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A Position-Based Force Control Approach to a Quad-rotor System

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Abstract : This paper presents the novel contact force control approach of a quad-rotor system to interact with the environment in the constrained space. Although the quad-rotor system is not rigid, a contact force in the altitude can be regulated by the position-based impedance force control scheme that adjusts the reference trajectory with respect to the applied force through an admittance filter. This simplifies the force control application. Simulation studies of force tracking control tasks are performed to evaluate the feasibility of the proposed force control schemes.

Keywords :Quad-rotors, position control, position-based force control.

1. Introduction

Recently, research on quad-rotor unmanned aerial vehicles (QUAVs) is enormously increasing in the control and robotics communities as the related technologies such as sensors, actuators, and digital hardware are developed. Feasible applications of using QUAVs are gradually appearing in the public safety to monitor highway traffic conditions, accidents on the roads, and fire in the urban buildings.

The majority of research on quad-rotor systems is focused on the attitude control [1-9], visual servoing control, and navigation [10,11], namely position controlled tasks. To fully use the advantage of the hovering capability of the quad-rotor system, not only position control but also interaction control with the environment should be available. The feasibility of a contact force control approach by the hovering capability of a single rotor system has been proposed [12].

Recently, interaction control applications between QUAVs and environments have been made and their research interests are gradually increasing. QUAV is flying in the indoor environment while interacting with a human [13]. QUAV is designed and controlled to grip an object and carry it to other location [14]. Building a tower with blocks by quad-rotor systems based on accurate position control has been well demonstrated in the literature.

In the meanwhile, QUAV is designed as a wall climbing robot and designed to have an extra rotor to generate a lateral force against the wall in the horizontal direction to control the contact force against the wall [15]. Applying force to the lateral direction is not easy due to the nature of QUAV flying.

Therefore, applying force to the altitude direction is more feasible. One of feasible tasks of constrained motions of QUAV is to change the light bulb or other objects installed on the high ceiling as shown in Figure 1. For QUAV to change the light bulb, not only hovering control but also contact force control is required. A constant force should be regulated to hold the light bulb and to rotate it in order to take it out. This task requires a force control scheme.

In this paper, therefore, the novel force control application of the quad-rotor system is presented to perform a possible constrained task. A contact force control scheme is added to the attitude control loop to adjust the desired trajectory with respect to the applied force. Force control can be accomplished with ease by adding another loop to the position controlled loop of the trajectory level.

The correction signal is filtered through an admittance filter by realizing the impedance function of the position-based impedance control scheme [16]. Although the quad-rotor system is not rigid, a hovering capability allows the contact force control with the environment to be feasible.

Simulation studies of an attitude control task and a force tracking control task are performed to evaluate the feasibility of the proposed force control scheme. Feasibility studies of force control application of changing a light bulb on the ceiling are conducted. Performances are evaluated by simulation studies.

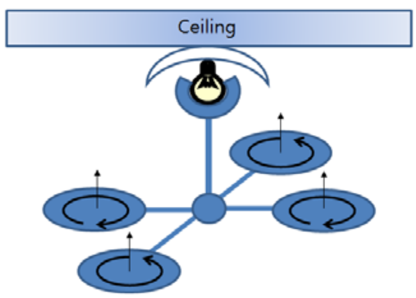


Fig.1 Concept of force control of quad-rotor

2. Attitude Control

Prior to the force control application of quad-rotor systems, the attitude control is accomplished first. Since the quad-rotor system is an under-actuated system, four rotors control six-axis motions. Specially, for the attitude control performance, the altitude and three angles are controlled.

The basic movements such as reaching a certain altitude and hovering and posing the attitude are considered for the attitude control. The hovering motion is related with control of roll, pitch, and yaw angles ($\phi\theta\psi$), and the altitude motion is related with control of the thrust force.

