2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Bilateral Teleoperation Control of a Quadrotor System with a Haptic Device : Experimental Studies

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***Abstract*—In this paper, experimental studies of bilateral teleoperation control of a quadrotor system are presented. Not only position control but force control of a quadrotor system is regulated by forming a force controlled loop. The contact force is measured by a load cell mounted on the top of the quadrotor system. The sensed force is used for a haptic device as an operator feels the force. This configuration forms the bilateral teleoperation control system. Contact force of a quadrotor system in the altitude direction is regulated by the command from the master. The quadrotor system is controlled by a master to fly up from the ground to the ceiling, and to maintain desired contact force against the ceiling, and finally to land back on the ground. This experimental work mimics the possible ceiling task performed by a quadrotor system to see the feasibility of applying the force control technique to the quadrotor system. Experimental studies confirm the feasible force control performance.**

I. INTRODUCTION

RESEARCH on quadrotor systems becomes quite active in control and robot communities so as to develop them as an unmanned aerial vehicle(UAV) for various purposes. Like other UAVs, quadrotor systems are mainly used to perform surveillance tasks by monitoring related areas. Quadrotor systems have several advantages of omni-directional movements, better maneuverability, simple structures, and better hovering performance over conventional UAVs [1-3].

Challenging flying demonstration of quadrotor systems are conducted in indoor environment since keen position control performance can be achieved due to the accurate measurements of position of quadrotor systems. Without disturbance like wind, quadrotor systems can be accurately controlled in indoor environment relying upon expensive and accurate motion capture systems.

Recently, quadrotor systems are practically used to monitor outdoor environment and their activities lead to the social issue of invading privacy.

Although we have the social issue of the invasion of privacy, research on quadrotor systems is enormously increasing. A majority of research on quadrotor systems is to improve the performance of attitude control with various control algorithms [4-11]. Vision-based tracking control of quadrotor systems is presented [12-14]. Aggressive driving control performance of several quadrotor systems has been demonstrated by University of Pennsylvania, USA. Fast maneuvering control of quadrotors systems is well demonstrated. Inverted pendulum on the quadrotor is controlled to maintain balance. Furthermore, the challenging demonstration of the pole passing task between two quadrotors is demonstrated by ETH. Initially, a pole is located on the top of quadrotor system maintaining balance. Then the quadrotor passes the pole to another quadrotor so that the receiver receives the pole and maintains balance nicely.

Different mechanism of a quadrotor system have been designed for both flying and driving [15,16]. The flymobile is designed for both driving and flying performances by using the tilting mechanism of each rotor [16]. Tilt up position of each rotor for flying and tilt down position for driving are utilized for different modes. An acceleration-based disturbance observer is designed for the robust attitude control [17,18].

The aforementioned research results regarding quadrotor systems are dependent upon the accurate measurement of position that leads to the good hovering performance which is one of the advantages of quadrotor systems. Well-maintained hovering performance of the quadrotor system allows the system to monitor objects for outdoor surveillance tasks. Furthermore, hovering performance can be extended for the feasible application of constrained tasks with environments. Research on constrained motion control of quadrotor systems is rare in the literature, but challenging [19-21]. Lateral force control of a quadrotor system is presented [19]. Lateral force is generated by an extra rotor to make contact with wall for possible tasks on the wall.

In this paper, a scenario of changing light bulb on the ceiling is simulated. The contact force control application of a quadrotor system with the desk that mimics the task on the ceiling is presented along with position control. Fig.1 shows the concept of force control application of a quadrotor system. Force in the altitude direction is regulated. The quadrotor system is controlled remotely by the haptic device, which forms the bilateral teleoperation system.

Manuscript received March 15, 2013. This work was supported in part by the 2012 Korea Research Fund and the center for autonomous intelligent manipulation (AIM) for service robots of the MKE (The Ministry of Knowledge Economy), Korea, under the Human Resources Development Program for Convergence Robot Specialists support program supervised by the NIPA (National IT Industry Promotion Agency) under NIPA-2012-H1502-12-1002.

