Quad Rotor Helicopter Control With Humanoid Robot

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***Abstract*—**In present study, we propose a new control method using an external input to P attitude control system of Quad Rotor Helicopter (QRH). We set a humanoid robot on the center of experimental QRH. When the humanoid robot takes a step forward, this motion causes the shift of center of gravity (COG), and it causes the attitude change of QRH. Then attitude control system generates counter torque to cancel the tilt angle. As a result, small inclination exists. This small inclination generates moving thrust, and QRH starts to slide. The results clearly suggest that we can control QRH with external independent devices attached on it.

***Keywords*—**Quad-rotor helicopter, P control, attitude control, center of gravity, external control.

I. INTRODUCTION

IN recent years, small and unmanned aircrafts and helicopters are widely used in the fields of aerial photography and aerial investigation. However, UAV (unmanned aerial vehicle) such as radio controlled (R/C) helicopter takes the place of the manned aircraft in proportion to rapid improvement of radio control technology. The operation cost of the R/C helicopter is lower than that of a manned helicopter. In addition, required heliport size for R/C helicopter is much smaller than that required by a manned helicopter. Thus, the R/C single helicopter has reasons why those are more excellent than an actual one, there are many reports of automatic control system for R/C single helicopter ([1],[2],[3]), and some additional auto pilot units are available in the market.

Studies on another type autonomous UAV, multi rotor helicopter (quad [4], hexa, octa, etc.) are reported. Main features of multi-rotor helicopter are "small" and "noise-less" as against single-rotor helicopter. Moreover, multi rotor helicopter has a simple control mechanisms and small-sized rotors that it is easier to handle. Therefore, multi rotor helicopter such as quad rotor helicopter is widely used for many researches, for example, real-time vision-based localization was performed on a quad rotor helicopter [5]. Motion capture system becomes common position/velocity sensor for UAV flight control system. Brescianini et.al reported the pole motion control by two quad copters. They succeeded to design a system that allows quad copters to balance an inverted pendulum, throw it into the air, and catch and balance it again on a second vehicle [6]. In other study, an onboard laser range finder was used for indoor position control of quad rotor helicopter [7]. Additionally, we developed new type of multi copter using ducted-fans instead of rotor blades. First one is inverted pendulum shape bi-copter using thrust vectoring [8], and second one is quad ducted-fan [9]. The purpose of these ducted-fan multi copters is to reduce the risk of collision.

In this study, we present a new operation method for multi copter such as QRH (**Figure 1**) by external input. The basis of proposed method is COG (center of gravity) shifting by external independent device mounted on test QRH. Usually, COG shift on UAV is treated as error or disturbance. The control system such as attitude controller or navigation system will perform fix operation. However, proposed method treats COG shift as operation input.

Advantage of proposed method is that a mounted independent agent machine (such as arm robot, car robot, humanoid robot, moreover human) can control test QRH without specialized mechanism or control system connected with flight controller. We set a humanoid robot (test humanoid robot) as external mechanism on test QRH main frame which is independent from the control system of test QRH. When test humanoid robot makes tilting posture, the COG is shifted, and it will cause attitude inclination and horizontal component of rotor thrust to slide the test QRH. It is similar to the wheeled inverted pendulum control system, such as Segway. From the viewpoint of transporter control method, the difference between proposed system and Segway is that proposed system is used for flying maneuver while Segway system is used on the ground.

II. ATTITUDE CONTROL OF QUAD ROTOR HELICOPTER WITH COG SHIFT

Thrusts of QRH are generated proportional to rotor revolution speed. QRH moves upward or down when all rotor revolutions equally change (**Figure 1 (a)**: T1 = T2 = T3 = T4). The QRH rotates around Yaw axis when opposing corner rotor revolutions equally change (**Figure 1 (b)**: T1 = T3 > T2 = T4). Also QRH rotates around Roll or Pitch axis when differential rotor thrust exists between pairs of adjacent rotor (**Figure 1 (c)**: T1 = T2 < T3 = T4). These thrust control is performed by attitude control system with desired attitude angle and height of QRH.

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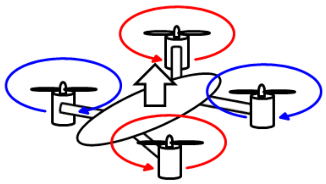
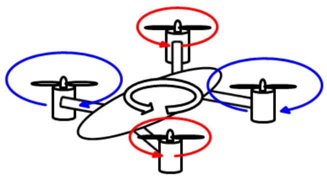
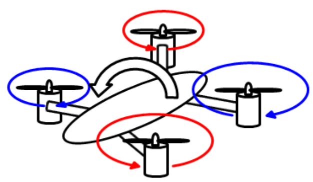
In our previous study [10], we tried to control QRH attitude by COG shift generated with an arm robot on test airframe, and the arm robot was independent from QRH control system. PI control was employed for attitude control. As shown in **Figure 2**, the arm robot tilts, causing a COG shift that generates attitude inclination and horizontal component of rotor thrust to slide the test airframe.