The force input to each rotor is described as

$$F = C_R U \tag{1}$$

where C_R is the rotor matrix. In detail, we have

$$\begin{bmatrix} F_F \\ F_B \\ F_R \\ F_L \end{bmatrix} = \begin{bmatrix} 1/4 & 0 & -\frac{1}{2l} & -\frac{1}{4C} \\ 1/4 & 0 & \frac{1}{2l} & -\frac{1}{4C} \\ 1/4 & -\frac{1}{2l} & 0 & \frac{1}{4C} \\ 1/4 & \frac{1}{2l} & 0 & \frac{1}{4C} \end{bmatrix} \begin{bmatrix} u_T \\ u_\phi \\ u_\theta \\ u_\psi \end{bmatrix} \tag{2}$$

where l is the distance from the COG to the rotor and C is a constant. The linear control input vector U is formed with error, $e = y_d - y$ as

$$U = K_P e + K_I \int e dt + K_D \dot{e} \tag{3}$$

where $U = [u_T, u_\phi, u_\theta, u_\psi]^T$, $y = [z, \phi, \theta, \psi]^T$, K_P, K_I, K_D are the gain matrices.

Figure 2 shows the control block diagram of partial state feedback for the attitude control. The altitude can be controlled by the gravity force compensation. The PID control method is used for the thrust control input based on the altitude measurement.

$$u_T = m(u_z + g)\frac{1}{\cos\theta\cos\phi} \tag{4}$$

where

$$u_z = k_{pz}(z_d - z) + k_{iz}\int(z_d - z)dt + k_{dz}(\dot{z}_d - \dot{z}) \tag{5}$$

where k_{pz}, k_{iz}, k_{dz} are PID controller gains, g is the gravitational acceleration, and z is the altitude from the ground.

Control inputs are given as a PID control structure.

$$\begin{aligned} u_\phi &= k_{p\phi}(\phi_d - \phi) + k_{i\phi}\int(\phi_d - \phi)dt + k_{d\phi}(\dot{\phi}_d - \dot{\phi}) \\ u_\theta &= k_{p\theta}(\theta_d - \theta) + k_{i\theta}\int(\theta_d - \theta)dt + k_{d\theta}(\dot{\theta}_d - \dot{\theta}) \\ u_\psi &= k_{p\psi}(\psi_d - \psi) + k_{i\psi}\int(\psi_d - \psi)dt + k_{d\psi}(\dot{\psi}_d - \dot{\psi}) \end{aligned} \tag{6}$$

where $k_{p\phi}, k_{i\phi}, k_{d\phi}$ are PID controller gains for the roll angle, $k_{p\theta}, k_{i\theta}, k_{d\theta}$ are for the pitch angle controller, and $k_{p\psi}, k_{i\psi}, k_{d\psi}$ are for the yaw angle controller.

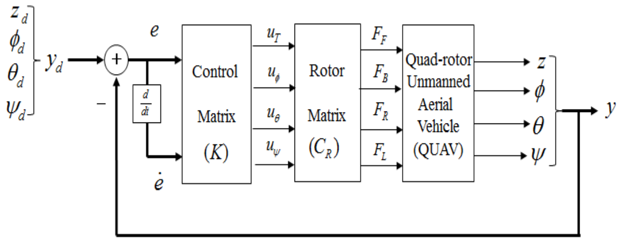


Fig. 2 Attitude control block diagram

3. Position-Based Force Control

In addition to the attitude control loop, another force control loop is added. To apply a force control to the attitude control structure of QUAV, an additional outer loop is simply added to the position-controlled loop. There is no need to modify internal position control structure as required to regulate the desired force as well as position.

We add another control loop outside to modify the position control loop by the external force as shown in Figure 3. Admittance filters can be designed based on different formulations of the impedance function.

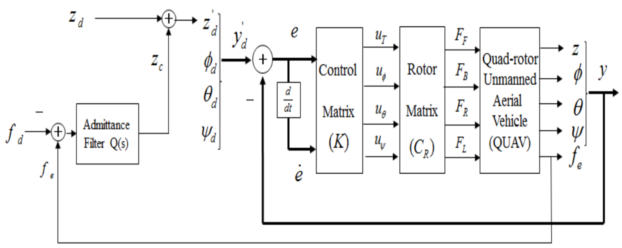


Fig. 3 Position-based force control block diagram

The original impedance function is described as the relationship between the applied force and the positional displacement [17].

$$f_e = a\ddot{e}_z + b\dot{e}_z + ke_z \tag{7}$$

where f_e is the external force measured by a force sensor, $e_z = z_r - z$, and a, b, k are impedance filter gains. Adjusting filter gains and specifying the reference trajectory, z_r can achieve the desired force tracking control. The reference trajectory to achieve $f_e = f_d$ is given as

$$z_r = z_e + \frac{f_d}{k_{eff}}, \qquad (8)$$

where f_d is a desired force, $k_{eff} = \frac{kk_e}{k+k_e}$, z_e is the environment position, and k_e is the environment stiffness. Eventually, to obtain the desired force tracking performance, z_e and k_e are exactly known *a priori*, which is quite difficult in practice.

