ATTITUDE CONTROL SYSTEM DESIGN FOR AGGRESSIVE MANEUVER OF A QUAD-ROTOR UAV

Byung-Yoon Lee, Dong-Wan Yoo, Min-Jea Tahk
Korea Advanced Institute of Science and Technology
N7 #3316, 291 Daehak-ro, Yuseong-gu, Daejeon/South Korea
bylee@fdcl.kaist.ac.kr, dwyoo@fdcl.kaist.ac.kr, mjtahk@fdcl.kaist.ac.kr

ABSTRACT
This paper addresses the methodologies of attitude control system design and aggressive maneuver for a Quad-rotor UAV. For this purpose, first of all, Quad-rotor UAV’s dynamic model is derived, and it was used for designing an attitude controller of the Quad-rotor UAV. Attitude controllers are designed by two different methods. One is open-loop control system design and the other one is closed-loop control system design. Performances of both controllers are tested by 6-DOF simulation assuming that using the motion capture system on indoor flight test. Closed-loop control system is designed by conventional PID control method. In case of the open-loop control system, control inputs are calculated by quad-rotor dynamic model and thrust system model that are identified by thrust test.

6-DOF simulation environment was constructed in order to verify the performances of attitude controllers. We assume that flight tests are performed with motion capture system in an indoor facility. Therefore, 6-DOF simulation environment considers the indoor motion capture system. In addition, we present a methodology for an aggressive maneuver; especially flip maneuver method that is applied from the designed controllers in previous researches.

KEY WORDS
Quad-Rotor UAV, Aggressive Maneuver, Open-loop control, 6 DOF Simulation

1. Introduction
Recently, the small UAV market is evolving at a rapid pace. Small UAVs are applied in various areas such as limited attack, aerial photography, surveillance and reconnaissance. In this small UAV market, many studies are underway especially for the Quad-rotor. Quad-rotor unmanned aerial vehicle is one that uses four rotors, which are equipped on the tips of cross-shaped rods.

In addition to this, Quad-rotor aggressive maneuver researches are actively underway as well, with the aid of the motion capture technology, which is a recent technology in this area. In case of small UAVs, MEMS gyros are widely used due to the limitations of the MEMS structure, which are constantly accumulated error and drift. Using motion capture system provides extremely small error and drift, which are even smaller than that of MEMS gyro, so that the system is capable to show more precise control performance.

The GRASP laboratory of University of Pennsylvania has conducted aggressive maneuvers such as perching, or flips maneuvers. They used three different types of controllers for performing these maneuvers, and those controllers are categorized as an attitude control, a hover control, and a three-dimensional trajectory follow control. In other words, at one point, only one controller is used to control the Quad-rotor system for each specific condition. When other condition for the Quad-rotor is met, then the controller switching logic is activated to switch the main controller to a different type of controller that is appropriate for the given condition [1].

In addition to this, the ACL at MIT has performed aggressive maneuvers with the variable pitch Quad-rotor [2].

This paper is composed as follows. First of all, Quad-rotor dynamic model is derived, and an appropriate control system is designed for the dynamic model of the Quad-rotor. We use conventional PID control method for a closed-loop control structure, and performed 6-DOF real time simulations, assuming the Quad-rotor flying in an indoor facility with the motion capture system.

2. Dynamic Modeling of the Quad-Rotor

2.1 6-DOF Rigid-body Equations of Motion

In this section, 6-DOF rigid-body equations of motion are introduced.
In this paper, we define that inertial frame is fixed on an arbitrary point on the ground, and body frame is fixed on the c.g point of the Quad-rotor. \( \mathbf{r} \) is the vector that represents the relative position of the origin of the body frame. Frame definitions are represented in Figure (1).

Force equations are expressed in Equations (1.a), (1.b), (1.c), and moment equations are expressed in Equations (2.a), (2.b) and (2.c) [3,4].

\[
\begin{align*}
\dot{u} &= rv - qw - g \sin \theta + \frac{F_x}{m} \\
\dot{v} &= -ru + pw + g \sin \phi \cos \theta + \frac{F_y}{m} \\
\dot{w} &= qu - pv + g \cos \phi \cos \theta + \frac{F_z}{m} \\
\dot{\theta} &= (I_{xy} - I_{zz})qr / I_{xx} + L / I_{xx} \\
\dot{\phi} &= (I_{zz} - I_{xx})pr / I_{yy} + M / I_{yy} \\
\dot{\psi} &= (I_{xx} - I_{yy})pq / I_{zz} + N / I_{zz}
\end{align*}
\]

\[ (1.a) \quad (1.b) \quad (1.c) \quad (2.a) \quad (2.b) \quad (2.c) \]

### 2.2 Quad-Rotor Configuration

Quad-rotor structure contains four rotors which are mounted on the tip of cross-shaped rods. This structure is shown in Figure (2).

![Quad-rotor configuration](image)

\[ \text{Figure 2. Quad-rotor configuration} \]

Four rotors are defined as rotors 1, 2, 3, and 4 in clockwise direction from the forward direction of the Quad-rotor. Rotor 1 and rotor 3 rotate clockwise direction, whereas rotor 2 and rotor 4 rotate in counter clockwise direction. Quad-rotor attitudes are changed by applying the angular velocity differences on those four rotors.

To generate a positive pitching moment, angular velocity of the rotor 1 should be increased, and angular velocity of the rotor 3 should be decreased at the same time. Similarly, to generate a positive rolling moment, angular velocity of the rotor 2 should be decreased, and angular velocity of the rotor 4 should be increased. However, in generating positive yawing moment, angular velocities of rotor 1 and rotor 3 should be decreased, and angular velocities of rotor 2 and rotor 4 should be increased. Then the Quad-rotor system provides a positive yawing moment by the counter torque, which is generated from the angular velocities of those four rotors.

We define the angular velocities of rotors as \( \Omega_1, \Omega_2, \Omega_3, \Omega_4 \), and the rotor dynamics is modeled as the first order system. Force \( T \) and torque \( \tau \) generated by a rotor can be determined by Equations (3.a) and (3.b). \( K_t \) is the motor thrust coefficient, and \( K_r \) is the motor torque coefficient.

\[
\begin{align*}
T &= K_t \Omega_i^2 \\
\tau &= K_r \Omega_i^2
\end{align*}
\]

\[ (3.a) \quad (3.b) \]

Forces acting in each direction of the Quad-rotor are generated by four rotors. These forces are represented as \( F_x, F_y, F_z \) for each direction, and they are shown in Equations (4.a), (4.b) and (4.c).

\[
\begin{align*}
F_x &= 0 \\
F_y &= 0 \\
F_z &= -K_t(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2)
\end{align*}
\]

\[ (4.a) \quad (4.b) \quad (4.c) \]

Considering the gyroscopic torque, the moments acting in each angular direction of the Quad-rotor are shown in Equations (5.a), (5.b) and (5.c).

\[
\begin{align*}
L &= K_r(-\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\
M &= K_r(\Omega_1^2 + \Omega_2^2) \\
N &= K_r(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 - \Omega_4^2)
\end{align*}
\]

\[ (5.a) \quad (5.b) \quad (5.c) \]

### 2.3 Quad-Rotor Control Allocation

Control allocation is required for converting typical rotorcraft control commands to rotor’s angular velocity commands. Equations (6.a), (6.b), (6.c) and (6.d) represent the control allocation logic for the Quad-rotor.

\[
\begin{align*}
\Omega_1 &= \Omega_{\text{nom}} + \Delta \Omega_x + \Delta \Omega_y - \Delta \Omega_z \\
\Omega_2 &= \Omega_{\text{nom}} + \Delta \Omega_z - \Delta \Omega_y + \Delta \Omega_x \\
\Omega_3 &= \Omega_{\text{nom}} + \Delta \Omega_y - \Delta \Omega_x + \Delta \Omega_z \\
\Omega_4 &= \Omega_{\text{nom}} + \Delta \Omega_x + \Delta \Omega_y + \Delta \Omega_z
\end{align*}
\]

\[ (6.a) \quad (6.b) \quad (6.c) \quad (6.d) \]

\( \Omega_{\text{nom}} \) is the nominal angular velocity of a rotor that keeps the Quad-rotor staying in a hover state. \( \Delta \Omega_z \) is the rotor angular velocity difference that generates vertical direction force of the Quad-rotor. \( \Delta \Omega_y \) is the rotor
angular velocity difference that generates roll-axis torque of the Quad-rotor. Likewise, \( \Delta \Omega_\phi \) is the rotor angular velocity difference that generates pitch-axis torque of the Quad-rotor, and \( \Delta \Omega_\psi \) is the rotor angular velocity differences that generate yaw-axis torque of the Quad-rotor system.