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In addition, a haptic device as a master and a quadrotor system as a slave robot form a bilateral teleoperation control system. The master controls the quadrotor system to fly up from the ground, and to make contact with the ceiling(desk). The quadrotor system is required to maintain contact against the ceiling with desired force commanded by the operator and to land on the ground.

To our knowledge, contact force control of a quadrotor system in the configuration of bilateral teleoperation is the first appearance in the literature. Experimental studies confirm the proposed force control performance.

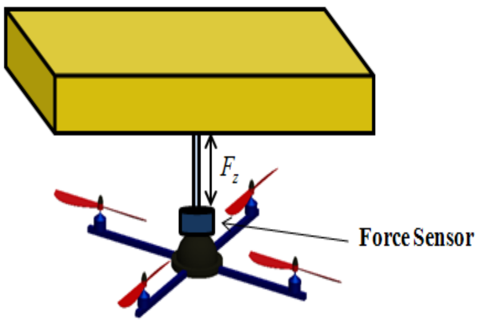


Fig.1 Concept of contact force control

II. Quadrotor System

A. Quad-rotor Dynamics

The coordinate of a quadrotor system is given in Fig. 2. The quadrotor system in the coordinate of ($O_V X_V Y_V Z_V$) is located in the world coordinate of ($O_W X_W Y_W Z_W$). The quadrotor has three rotational angles of roll(ϕ), pitch(θ) and yaw(ψ). Each rotor generates the thrust forces, front, left, back, and right, F_F, F_L, F_B, F_R, respectively. Two pairs of rotors rotate in the same direction.

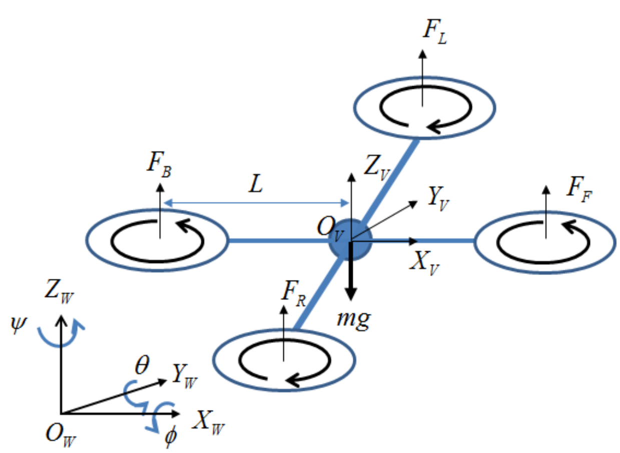


Fig. 2 Coordinate of Quad-rotor system

Simplified dynamic equations ignoring Coriolis force and other dynamic terms of a quadrotor system can be described as

$$
\begin{aligned}
m\ddot{x} &= f_{th}(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \\
m\ddot{y} &= f_{th}(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \\
m\ddot{z} &= f_{th}\cos\theta\cos\phi - mg \\
I_{xx}\ddot{\phi} &= \tau_\phi \\
I_{yy}\ddot{\theta} &= \tau_\theta \\
I_{zz}\ddot{\psi} &= \tau_\psi
\end{aligned}
\tag{1}
$$

where m is the mass of the system, f_{th} is the total thrust force, g is the gravitational acceleration, I_{xx}, I_{yy}, I_{zz} are moments of inertia, and $\tau_\phi, \tau_\theta, \tau_\psi$ are torques about x, y z axis, respectively.