From the original impedance function relationship (7), we can have the admittance filter $Q_0(s)$ as

$$Q_0(s) = \frac{E_z(s)}{F_e(s)} = \frac{1}{as^2 + bs + k} \qquad (9)$$

The position $E_z(s)$ can be modified by the external force measurement, $F_e(s)$.

One weak point of the filter in (9) is the lack of regulating a desired force, f_d , directly so that contact force is regulated by adjusting impedance parameters, which is quite difficult. In order to have the force tracking capability, the filter can take the force error, $e_f = f_e - f_d$ as an input. The original impedance function can be modified as the relationship between the force tracking error and the positional displacement, ε_z .

$$f_e - f_d = a\ddot{\varepsilon}_z + b\dot{\varepsilon}_z + k\varepsilon_z \qquad (10)$$

where $\varepsilon_z = z_e - z$ and f_d is the desired force.

The external force can be approximated as

$$f_e = k_e(z - z_e) = -k_e\varepsilon_z \qquad (11)$$

The external force error passes through the filter $Q_i(s)$ to generate the modification signal z_c as shown in Figure 4. A new modified trajectory is obtained as

$$z_d^{'} = z_d + z_c \qquad (12)$$

Although the filter structure is same as (9), the input to the filter is now the force error, not the force.

$$Q_1(s) = \frac{\varepsilon_z(s)}{E_f(s)} = \frac{1}{as^2 + bs + k} \qquad (13)$$

where $E_f(s) = F_e(s) - F_d(s)$.

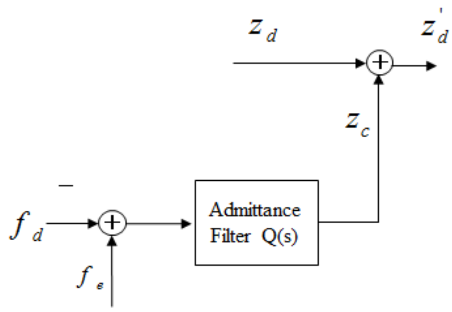


Fig. 4 Position adjustment by force

4. Simulation Studies

1. Attitude control

Firstly, the altitude control of the QUAV is tested. Table 1 lists the control parameters of the quad-rotor system used for simulation studies. The mass of the quad-rotor system is 1 *Kg* and the length is 0.25 *m*.

Desired angles are set to zero and the desired altitude is controlled where the ceiling is assumed to be located at 5*m* above the ground. The QUAV is required to move upward to the first desired altitude at 4.98*m*, and then move up to the second desired altitude of 5*m* at 10 seconds. The reason of performing two-stage movements is to reduce the initial contact force occurred when QUAV contacts with the environment.

Table 1. Controller gains for the altitude control

	Roll, ϕ	Pitch, θ	Yaw, ψ	Altitude, z
k_p	10	10	20	20
k_d	4	4	4	8

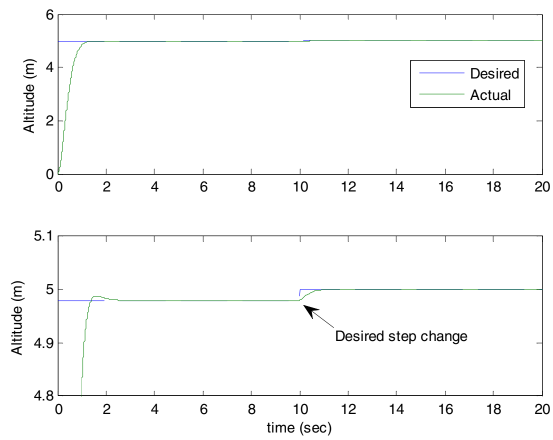


Fig. 5 Altitude control result

2. Force control

Here we are simulating the situation where QUAV performs the task to change a light bulb mounted on the ceiling located at 5*m* above the ground. Initially QUAV flies from the ground to reach the altitude of 4.98*m*, and then flies up to 5*m* to make contact for regulating the desired force of 5*N*. Then QUAV rotates in the yaw angle direction in order to take the light bulb out.