(a) Height control (T1 = T2 = T3 = T4)

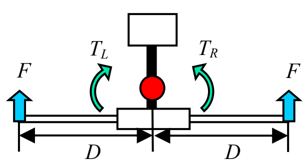


(b) Yaw control (T1 = T3 > T2 = T4)

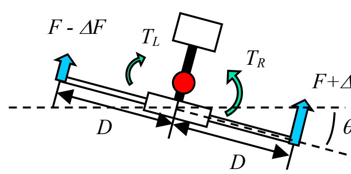


(c) Tilting control (Roll) (T1 = T2 < T3 = T4)

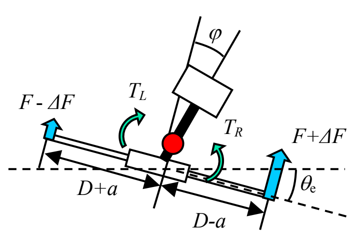
Figure 1 Attitude control of Quad Rotor Helicopter (QRH)



(a) Balanced condition



(b) Thrust change



(c) COG shift and thrust change

Figure 2 COG shift and thrust change [10]

Figure 2 shows the shift of COG. In **Figure 2(a)**, left thrust torque T_L (= $-FD$) and right thrust torque T_R (=FD) are balanced ($T_L+T_R = 0$), where F is the thrust and D is the distance between motor and COG.

P control is designed to moderate the thrust as F-ΔF for left motor and $F+\Delta F$ for right motor to generate counter torque $2\Delta FD = K_p\theta$, where K_p is the proportional gain of P control. When test airframe was tilted as θ (**Figure 2(b)**), T_L becomes –(F-ΔF) D and T_R becomes ($F+\Delta F$) D. Total torque T_{total} (=T_L+T_R) becomes 2ΔFD.

Figure 3 Scene of an experimental flight [10]

When COG shifts as distance a and the airframe tilts as θ (**Figure 2(c)**), T_L becomes -$F(D+a)$ and TR becomes $F(D$-$a)$. So the torque balance breaks down, total torque T_{total} (=T_L+T_R) becomes -2Fa. In this case, $T_{total} = 2\Delta FD - 2Fa = K_p\theta - 2Fa$. From this equation, T_{total} becomes 0 when $\theta = \theta_e = 2Fa/ K_p$. It means that θ_e remains as steady state error of P control. Also θ_e is the function of COG shift distance a. It is well known that I control will cancel steady state error. So, we set I gain to 0 (i.e. PI control becomes P control) to keep the θ_e as the output attitude of COG shifting. Thus, attitude of test airframe is controlled by COG shift. **Figure 3** shows the scene of an experimental flight.

III. EXPERIMENTAL SETUP

Commercial Quad Rotor Helicopter (Enroute: Zion Pro 520) is used as a test QRH. ArduPilotMega2.5 (APM:

3DRobotics) with Arducopter 2.9.1 (DIY Drones: freeware [11]) is used as flight controller for the test QRH. APM includes IMU (consists of 3-axis gyro sensor, 3-axis acceleration sensor and 3-axis magnetic sensor) and barometric altimeter. APM is linked with PC via XBee (Digi international: XBee Pro ZB). Radio controller set (Futaba: FF-9) is used for experiments operation.

A small-sized humanoid robot (Himeji Softworks: JO-Zero, mass is 960 g) is set on test QRH. The robot is controlled by IR remote controller consists from the 2nd APM and IR LED circuit. Channel 8 and 9 signal of FF-9 is connected to the 2nd APM to send IR commands for the humanoid robot. These commands activate the pre-programmed posture motions. **Figure 4** shows the test QRH with the small humanoid robot. **TABLE I** shows the specifications of experimental setup.

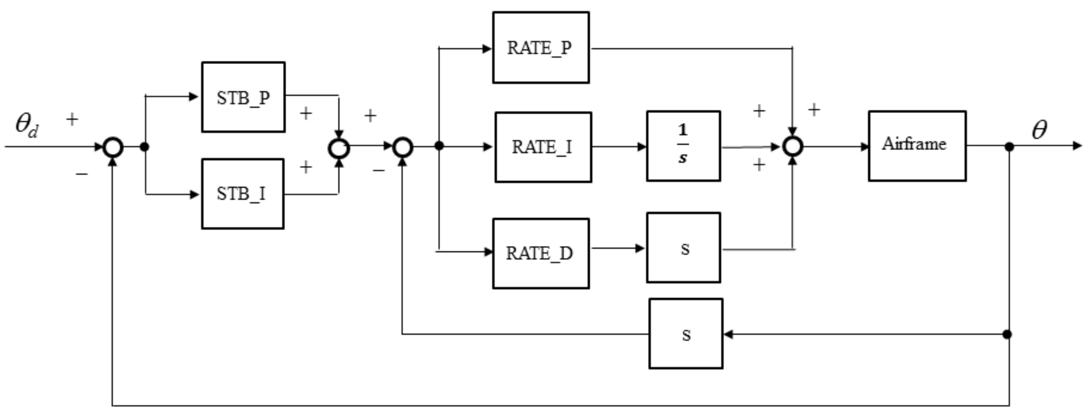
Attitude controller of roll/pitch axis consists of PI controller for attitude and PID controller for angular velocity.

Direction controller of yaw axis consists of P gain for angular velocity, PI controller for attitude and PID controller for angular velocity. Altitude controller consists of PI controller for altitude, PID controller for climb rate and PID controller for climb acceleration. **Figure 5** and **Figure 6** show block diagrams of attitude controller, direction controller and altitude controller, respectively. **TABLE II**, **TABLE III**, and **TABLE IV** show control parameters. These parameters and trims were adjusted according to indoor flight test results. In this study, I gain of attitude controller was set as 0, so attitude was hold by P control.

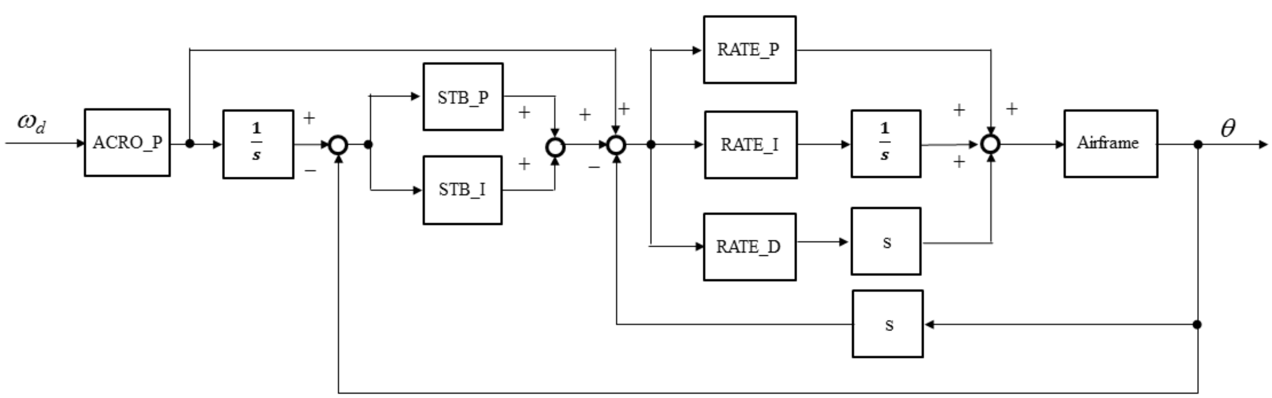
Figure 4 Test QRH with humanoid robot (standing posture)

TABLE I Specification of test helicopter

Rotor axis distance	520 mm
Rotor diameter	330 mm (13 inch)
Height	310 mm
Width	407 mm
Mass	1.89 kg

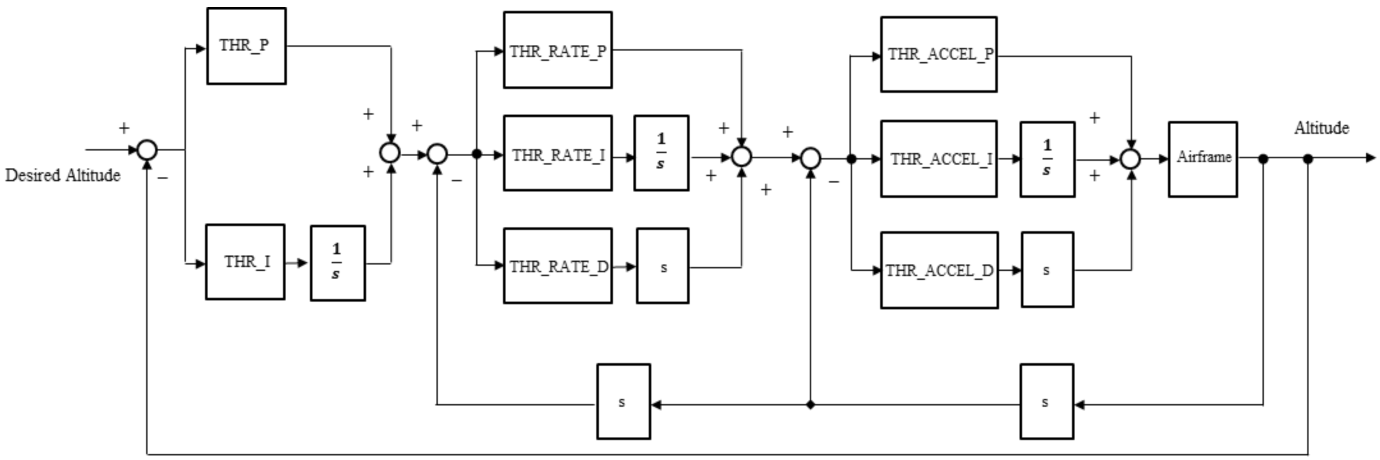


(a) Attitude control system for roll and pitch axis
Attitude PI control gains are STB_P and STB_I, angular velocity PID control gains are RATE_P,RATE_I and RATE_D, respectively.
θ_d: desired angle, θ: attitude angle



(b) Direction control system for yaw axis
Attitude PI control gains are STB_P and STB_I, angular velocity PID control gains are RATE_P, RATE_I and RATE_D, respectively.
ACRO_P is the conversion gain of angular velocity to direction gain. ω_d: desired angular velocity, θ: direction

Figure 5 Attitude control system



Altitude PI control gains are THR_P and THR_I, climb rate PID control gains are THR_RATE_P, THR_RATE_I and THR_RATE_D. Climb acceleration PID control gains are THR_ACCEL_P, THR_ACCEL_I and THR_ACCEL_D, respectively.