3. Control System Design

3.1 Open Loop Attitude Control

To control the attitude of the Quad-rotor, one needs to generate system torques by controlling each rotor angular velocity, and attitude rate of the Quad-rotor should be near zero when the Quad-rotor reaches the desired attitude. Since this method does not use any feedback control, this method is called the open-loop attitude control.

For this purpose, system torque acting on the Quad-rotor is divided into three stages: acceleration stage, deceleration stage, and stabilization stage. During the acceleration stage, Quad-rotor angular velocity should be accelerated to the maximum value. In contrast, in the deceleration stage, Quad-rotor angular velocity should be decelerated to minimum value. Finally, in the stabilization stage, all rotors should rotate in the same angular velocities in order for the Quad-rotor to return safely to original hovering state.

One good application is to consider the Quad-rotor performing a positive roll flip maneuver. We assume that the gyroscopic effect and disturbance are small enough to be negligible. Graphical representation of each stage of the flip maneuver is illustrated in Figure 3. Before conducting the open-loop attitude control, Quad-rotor should hold the hover state, then all rotors should rotate with the identical nominal angular velocity, \( \Omega_{\text{nom}} \). We have already assumed that gyroscopic effect and disturbance are negligible, so that there is no system torque on the pitch axis in all stages. Therefore, rotors 1 and 2 hold their angular velocities as \( \Omega_{\text{nom}} \) in all stages.

In acceleration and deceleration stages, torques and differences of angular velocities and Euler angles are as follows. In the acceleration stage, angular velocity of rotor 2 decreases whereas angular velocity of rotor 4 increases. Rotor 2 should rotate with the minimum angular velocity, \( \Omega_{\text{min}} \), and rotor 4 should rotate in the maximum angular velocity, \( \Omega_{\text{max}} \). Maximum and minimum angular velocities, \( \Omega_{\text{max}} \) and \( \Omega_{\text{min}} \) can be obtained as Equations (7.a) and (7.b).

\[
\Omega_{\text{max}} = \Omega_{\text{nom}} + \Delta \Omega_{\text{max}} \tag{7.a}
\]
\[
\Omega_{\text{min}} = \Omega_{\text{nom}} - \Delta \Omega_{\text{min}} \tag{7.b}
\]

where \( \Delta \Omega_{\text{max}} \) and \( \Delta \Omega_{\text{min}} \) represent maximum and minimum angular velocity changes, respectively.

In this paper, we assume that \( \Delta \Omega_{\text{min}} = \Delta \Omega_{\text{max}} \), and it indicates that there is no extra torque generated from the flip maneuver except for the roll torque. In addition, hovering stage, acceleration stage, deceleration stage, and stabilization stage are numbered as stages zero, one, two, and three, respectively. Now, in the \( x \)-th stage, angular velocities of rotor 2 and rotor 4 are denoted as \( \Omega_{2,x} \) and \( \Omega_{4,x} \), and the angular velocity variations during \( x \)-th stage are denoted as \( \Delta \Omega_x \). Accordingly, angular velocities of rotor 2 and rotor 4 are expressed in Equations (8.a) and (8.b).

\[
\Omega_{2,x} = \Omega_{2,x-1} - \Delta \Omega_x \tag{8.a}
\]
\[
\Omega_{4,x} = \Omega_{4,x-1} + \Delta \Omega_x \tag{8.b}
\]

Angular velocity variations in \( x \)-th stage and angular velocities of rotor 2 and rotor 4 in \( x-1 \)-th stage can be found in Table 1.

<table>
<thead>
<tr>
<th>Stage(x)</th>
<th>Acc. (1)</th>
<th>Dec. (2)</th>
<th>Stab. (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( t_s )</td>
<td>( t_0 \sim t_1 )</td>
<td>( t_1 \sim t_2 )</td>
</tr>
<tr>
<td>( \Omega_{2,x-1} )</td>
<td>( \Omega_{\text{nom}} )</td>
<td>( \Omega_{\text{nom}} - \Delta \Omega_{\text{max}} )</td>
<td>( \Omega_{\text{nom}} + \Delta \Omega_{\text{max}} )</td>
</tr>
<tr>
<td>( \Omega_{4,x-1} )</td>
<td>( \Omega_{\text{nom}} )</td>
<td>( \Omega_{\text{nom}} + \Delta \Omega_{\text{max}} )</td>
<td>( \Omega_{\text{nom}} - \Delta \Omega_{\text{max}} )</td>
</tr>
<tr>
<td>( \Delta \Omega_x )</td>
<td>( \Delta \Omega_{\text{max}} )</td>
<td>(-2\Delta \Omega_{\text{max}} )</td>
<td>( \Delta \Omega_{\text{max}} )</td>
</tr>
</tbody>
</table>