Impedance filter gains, *m=1, b=400, k=1* are used and controller gains are listed in Table 2. The admittance filter is highly damped to suppress the force overshoot.

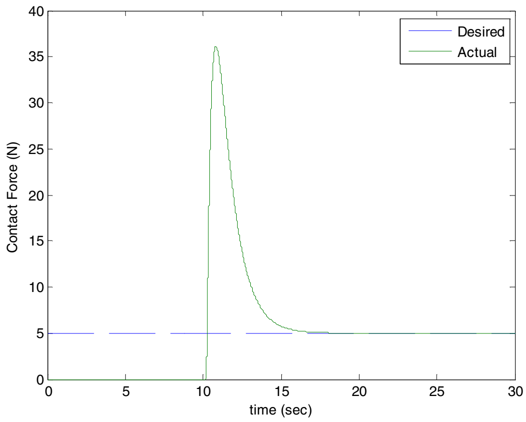
$$Q_1(s) = \frac{1}{s^2 + 400s + 1}$$

The environment is considered as soft material so that its stiffness is k_e =1,000 N/m.

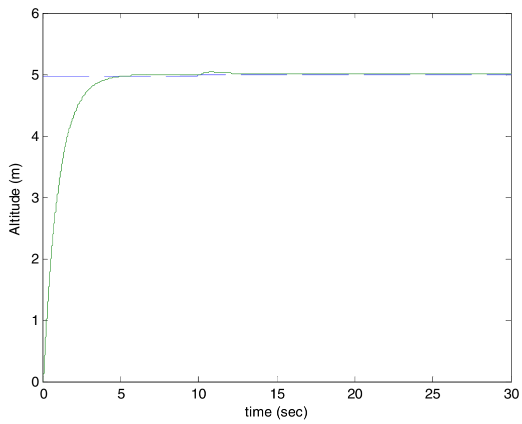
Table 2. Controller gains for the force control

	Roll, ϕ	Pitch, θ	Yaw, ψ	Altitude, z
k_p	10	10	20	30
k_i	0	0	0	0.1
k_d	4	4	4	30

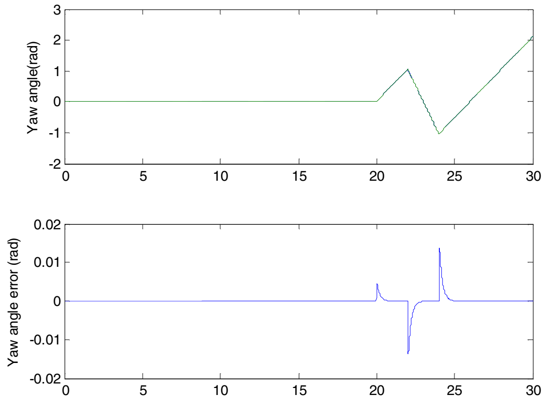
Figure 6 (a) shows the force tracking result. The QUAV makes contact at just after 10 seconds, and 37*N* force overshoot occurs at the initial contact and the force is settled down to the desired force of 5 *N* at 18 seconds. Figure 6 (b) shows the corresponding altitude tracking result. Rotation of yaw angle mimics the rotation of the end-effector of QUAV. The yaw angle tracking result is shown in Figure 6 (c) while force is regulated in the altitude direction.



(a) Contact force tracking



(b) Altitude tracking result



(c) Yaw angle tracking result

Fig. 6 Contact force control result

5. Conclusion

This paper presents the novel force control application to a quad-rotor system for a possible constrained task of changing the light bulb on the ceiling. Impedance function is realized by the position-based impedance force control method by closing the attitude control loop with a force control loop. The admittance filter is used to reduce the force tracking error. Although the quad-rotor system is not rigid and it is designed for position controlled tasks, the feasibility of conducting force control tasks has been tested by simulation studies.

However, we have observed that initial contact force is somewhat large. To reduce the force overshoot, different admittance filters may be designed and adopted in the future.

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