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Combined Quadrotor Autopilot System and Differential Morphing System Design

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Abstract

The aim of this article is to design and model a quadrotor with autopilot system and differential morphing using the Simultaneous Perturbation Stochastic Approximation (SPSA) optimization algorithm. Along with differential morphing, quadrotor modelling and control was also done. Although it is simple in structure, it has a complex structure in terms of model and control. Newton-Euler method was used for the dynamic model. Non-linear motion equations have been converted to linear motion equations. The full quadrotor model was drawn in the Solidworks program. Mass and moment of inertia information was obtained from this model. Simulation model was created by using state space model approach in Matlab / Simulink environment. Proportional integral derivative (PID) algorithm was used as the control structure. Differential morphing and PID coefficients rates were determined with SPSA. With the optimization method, determining the differential morphing rate, PID coefficients and applying it to the quadrotor provides a very innovative method.

Keywords: Quadrotor, SPSA, PID, Optimization, Morphing

1. Introduction

Unmanned Aerial Vehicle (UAV), which is commonly known and used, is a quadrotor / quadcopter that can remotely control and automatically move on a certain flight plan. In parallel with the rapidly developing technology, the frequency of use is increasing day by day. Especially its use by military purposes and security forces is vital. Many UAV models have been developed for better intelligence and better land control in the field of defence. Among the UAVs, quadrotors whose working area is larger than other models are considered as UAVs of the future.

Quadrotors are defined as unmanned aerial vehicles with 4 rotors and 6 degrees of freedom on 3 axes (x, y, z). The increasing use of hardware and accessories increases the academic and engineering applications on quadrotors.

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Quadrotors have vertical take-off and landing (VTOL) features. Because of these features, they do not need a runway like planes. Quadrotor type unmanned aerial vehicles are cheap, mechanically less complex and safer. In addition, since such unmanned aerial vehicles are controlled remotely and do not carry a pilot on them, they also eliminate the life risks of pilots. So quadrotor type unmanned aerial vehicles are frequently preferred in surveillance, transportation, geographic operations, photography, hobby and military.

Multicopter systems are also defined as multi-engine unmanned aerial vehicles. Produced with 3-4-6-8 engines, multicopters have started to take the first place among UAVs in the field of monitoring, search and rescue and defence thanks to their stable flights and features. Especially studies on quadrotor (quadcopter) have a big place in these systems. While there have been many studies on quadrotor modelling and control in recent years, less studies in the field of morphing have attracted attention. T. Oktay and O. Kose[1] studied the quadrotor dynamic model and its control. They used the situation space model approach in their work. As the controller, they used the PID algorithm. They performed the simulations in Matlab / Simulink environment. They carried out quadrotor altitude control with PID algorithm. While the quadrotor given altitude exits successfully, they ignored the change of other system parameters. T. Oktay and O. Kose[2] modeled the quadrotor forward flight using PID algorithm. They performed quadrotor modeling in Matlab / Simulink environment using the state space model approach. During the forward flight, the quadrotor successfully tracked the given trajectory and the system parameters did not exhibit excessive behaviour. A. Mulyadi and B. Siswojo[3] discussed the quadrotor model and control design. They made the modeling using the Laplace transform method. Movement stability is affected by body weight, propeller speed and wind. This face oscillated until the quadrotor was steady state. Ziegler-Nichols PID and fuzzy gain scheduling were used as control algorithm. In simulations, they found that fuzzy gain scheduling reduced the overshoot value by 0.1%. B. Milan et. al.[4] addressed a solution to developing classic PID controls with the combination of PID and PD controls and a real-time quadrotor control and stabilization problem. An algorithm is given for the implementation of a PID controller in a separate form, with the possibility of turning off the integral effect of the controller during operation and thus reaching the PID-PD controller. Results were obtained in computer simulations using a random system sample controlled by a PID controller, after which the controller was replaced with a new PID-PD controller and the results were shown in graphs. The second test was carried out experimentally by testing on the quadrotor development system, which provides data via Bluetooth communication and enables real-time monitoring of the system response so that the data from the real system can also be displayed on the graph. D. A. Wallace and C. Lum[5] took active quadrotor control with geometric morphing. Quadrotor used the Newton-Euler method to define the dynamic model. The quadrotor could perform the morphing feature by moving from the point where the arms meet the body. When the quadrotor performed the morphing event, there was a change in the moments of inertia as there was a change in the structure of the rigid body, and the author provided control of these moments with various equations. Linear Quadratic Control (LQR) was used as the quadrotor control algorithm. They worked on the state space model of the system for LQR control. Simulations have revealed that the quadrotor arm angle is controllable when it changes. N. Bucki and M. W. Mueller[6] worked on a quadrotor design and control with passive morphing. In this study, the arms fixed to the quadrotor body were attached with the hinges, allowing the arms to move down. The movement of the arms downward caused a decrease of approximately 50% in the quadrotor size. This allowed the quadrotor to pass easily through gaps that it could not pass. G. Barbaraci[7] discussed the design and control of the quadrotor with its changing geometric arms. Nonlinear mathematical models converted the linear state and used the quadrotor mathematical model. Quadrotor arm obtained morphing by changing the angle of intersection. Changing the arm intersection angles showed that there would be changes in the moments of inertia. Simulation results showed that changing arm angles significantly reduced quadrotor stabilization and vibrations. T. Oktay and O. Kose[8]–[10] have discussed quadrotor collective morphing. For collective morphing, longitudinal, lateral and hover flight, which are each flight situation, were examined separately. Collective morphing was performed by extending or shortening all of the quadrotor arms at the same time and in the same amount. They drew the quadrotor full model and collective morphing states separately in the Solidworks program. Since collective morphing quadrotor moments of inertia changed, they needed to draw each situation separately. They used the PID algorithm as the quadrotor control algorithm. For each flight, modelling was done in Matlab / Simulink environment and trajectories were successfully tracked. T. Oktay and S. Coban[11] used both active and passive metamorphosis on TUAVs for longitudinal and longitudinal flight. In their studies, TUAVs performed the morphing process by lengthening or shortening the wing tips. PID algorithm is used for TUAVs control. TUAVs morphing amount and PID coefficient values were calculated with SPSA optimization algorithm. