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Control of a Quadrotor Equipped with Robotic Arm Based on Disturbance Estimation

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ABSTRACT: In recent years, unmanned vehicles especially unmanned aerial vehicles have become very popular in many countries in the military, industrial and scientific research fields because of their high speed and maneuverability. This research investigates a compound system consisting of a quadrotor and a series of a robotic manipulators. Joining these two systems aims at combining the agility and flexibility of multi-rotor unmanned aerial vehicles and the dexterity of robotic arms. This combination makes unmanned aerial vehicles able to perform more complicated tasks. In this thesis, the first kinematics and dynamics of a quadrotor are written using quaternion and Newton-Euler equations. Next, a 3-degree of freedom robotic arm that is connected to the bottom of a quadrotor is considered and its kinematics and dynamics are derived using Newton-Euler recursive algorithm. To control the quadrotor, two inner-outer loops are used for its orientation and position respectively. Toque due to arm operation or exerted force to its end effector is estimated using Kalman filter and is fed into quadrotor inner control loop. For trajectory tracking of an arm end effector, an inverse kinematic algorithm is used. The compound system including unmanned aerial vehicles and arm is simulated with different scenarios to verify its performance.

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1- Introduction

The use of drones has increased dramatically in various fields in recent years. Unmanned Aerial Vehicles (UAVs) are divided into different categories based on application, size, operating altitude, speed, and configuration. UAV applications cover a wide range of military and civilian fields. The use of several UAVs in disaster management is discussed in Ref. [1]. One of the most popular types of drones is the quadrotor, which includes a simple set of four motors with propellers.

Due to the fact that the flight dynamics of quadrotors include six degrees of freedom in space, the use of four independent actuators to control the flight of this system leads to under actuation. A common method to control quadrotors is to use hierarchical architecture including inner and outer loops [2].

The use of a robotic arm attached to the drone increases the degrees of freedom of the end-effector. Another advantage is that there is no need for human intervention when picking up and placing objects. A lot of research has been done on the control of arm-equipped drones. However, a few of the proposed controllers include the estimation of forces and torques applied to the quadrotor due to arm operation.

The purpose of this paper is to present an algorithm for controlling a quadrotor with a three-degree-of-freedom series robotic arm mounted at the bottom. The control purpose of the system is desired path following for the quadrotor mass center and the end-effector of the arm. Also, disturbing torques and forces acting on the quadrotor due to the performed tasks are estimated for an improved response.

2- Methodology

2- 1- Kinematics and dynamics of the system

The method used to describe the quadrotor dynamics in this study is Newton-Euler and the quaternion vector was used to describe the quadrotor orientation in space. The arm dynamics equations were also obtained using the Newton-Euler recursive algorithm. The material of the quadrotor structure was assumed to be rigid and the shape of the structure is cross-shaped and symmetrical. The robotic arm consists of three consecutive degrees of rotational freedom and the command of the arm joints is performed by servo motors.

The translational kinematics and dynamics of the quadrotor in the inertial coordinates are written as follows:

$$\dot{p} = V, \sum F = m\dot{V}, \dot{V} = g - \frac{1}{m}C^T F + F_{arm}, F = (0,0,F_T)^T \qquad (1)$$

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Where the vector p represents the three components of the position of the quadrotor in the inertial coordinate, V represents the speed of the quadrotor, m represents the mass of the quadrotor and F is the vector of the thrust force produced by the blades. C is the matrix converting the coordinates from inertia to the body. Rotational dynamics of the quadrotor in the body coordinates are written as follows:

$$J\dot{\omega} = -\omega \times J\omega + T + T_{arm} \quad (2)$$

Where ω is the angular velocity vector, J is the diagonal inertia matrix, T is the torque vector applied to the quadrotor due to the difference in motors speeds, and T_{arm} is the torque applied by the arm.

For the kinematics of the arm, starting from the first link (i = 0 ,1, 2) we can write [3]:

$$\begin{aligned}
&\omega_{i+1}^{i+1} = R_i^{i+1}\omega_i^i + \dot{\theta}_{i+1}\hat{Z}_{i+1}^{i+1}, \dot{\omega}_{i+1}^{i+1} = R_i^{i+1}\dot{\omega}_i^i + R_i^{i+1}\omega_i^i \times \dot{\theta}_{i+1}\hat{Z}_{i+1}^{i+1} + \ddot{\theta}_{i+1}\hat{Z}_{i+1}^{i+1} \\
&\dot{V}_{i+1}^{i+1} = R_i^{i+1}(\dot{\omega}_i^i \times P_{i+1}^i + \omega_i^i \times (\omega_i^i \times P_{i+1}^i) + \dot{V}_i^i) \\
&\dot{V}_{C_{i+1}}^{i+1} = \dot{\omega}_{i+1}^{i+1} \times P_{C_{i+1}}^{i+1} + \omega_{i+1}^{i+1} \times (\omega_{i+1}^{i+1} \times P_{C_{i+1}}^{i+1}) + \dot{V}_{i+1}^{i+1} \\
&F_{i+1}^{i+1} = m_{i+1}\dot{V}_{C_{i+1}}^{i+1}, N_{i+1}^{i+1} = I_{i+1}^{C,i+1}\dot{\omega}_{i+1}^{i+1} + \omega_{i+1}^{i+1} \times I_{i+1}^{C,i+1}\omega_{i+1}^{i+1}
\end{aligned} \quad (3)$$

For arm dynamics, starting from the last arm (i = 2 ,1, 0) we have

$$f_i^i = R_{i+1}^i f_{i+1}^{i+1} + F_i^i, n_i^i = N_i^i + R_{i+1}^i n_{i+1}^{i+1} + P_{C_i}^i \times F_i^i + P_{i+1}^i \times R_{i+1}^i f_{i+1}^{i+1} \quad (4)$$

In these equations, θ_i is the angle of the joint i, ω_{i+1}^{i+1} is the angular velocity of the link i+1, P_{i+1}^i is the position of the origin of the coordinate i+1 relative to the coordinate i, $\dot{V}_i^i$ and $\dot{V}_{C_i}^i$, are respectively the acceleration of origin of the coordinates and the center of mass of the link i, R_{i+1}^i is the matrix converting the coordinates from the i+1 to i, m_i is the mass of each link, F is the inertia force of each link, N is the moment of inertia of each link and f_i^i and n_i^i are force and torque exerted from the previous link to the link i.