Figure 6 Block diagrams of altitude control system

TABLE II PID parameters of attitude control

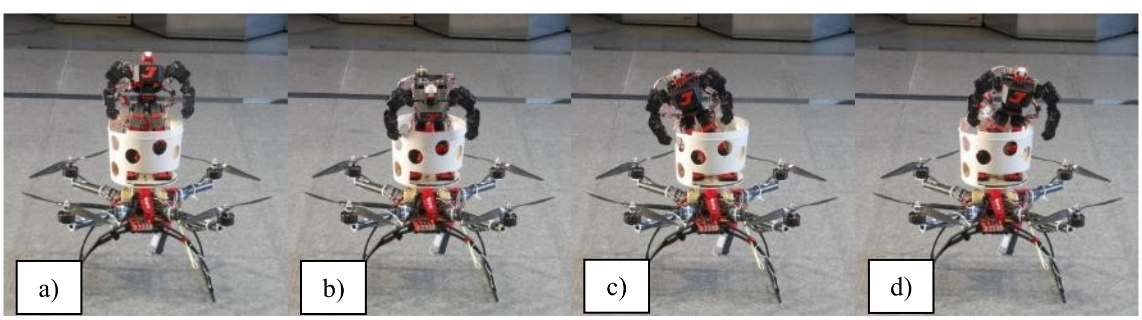
Attitude control	
P (STB_RLL_P, STB_PIT_P)	4.5
I (STB_RLL_I, STB_PIT_I)	0
Angular rate control	
P (RATE_RLL_P, RATE_PIT_P)	0.15
I (RATE_RLL_I, RATE_PIT_I)	0.1
D (RATE_RLL_D, RATE_PIT_D)	0.004

TABLE III PID parameters of direction control

Angular velocity gain	
P (ACRO_P)	4.5
Attitude control	
P (STB_RLL_P, STB_PIT_P)	4.5
I (STB_RLL_I, STB_PIT_I)	0
Angular rate control	
P (RATE_RLL_P, RATE_PIT_P)	0.15
I (RATE_RLL_I, RATE_PIT_I)	0.1
D (RATE_RLL_D, RATE_PIT_D)	0.004

TABLE IV PID parameters of altitude control

Altitude control	
P (THR_ALT_P)	1
I (THR_ALT_I)	0
Climb rate control	
P (THR_RATE_P)	6
I (THR_RATE_I)	0
D (THR_RATE_D)	0
Climb acceleration control	
P (THR_ACCEL_P)	0.75
I (THR_ACCEL_I)	0.15
D (THR_ACCEL_D)	0



(a) Back posture (b) Forward posture (c) Right posture (d) Left posture

Figure 7 Tilting postures

IV. Results and Discussion

A. Attitude Control with Humanoid Robot Posture

Attitude control tests were done indoors. Experiments were performed as following procedures. At first, test QRH was taken-off with "Stabilize mode" (only attitude is hold by attitude control system) of Arducopter function by manual operation, then it hovered with “Alt-hold mode” (attitude and altitude are hold by attitude controller and altitude controller, respectively) by automatic operation.

When the test QRH hovered stably, test humanoid robot was operated by IR controller with selected posture command. These posture motions (Figure 7) cause the shift in the position of COG. Attitude of test QRH was held by PI control, but I gain was set to 0 (i.e. P control). **Figure 8** shows the scene of an experimental flight. In **Figure 8(a)**, test QRH hovered stably. In **Figure 8(b)**, forward posture command was sent and test humanoid robot tilted its body to forward. As the result, test QRH was tilted to forward, and it started to shift as **Figure 8(c)**. In **Figure 8(d)**, standing posture command was sent so that test humanoid robot returned to standing posture, test QRH was tilted to backward (**Figure 8(e)**), then it returned to horizontal level and stopped (**Figure 8(f)**). **Figure 9** shows the scene of another experimental flight. In **Figure 9(a)**, test QRH hovered stably. In **Figure 9(b)**, left posture command was sent and test humanoid robot tilted its body to left. Test QRH was tilted to left, and it started to shift as **Figure 9(c)**. In **Figure 9(d)**, standing posture command was sent; test humanoid robot returned to standing posture, and test QRH was tilted to right (**Figure 9(e)**). Then test QRH returned to horizontal level and stopped (**Figure 9(f)**).