In this paper, the rotor system is modeled as a first order system with a time constant \( \tau \). Therefore, angular velocity of rotor 2 during the flip maneuver \( \Omega_2(t) \) is expressed in Equation (9).
Angular velocity of rotor 4, \( \Omega_4(t) \), is similar to that of Equation (9), but all the signs are opposite. System torque acting on the Quad-rotor’s roll-axis is expressed in Equation (10).

\[
L = K_f(-\Omega_4^2 + \Omega_z^2)d
\]

Now, we can calculate the angular acceleration of the Quad-rotor, \( \alpha(t) \), by manipulating Equation (10) and Quad-rotor’s inertia. In addition to this, we can obtain angular velocities and Euler angles of the Quad-rotor at time \( t \), by integrating \( \alpha(t) \) with respect to time. Angular velocities and Euler angles of the Quad-rotor are denoted as \( \dot{p}(t) \) and \( \dot{q}(t) \) and \( \dot{r}(t) \) will be decided. In other words, when the open-loop attitude control is finished, allowable error of the angular acceleration are defined as \( \pm E_\alpha \text{ rad/sec}^2 \).

In the same manner, allowable errors of the angular velocities at that specific moment are defined as \( \pm E_p \text{ rad/sec} \).

In case of flip maneuver, terminal condition of roll angle is 360 degree. These terminal conditions are expressed in Equations (11.a), (11.b) and (11.c). Now, we can calculate \( t_1 \) and \( t_2 \) that satisfy the terminal condition. Then, it leads to a successful calculation of the control input for the open-loop flip maneuver.

\[
\begin{align*}
-\Delta t_1 &\leq \alpha(t) & \leq \Delta t_1 \quad \text{(11.a)} \\
-\Delta t_2 &\leq p(t) & \leq \Delta t_2 \quad \text{(11.b)} \\
\dot{\phi}(t) &= \pm 2\pi \quad \text{(11.c)}
\end{align*}
\]

### 3.2 Closed Loop Attitude Control

Closed-loop control is designed by a conventional Proportional-Derivative (PD) control method. Structure and equations of attitude control are expressed in Equations (12.a), (12.b) and (12.c) and Figure 3.

\[
\begin{align*}
\Delta \Omega_\phi &= K_{d,\phi} (\phi_{cmd} - \phi) - p \quad \text{(12.a)} \\
\Delta \Omega_\theta &= K_{d,\theta} (\theta_{cmd} - \theta) - q \quad \text{(12.b)} \\
\Delta \Omega_\psi &= K_{d,\psi} (\psi_{cmd} - \psi) - r \quad \text{(12.c)}
\end{align*}
\]

3.3 Position Control

Purpose of the position control is to locate the Quad-rotor at the desired position in the inertial frame. For this purpose, the position controller contains the attitude controller as an inner loop structure as shown in Figure (3). Therefore, Euler angle commands \( \phi_{cmd} \) and \( \theta_{cmd} \) should be the output of the position controller. At this time, if yaw angle, \( \psi \), is zero, then \( \phi_{cmd} \) and \( \theta_{cmd} \) are directly related to the position of y axis and x axis of the inertial frame. However, if system’s yaw angle is not zero, then \( x_{cmd} \) and \( y_{cmd} \) are adjusted by applying the appropriate yaw angle command, holding the system’s heading to the commanded position all the time.

For position control, we use conventional PID control method, and the output of the position controller are denoted as \( \phi_{cmd} ' \) and \( \theta_{cmd} ' \). By using these outputs with nonzero yaw angle, \( \psi \), we can calculate Euler angle commands, \( \phi_{cmd} \) and \( \theta_{cmd} \), with respect to the body frame. Equations of the position controller are expressed in Equations (13.a), (13.b) and (13.c), and the structure of the position controller is illustrated in Figure 4.

\[
\begin{align*}
\phi_{cmd} &= -((K_{p,\phi} (x_{cmd} - x) - K_{d,\phi} Vx) + \frac{K_{i,\phi}}{s}) \sin \psi \\
&\quad + ((K_{p,\psi} (y_{cmd} - y) - K_{d,\psi} Vy) + \frac{K_{i,\psi}}{s}) \cos \psi \quad \text{(13.a)} \\
&\quad = -\theta_{cmd} ' \cos \psi + \phi_{cmd} ' \sin \psi \\
\theta_{cmd} &= -((K_{p,\theta} (x_{cmd} - x) - K_{d,\theta} Vx) + \frac{K_{i,\theta}}{s}) \cos \psi \\
&\quad -((K_{p,\psi} (y_{cmd} - y) - K_{d,\psi} Vy) + \frac{K_{i,\psi}}{s}) \sin \psi \quad \text{(13.b)} \\
&\quad = -\theta_{cmd} ' \cos \psi - \phi_{cmd} ' \sin \psi \\
\Delta \Omega_z &= -(K_{p,z} (z_{cmd} - z) - K_{d,z} Vz) + \frac{K_{i,z}}{s} \quad \text{(13.c)}
\end{align*}
\]
4. System Configuration

4.1 Quad-Rotor Frame

In this paper, Quad-rotor frame was built to verify the performance of the controller, and it is shown in Figure 5. The Quad-rotor frame can also be used for the flight tests in subsequent studies.

![Quad-rotor frame structure](image)

Quad-rotor frame is based on Mikrokopter Company’s Quad-rotor frame. Each rod is made of aluminum, and motors and propellers are equipped at the tips of the rods. There are electric speed controllers (ESC), which are installed on the bottom center of the Quad-rotor frame. Flight control system is located on top of the ESCs, and the IMU is located right above the FCS. Parts that compose the Quad-rotor frame are listed in the Table 2.

<table>
<thead>
<tr>
<th>Base platform</th>
<th>MikroKopter L4-ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust System</td>
<td>Roxy 2827/35 Motor, APC 10 x 4.5 propeller, Bl-Ctrl V1.2 Electric Speed Controller, Vislero Li-Po battery (14.8V, 2200mAh)</td>
</tr>
<tr>
<td>IMU</td>
<td>3DM-GX3-35</td>
</tr>
<tr>
<td>FCS</td>
<td>Overo Fire COM, Voltage Converter</td>
</tr>
</tbody>
</table>

Finally, Quad-rotor parameters are determined by measured data and calculated data using previously built Quad-rotor frame.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>Mass</td>
<td>0.970 kg</td>
<td>kg</td>
</tr>
<tr>
<td>$I_\tau$</td>
<td>Rotor Inertia</td>
<td>$5.716 \times 10^{-3}$ kg·m²</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Thrust System

Thrust system of Quad-rotor frame is composed of propeller, motor, ESC and battery. Thrust test was performed in order to measure thrust coefficient and torque coefficient of the thrust system. Test environment has been set up as shown in Figure 6. At this time, the rotor thrusts are measured by load cell, and the angular velocity of the rotor are measured by laser sensor simultaneously.

![Thrust test environment for single thrust system](image)

By observing thrust test results, thrust coefficient is determined as $K_t = 1.764 \times 10^{-5} \ (N/(rad/sec)^2)$ and torque coefficient is determined as $K_\tau = 2.547 \times 10^{-7} \ (N\cdot m/(rad/sec)^2)$.

In addition to this, system identification was performed in order to obtain thrust system model, and for this purpose, response of $+240 \ rad/sec$ command input was recorded: the rotor angular velocity input varied from 440 rad/sec up to 680 rad/sec.

Depending on the test results, we modeled thrust system as two different models that the one is the first order system model, and the other one is the second order system model. These system model parameters are listed in Table 4, and responses of these system models are represented in Figure 7. P1D graph is response of the first order system model and P2DU graph is response of the second order system model.
### Table 4. Parameters of thrust models

<table>
<thead>
<tr>
<th>Equation</th>
<th>$T_d$</th>
<th>$\frac{1}{a}$</th>
<th>$\zeta$</th>
<th>$\frac{1}{\omega_s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{s+a} \times e^{-T_s}$</td>
<td>0.02</td>
<td>0.155</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\frac{1}{s^2 + 2\zeta \omega_s s + \omega_s^2} \times e^{-T_s}$</td>
<td>0.02</td>
<td>-</td>
<td>0.8326</td>
<td>0.0981</td>
</tr>
</tbody>
</table>

![Figure 7. Test results for identifying thrust model](image)

### 4.3 Hardware Architecture

Ground control system is constructed by MATLAB Real-time Workshop and Simulink. Motion capture system is used to obtain the position of the markers that are attached on the Quad-rotor frame. From position information of markers, we can calculate position, Euler angles, linear velocities and angular velocities of the Quad-rotor frame. This information is used for generating a control signal for the Quad-rotor frame. Structure of FCS and GCS, and overall signal flows are illustrated in Figure 8.