2- 2- Inner loop controller

In this section, the control law used to stabilize the rotational motion and track the desired path is presented. The control law is given by Eq. (5) [4]. It can be proved that the closed-loop system including the rotational dynamics of the quadrotor and the proposed control law is Locally Asymptotically Stable (LAS).

$$T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix}, T_i = -\text{sat}_{M_{i2}}(T_{arm_i} + \text{sat}_{M_{i1}}(\lambda[\omega_i + \rho_i q_{e_i}])) \quad (5)$$

$$q_e = q_d^{-1} * q \quad (6)$$

In this equation, $sat_{M_{i2}}$ is a saturation function with saturation limit M_{i2}, T_{arm_i} is the component i of the estimated disturbance torque acting on the quadrotor, ω_i is the component i of the quadrotor angular velocity vector, and λ and ρ_i are the positive control coefficients. q_{ei} is the i^{th} component of the quaternion error vector as calculated in Eq. (6). In this equation, q_d is the desired value of the quaternion vector.

2- 3- Outer loop controller

This controller uses three components of position and yaw angle of the quadrotor and their desired values and produces the desired quaternion vector and the necessary thrust force. The control and estimation laws of this controller are as follows [5]:

$$\begin{aligned}
&\dot{\hat{\omega}} = -\frac{\partial \beta}{\partial e^T}\dot{e} - \frac{\partial \beta}{\partial r^T}(q' + \nu(\hat{\omega} + \beta) + \rho) \\
&q' = -k_p r_p - \nu.(\hat{\omega} + \beta) - \rho
\end{aligned} \quad (7)$$

The vector ω is the estimated variable, that is the disturbance forces acting on the quadrotor and q' is the output force of the controller.

2- 4- Estimation of disturbance torque with Kalman filter

The expression for the estimated torque in the orientation controller is calculated using the discrete Kalman filter to improve the performance of the inner loop controller and reduce overshoot in its response. Kalman filter equations are written according to Ref. [6].

3- Results and Discussion

To evaluate the performance of the proposed algorithms, a set of simulations (missions) has been performed using MATLAB software.

3- 1- Missions

In the first mission, the quadrotor first goes to a specific position in space. At the same time, the arm moves and goes to the desired point in its workspace. Finally, a torque vector is applied to the end-effector and the system must maintain its position. In the second mission, the quadrotor and the arm tried to follow a desired path in the plane in a simultaneous motion. The end-effector desired path in this mission is a chain of consecutive lines and circles. The end-effector must also apply force to the plane. This mission demonstrates the system's ability to follow complex paths that require the cooperation of both members.

3- 2- Results

The following figure shows the position of the end-effector in mission 1 in the inertial coordinates.

As it can be seen, the movement of the arm and the applied torque to the end-effector has a slight effect on the position of the system.

The path following the end-effector in the second mission

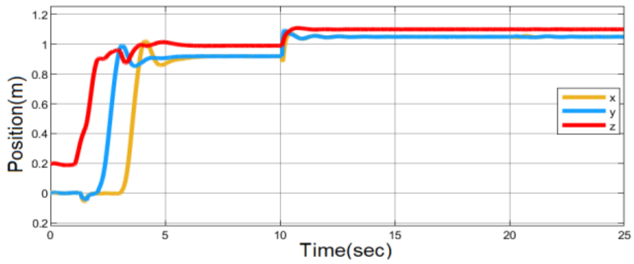

Fig. 1. the position of the end-effector in mission 1 in the inertial coordinates

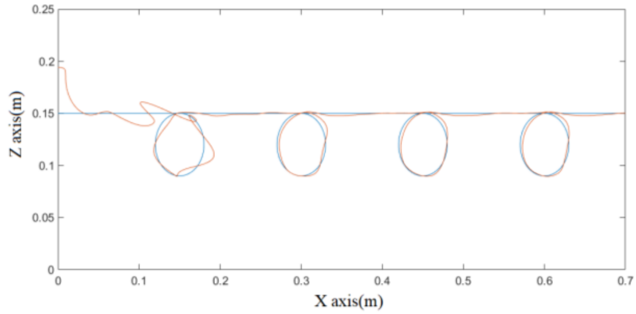

Fig. 2. The path following the end-effector in the second mission

is shown in the figure 2. It can be seen that at the moment of applying the force, the error of position tracking is magnified for short moments. But then the force and torque applied to the quadrotor are estimated and compensated at a reasonable speed.

4- Conclusion

The purpose of this study was to achieve a control law for a system consisting of a quadrotor and a 3-Degrree of Freedom (DOF) arm. The use of torque and force estimation algorithms improved the control performance. Inverse kinematics was used to track the end-effector path.

Examination of the results showed that the performance of the system when encountering disturbance forces and torques was acceptable and tracking was done with reasonable accuracy.

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