Figure 10 shows the attitude change of forward /back posture experiment. In this figures, + degrees mean “nose up” and – degrees mean “nose down”. “Forward posture”, “Back posture”, and “Standing posture” show trigger points of forward posture, back posture and standing posture, respectively. In **Figure 10(a)**, neutral angle of pitch is about 1.2 degrees. When pitch angle is 1.2 degrees, test QRH hovers stably. Forward posture command was sent at 95 sec, and pitch angle of test QRH increased to 2.5 degrees. This motion (counter peak) is caused by the counter torque of forward posture motion. Moreover, pitch angle decreased to about -7 degrees (main peak). Then it increased to near 0.8 degrees with damped vibration, and it causes a steady-state deviation about -0.4 degrees. Test QRH started to shift with main peak, and it kept forward movement at a constant speed by the steady-state deviation. Standing posture command was sent at 101.9 sec, this motion made a small counter peak and main peak increased 9 degrees, then pitch angle returned to neutral pitch angle. These motions produced by standing posture cancel the steady-state deviation and forward movement.

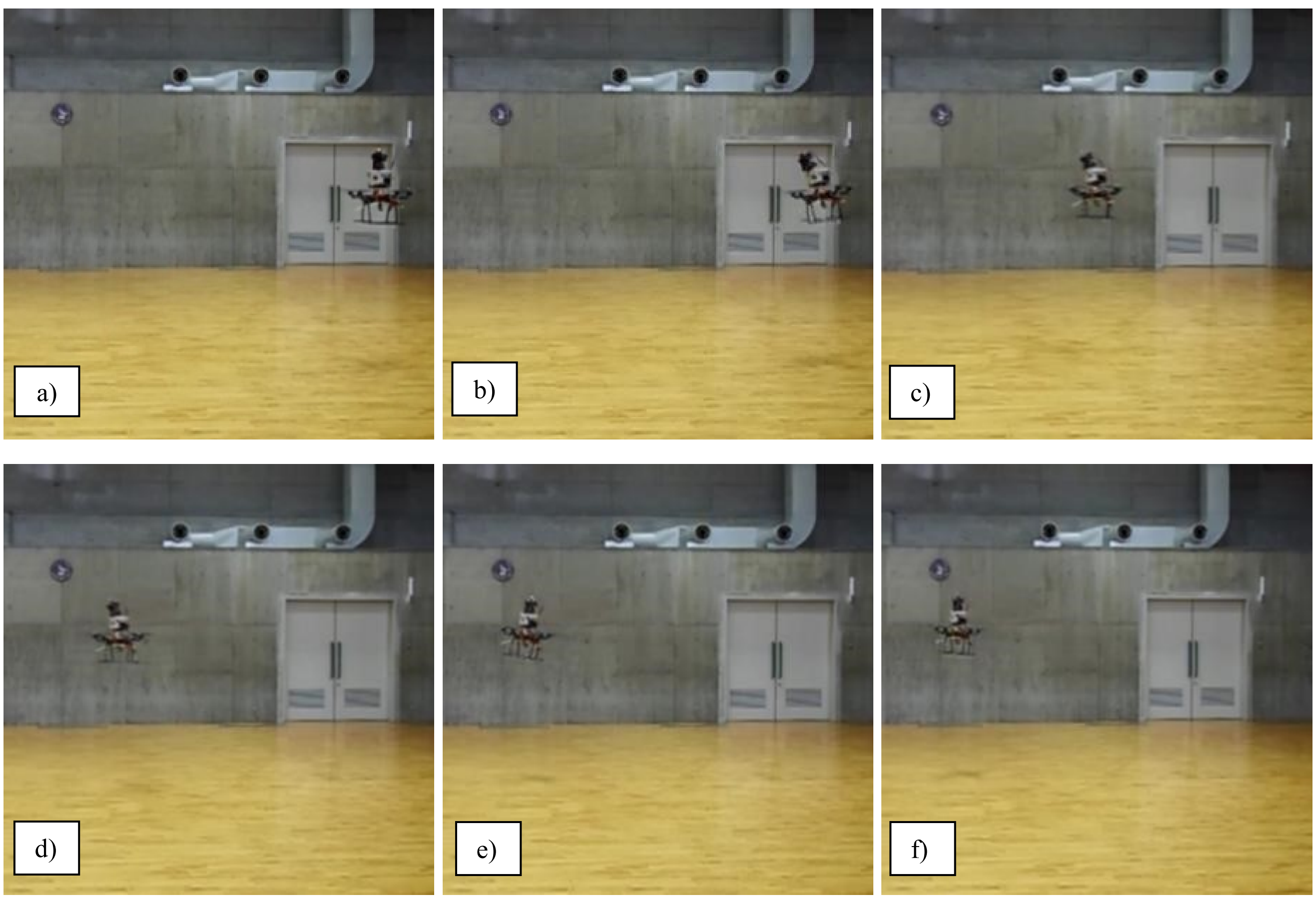


Figure 8 Forward motion test

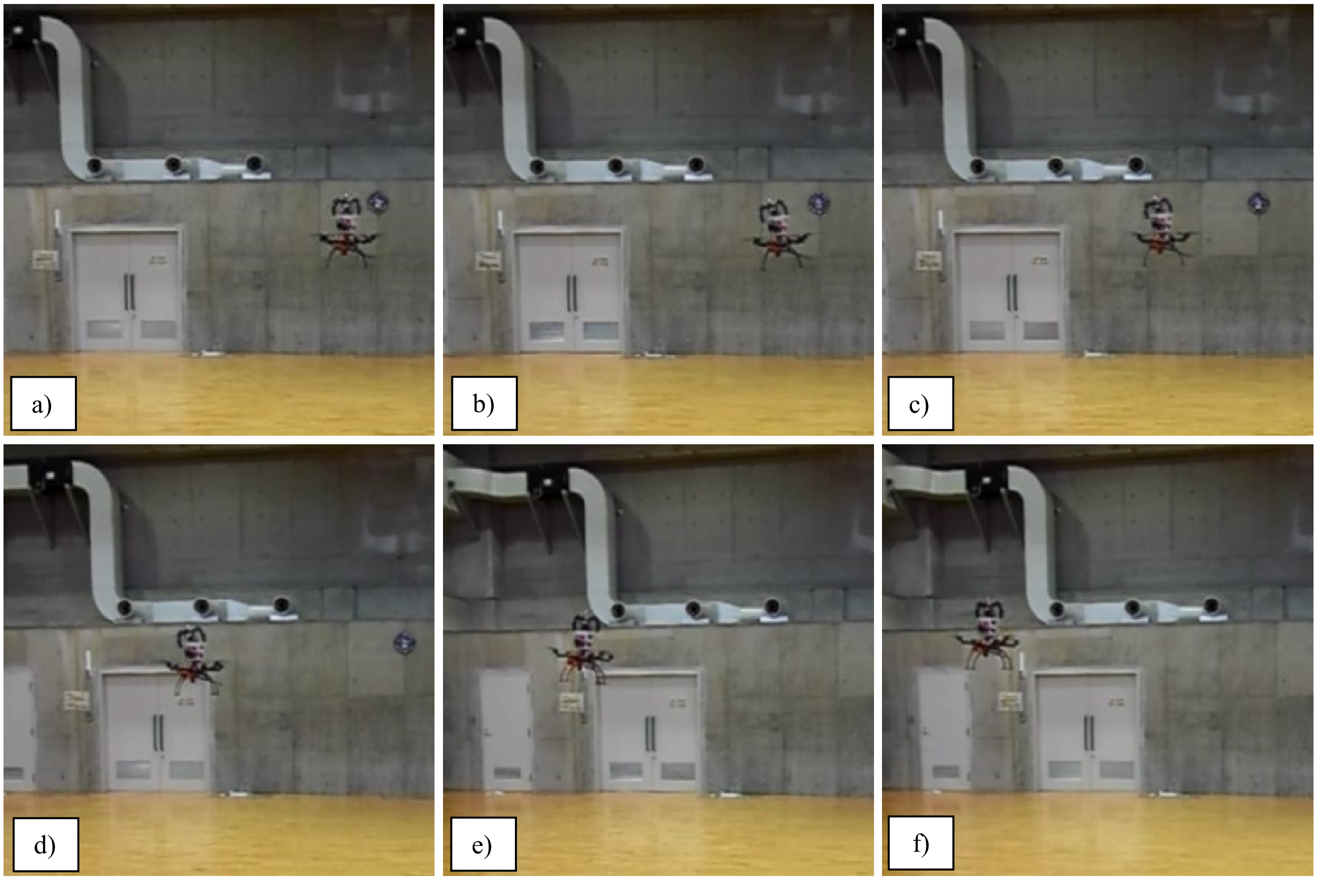
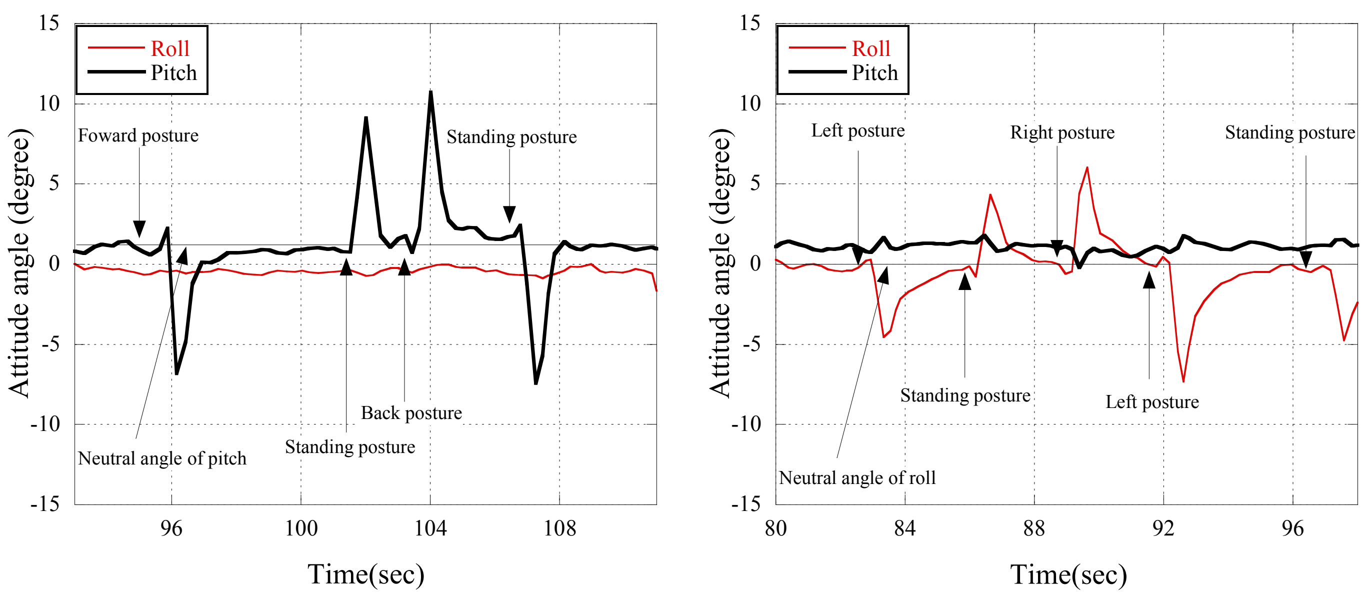