![Figure 8. Overall hardware architecture of Quad-rotor control system](image)

### 5. Simulation

In this paper, we constructed 6-DOF simulation environment for verification of theory and test. Since the flight test with motion capture system will be carried out in subsequent studies, similar motion capture system environment, which emulates the real test area, should be considered by the 6-DOF simulation. We can predict that when we are performing the flight test, delay caused by the motion capture system could incur. Therefore, this delay component should be included in 6-DOF simulation environment. Structure of 6-DOF simulation environment, which is constructed by Simulink, is illustrated in Figure 9.

![Figure 9. 6-DOF simulation structure of Quad-rotor control system constructed by Simulink](image)

#### 5.1 Open-loop Attitude Control

Equation (9) in section 3.1, and parameters of Quad-rotor frame that is introduced in chapter 4 are used for an open-loop attitude control. At this time, terminal condition of angular acceleration allowable error is defined as $E_a = 0.1 \text{ rad/sec}^2$, and terminal condition of allowable error of angular velocity is defined as $E_p = 0.1 \text{ rad/sec}$.

In this paper, we have performed a flip maneuver as an example of consecutive steps of the attitude control. Now, Equation (9), and Table 3 are used to calculate for $t_1$, $t_2$, and $t_f$. The results of the calculation are obtained as $t_1 = 0.196$, $t_2 = 0.392$, and $t_f = 1.462$. In other words, when Quad-rotor starts the open-loop attitude control, deceleration stage should start $0.196$ sec after the start of acceleration stage, and stabilization stage should start $0.196$ sec after the start of deceleration stage. Finally, after $1.07$ sec of the start of stabilization stage, terminal condition will be satisfied. When all previous steps are gone through, open-loop attitude control is completed.

6-DOF simulation results of Euler angles are shown in Figure 10. Roll angle $\phi$ is reached at 360 degree within $0.5$ second after the start of open-loop control. 6-DOF simulation results of angular velocities are shown in Figure 11. We can observe that roll angular velocity, $p$, is increased to $1100$ deg/sec during the flip maneuver.
angles are shown in Figure 12, and simulation results of angular velocities are shown in Figure 13. Observing results of Figure 12, flip maneuver takes approximately 1 second. This result is twice slower than the result of the open-loop attitude control. By only using PD control, it is clearly seemed difficult to reach the desired attitude faster than the open-loop controller does because of the damping term of PD controller. However, closed-loop control has a great benefit by having an error feedback loop. This benefit would decrease the error signal, and the closed-loop controller can hold stabilization state of the Quad-rotor.

5.3 Position Control

In this paper, position control method is designed with conventional PID control logic. We have used closed-loop attitude controller to control the attitude of the Quad-rotor. 6-DOF simulation was performed in the following sequences.

1. t=0 sec, free fall start, start position [0 0 0] (m).
2. After 1.5 sec, Rotor start, following [0 0 0] (m).
Positions in NED frame of 6-DOF Simulation results are shown in Figure 14. Quad-rotor’s 3D-trajectory is plotted in Figure 15. From observed results of Figure 14, tracking rate in the height control of the Quad-rotor is slower than that of other directions. It is because of the following reason. In height axis, Quad-rotor would change its position by changing the rotor angular velocity, which shows a slower response time than that of the Quad-rotor attitude.

6. Conclusion and Future Works

In this paper, we have designed attitude control system in two different ways in order for the Quad-rotor to reach a desired attitude. In case of the open-loop control, convergence speed is fast, but failed to hold the stability of the system. In contrary, closed-loop control system satisfies a successful stabilization of the Quad-rotor with one drawback: convergence speed is slower than that of open-loop control system. We have plans to have the flight tests with the motion capture system in subsequent studies, and that is the reason for having 6 DOF simulations emulating real environment with the motion capture system. Consequently, more precise results are expected in subsequent studies.

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