Further simplified dynamic equations for the attitude control of a quadrotor system can be described as

$$
\begin{aligned}
m\ddot{z} &= f_{th}\cos\theta\cos\phi - mg \\
I_{xx}\ddot{\phi} &= \tau_\phi \\
I_{yy}\ddot{\theta} &= \tau_\theta \\
I_{zz}\ddot{\psi} &= \tau_\psi
\end{aligned}
\tag{2}
$$

Torques and the thrust force of each rotor have the following rotor relationship.

$$
\begin{aligned}
f_{th} &= F_F + F_B + F_R + F_L \\
\tau_\phi &= L(F_L - F_R) \\
\tau_\theta &= L(F_B - F_F) \\
\tau_\psi &= C(F_R + F_L - F_F - F_B)
\end{aligned}
\tag{3}
$$

where L is the distance from the center of the mass to the ce nter of each rotor and C is a constant factor.

III. Attitude Control Schemes

Prior to applying force control to the quadrotor system, the hovering control performance should be guaranteed. For the hovering control performance, Euler angles and altitude are controlled. Here a linear control method is used for attitude control. Each control input to the angle is defined as

$$
\begin{aligned}
u_\phi &= k_{p\phi}(\phi_d - \phi) + k_{d\phi}(\dot{\phi}_d - \dot{\phi}) \\
u_\theta &= k_{p\theta}(\theta_d - \theta) + k_{d\theta}(\dot{\theta}_d - \dot{\theta}) \\
u_\psi &= k_{p\psi}\psi_{rc} + k_{d\psi}(\dot{\psi}_d - \dot{\psi})
\end{aligned}
\tag{4}
$$

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

The PID control method is used for the thrust control input based on the altitude measurement.

$$
u_{th} = m(u_z + g)\frac{1}{\cos\theta\cos\phi} \tag{5}
$$

$$u_z = k_{pz}(z_d - z) + k_{iz}\int (z_d - z)dt + k_{dz}(\dot{z}_d - \dot{z}) \quad (6)$$

where k_{pz}, k_{dz}, k_{iz} are PID controller gains.

Fig. 3 show the control block diagram of the attitude control

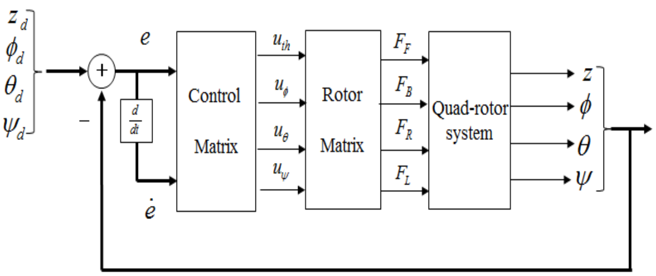


Fig. 3Control block diagram

IV. Bilateral Teleoperation Control

In the configuration of bilateral teleoperation control, there are several procedures to close the control loop. Firstly, the master haptic device commands the quadrotor system to fly up. Secondly, the quadrotor system makes contact with the environment and sensed contact force. Thirdly, the sensed force is transferred to the haptic device so that the operator feels the contact force.

The haptic device as the master and a quadrotor system as the slave form a bilateral teleoperation structure shown in Fig. 4. The key performance of the teleoperation task is the transparency such that the operator feels the same contact force as the slave feels.

The closed loop transfer function of the slave is given by

$$T_s(s) = \frac{G_s(s)C_s(s)}{1 + G_s(s)C_s(s) + G_s(s)Z_e(s)} \quad (7)$$

where $Z_e(s)$ is the impedance function.

Define the closed loop transfer function of the slave as $T_s(s)$. Then the overall transfer function can be described as

$$\frac{X(s)}{F_h(s)} = \frac{G_m(s)C_m(s)T_s(s)e^{-ST_f}}{1 + G_m(s)C_m(s)T_s(s)e^{-S(T_f+T_b)}} \quad (8)$$

where T_f, T_b are time delays in forward and backward direction, respectively.

In our system, the z direction of the altitude direction is force controlled. The contact force of the quadrotor system is sensed by a load cell and fed back to the haptic device as a spring constant so that the applied force has linear relationship with the spring constant considered as $Z_e(s)$.