Figure 9 Left motion test



(a) Forward/back posture experiment (b) Left/right posture test

Figure 10 Attitude change and test robot motion timing

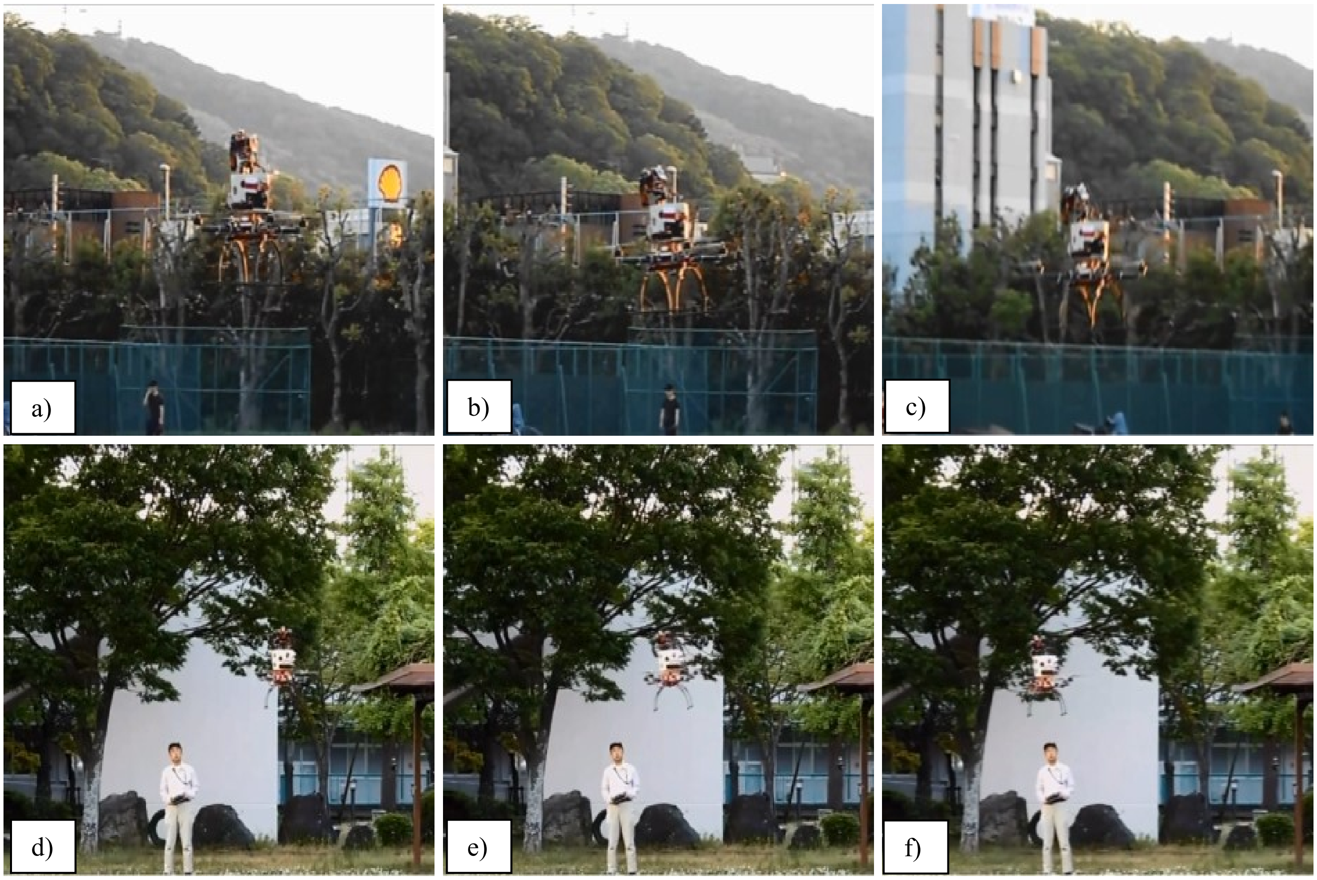


Figure 11 Scene of outdoor flight test

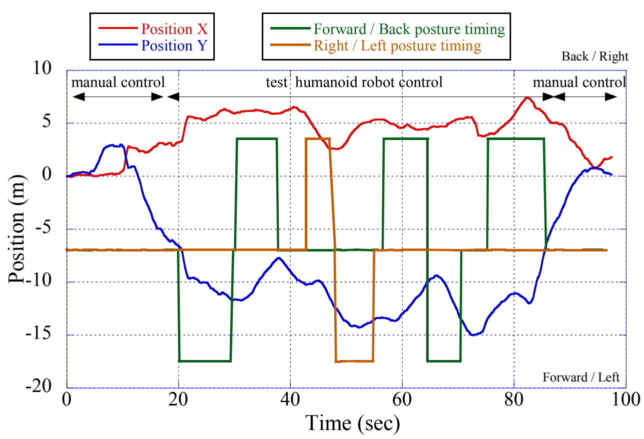


Figure 12 Attitude and position variation during outdoor flight test

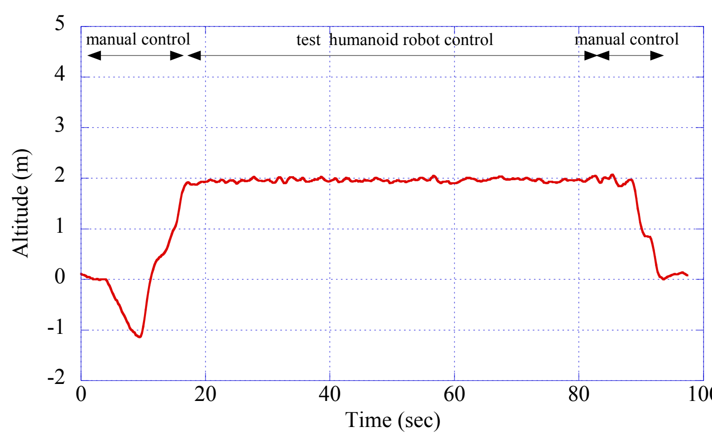


Figure 13 Altitude variation measured in atmospheric pressure during outdoor flight test

Next, back posture command (at 103.3 sec) and standing posture command (at 106.5 sec) were sent to test backward movement. The movement process is same as forward movement, the steady-state deviation of about 0.4 degree causes backward movement at a constant speed, and standing posture command cancels backward motion.

Figure 10(b) shows the attitude change of left/right posture experiment. In this figures, + degrees mean "left roll" and – degrees mean "right roll". "Left posture", "Right posture", and "Standing posture" show trigger points of left posture, right posture and standing posture, respectively. As in **Figure 10(a)**, left/right posture makes leftward/rightward movement at a constant speed and standing posture cancels these movements.

B. Outdoor Flight Test of Attitude Control and Shifting

Outdoor flight tests were done with the following results. **Figure 11** shows the scene of outdoor flight test. **Figure 11(a)**, **Figure 11(b)**, and **Figure 11(c)** show the forward movement, and **Figure 11(d)**, **Figure 11(e)** and **Figure 11(f)** show the rightward movement. Wind speed was ranging from 0 to 1.5 m/sec. **Figure 12** shows the posture timing and position of test QRH. **Figure 11(a)**, **Figure 11(b)**, and **Figure 11(c)** show the forward movement from 64 sec to 70.5 sec in **Figure 12**, **Figure 11(d)**, **Figure 11(e)** and **Figure 11(f)** show the rightward motion from 42.7 sec to 47 sec in **Figure 12**. From these results, posture motion of humanoid robot can control COG shifting, and it results as test QRH flight control in horizontal plane.

