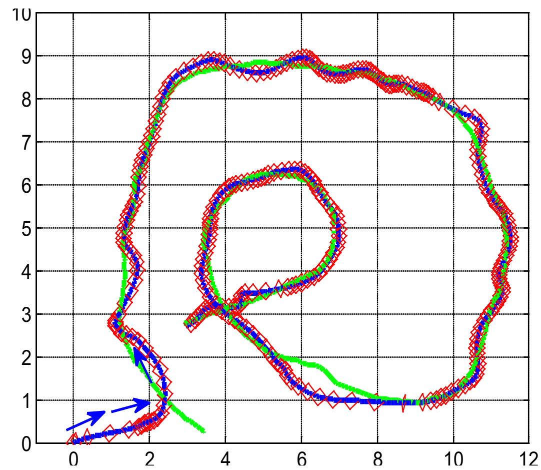

Fig. 11. Target tracking, the position of the moving target (green dashed line) and controlled position of the quadrotor (blue solid line) (only x and y)

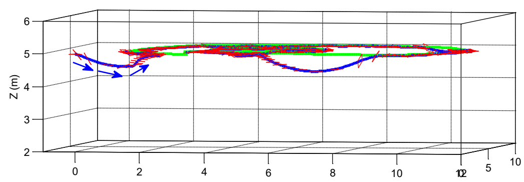

Fig. 12. Target tracking, the position of the moving target (green dashed line) and controlled position of the quadrotor (blue solid line) (only Altitude)

V. CONCLUSION

In the previous section the control and guidance algorithms are presented and the results are shown using different figures. According to the results, quadrotor always is within a cone with a radius of half a meter and a height of 5 meters above the ground moving target that represents a very good performance of algorithms and designed controllers.

The ground moving target detection and path of target detection algorithm that achieved based on image processing work very well and satisfy any desired commands. Also from figures can understand that using the Kalman filter algorithm to estimate the path of moving target have high performance when images have noise and distortion.

PID controllers which used for attitude and position control of the quadrotor worked very well and the quadrotor is so close to the target any moment.

APPENDIX

Some constant's values which used in the simulation of the quadrotor are showed in Table.1. This constant's values selected from a real quadrotor in laboratory of mechatronic in the University of Tehran.

TABLE I
TABLE OF CONSTANTS

Symbol	Description and unit	value
φ	Roll angle (rad)	_
θ	Pitch angle (rad)	_
ψ	Yaw angle (rad)	_
m	Mass of the quadrotor (Kg)	1.25
l	Center of quadrotor to center of propeller distance (m)	0.2
I_x	Body moment of inertia around the x-axis (Nms^2)	0.002353
I_y	Body moment of inertia around the y-axis (Nms^2)	0.002353
I_z	Body moment of inertia around the z-axis (Nms^2)	0.004706
b	Thrust factor	2.92×10^{-6}
d	Drag factor	1.12×10^{-7}
I_R	Rotor inertia (Nms^2)	2×10^{-5}

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