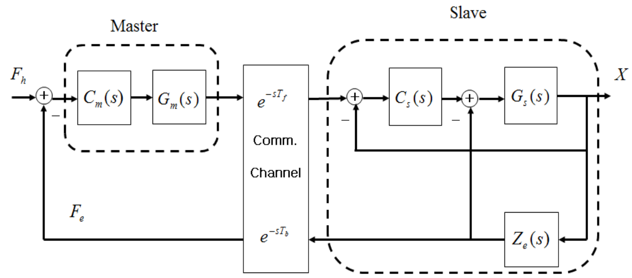


Fig.4 Bilateral teleoperation

A bilateral teleoperation task is configured by forming a master robot, haptic device and a slave robot, quadrotor system. Fig.5 explains the structure of the bilateral teleoperation system. As an operator controls the Phantom omni haptic device, the quadrotor system moves after that. Force induced by the quadrotor system in the altitude direction is regulated.

For the sensing of contact force in the altitude direction, a load cell is designed and mounted on the top of the quadrotor system. The sensed force is transferred to the computer in the ground and used it for the haptic device as a force feedback. Force feedback to the haptic device can be calculated with a spring constant and a height.

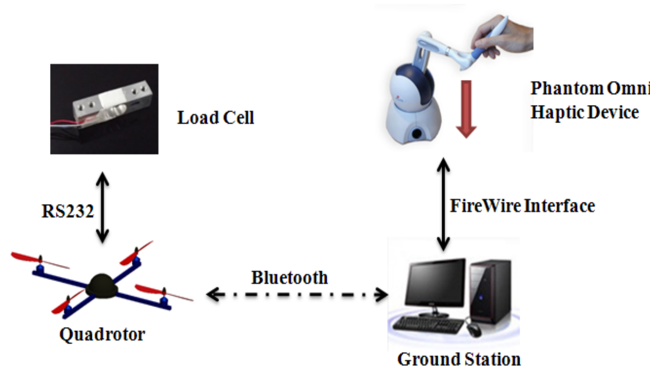


Fig.5 Overall system structure

V. Experiment

A. Experimental Setup

The experimental setup of bilateral teleoperation is described in Fig. 6 and 7. The master, a haptic device and the slave, a quadrotor system are described in Fig. 6 and 7, respectively. The master robot is a commercial haptic device and is connected to the computer which is remotely located. Then the command signals are passed through the wireless communication between the computer and the quadrotor system. The commanded signals include Euler angles, altitude, and force data.

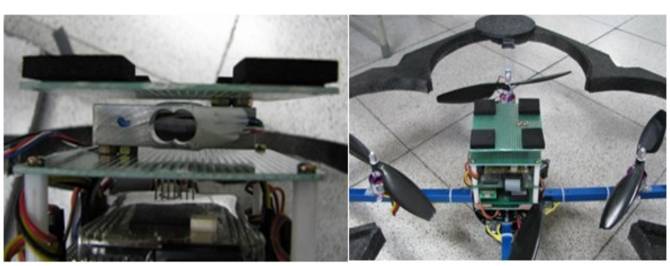
The Euler angles are controlled by the haptic device. The end position of the haptic device indicates the height of the quadrotor system so that positioning the end position of the device controls actually the height of the quadrotor system.

The quadrotor system is required to push against the desk by maintaining a desired force commanded from the haptic device. Several different force levels are applied and tested. The ceiling is located $1m$ away from the ground. The haptic device controls the height of the quadrotor system.

Fig.6 Master haptic device

Fig. 7 Slave robot under the ceiling

The slave robot, the quadrotor system, is equipped with a force sensor made of a strain gauge which measures force in one direction. Fig. 8(a) shows the load cell attached to the top of the quadrotor system. To reduce the contact overshoot, soft materials are placed on the top of the system as shown in Fig. 8(b). This part can be replaced with a manipulator for possible applications.



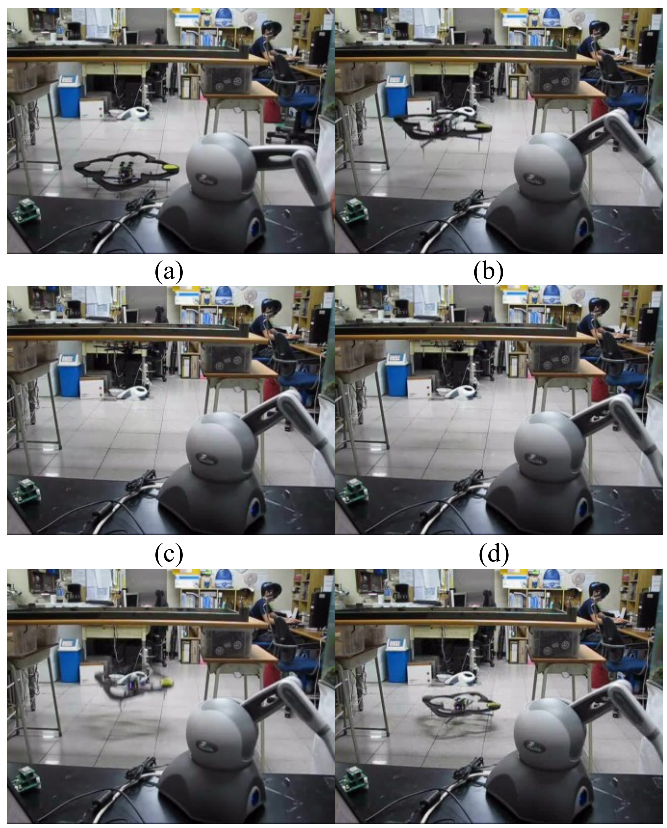
(a) Load cell (b) Top of a slave robot

Fig.8 Slave robot

B. *Experimental Results*

Experimental demonstration is displayed in Fig. 9. Several image cuts are shown to demonstrate the experimental process. Initially the quadrorotor system is located on the ground (Fig. 9 (a)). As the operator moves the haptic device up, the quadrotor flies up (Fig. 9 (b)) and makes contact with the desk (Fig. 9 (c)). The quadrotor system maintains a certain force for a while (Fig. (d)). Finally, the quadrotor lands back on the ground (Fig. 9 (e,f)).

A constant force is applied to the haptic device so that the quadrotor system also maintains contact with the desk with the applied force. Firstly, the operator applies 30gf(0.3N) to the haptic device. The corresponding force plots are shown in Fig. 10 (a). Contact has been made around 13 seconds and force overshoot is about 35 gf. The corresponding height is also plotted in the same figure. The height is measured by a distance sensor. The plot indicates that the height is 100cm.

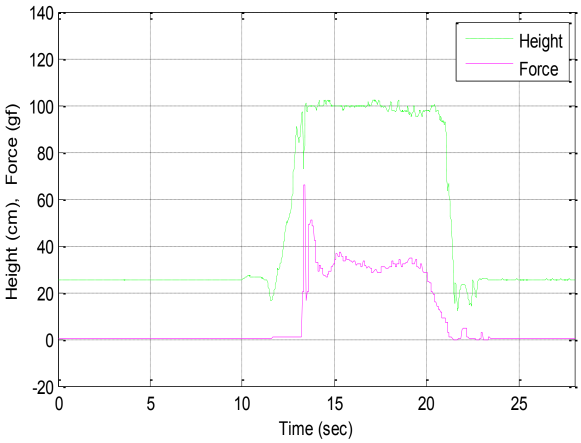


(a) (b) (c) (d) (e) (f)