Test QRH movement at intervals is affected by wind disturbance. For example, x and y direction movements from 20 sec to 21.6 sec and from 72.6 sec to 85 sec were affected by wind, and test QRH were moved. In other experiments, wind blew off test QRH despite the existence of tilted attitude by test humanoid posture. Each posture consists of pre-programmed motions and generates a certain steady-state deviation. So, it is difficult to overcome the disturbance such as wind.

Figure 13 shows the result of altitude control during outdoor flight test. Test QRH took off at 5 sec and altitude showed negative values. It means that barometric altimeter detected pressure of the compressed air by ground effect at take-off. Then, barometric altimeter began to operate normally from 14 sec. During this outdoor flight test, altitude was kept around 2 m.

V. CONCLUSION

Test humanoid robot was set on test QRH main frame, and it changed its posture to generate COG shift for tilting test QRH attitude. From test flight experiments, test QRH attitude is controlled with COG shift, caused by tilting posture of test humanoid robot, enabling it to slide the test QRH. This control method is similar to the wheeled inverted pendulum control system, such as Segway. In future experiments, we will try to add GPS position data and feed-back posture motion generator program on test humanoid robot to cancel the disturbance. We will also investigate how to implement yaw axis and up/down control function to test humanoid robot on test QRH using its nature motion performance.

This paper is the model test of new flying machine operation, like a “Flying Segway”. We expect that people will ride on large QRH, and can control it easily and intuitively by our proposed method.

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