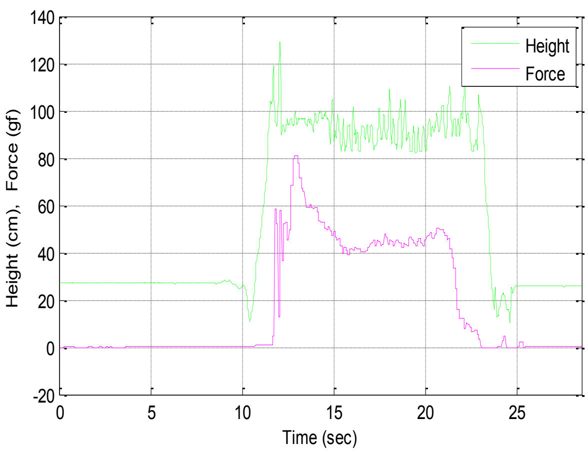
Fig. 9 Haptic demonstration (a-b-c-d-e-f)

Secondly, the operator pushes more to have 40 gf(0.4N). At around 12seconds in Fig. 10(b), the quadrotor made contact with the desk, which shows about 50% force overshoot of 80gf. Then the quadrotor settles down to 40 gf at around 15 seconds. It maintains at 40gf for the time being, then it flies down on the ground as the operator releases it. The height data seem noisy because the vibration of the quadrotr system was passed to the sensor.

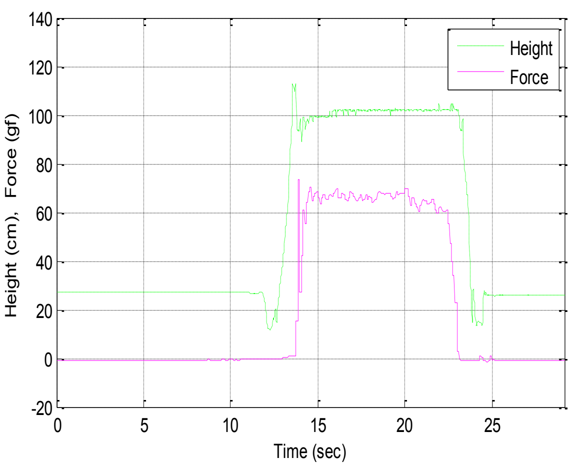
Lastly, we increase the contact force to 70gf(0.69N). For the case of 70gf force, Fig. 10 (c) shows the resulting contact force of 70 gf. We observed the smaller force overshoot less than 5%. A contact force error is smaller than that of 40gf(0.4N). This is because the larger force is easy to maintain due to the low resolution of the sensor.



(a) 30 gf



(b) 40 gf



(c) 70 gf

Fig. 10 Reflecting force and height

The corresponding altitude data are also plotted in Fig. 10. The altitude data of 70gf force is also better with less oscillation.

As a result, all three cases of different desired forces are well regulated although the quadrotor introduces vibration. Although there are vibrations, the quadrotor system does not lose contact with the wall. Experimental studies confirm the possible application of quad-rotor systems in the constrained tasks.

However, there are many problems to be solved. Firstly, the time-delay problem of the network which is a major problem in the teleoperation control should be addressed. Secondly, the resolution of the force sensor should be improved. Thirdly, force control algorithm is required to be upgraded.

VI. Conclusion

This paper presents the teleoperation control application during the feasible scenario of changing a light bulb on the ceiling. Experimental studies confirm the feasibility of applying a force control technique to the quadrotor system in the configuration of bilateral teleoperation. Although the environment is simplified as a desk to check the contact force regulation in the bilateral teleoperation configuration, experimental studies have shown that the quadrotor is well regulated with applied forces from the master device. This is the positive sign for further research on the contact force control application.

In the other hand, there are several problems to be solved in the future. The time delay issue in the communication channel is a well-known problem and has to be solved in the future. Since the resolution of the load cell is low, it is required to have the better sensor to achieve more accurate force control tasks. The quadrotor has to be redesigned and rebuilt to generate higher force and payload for real applications to satisfy desired specifications.

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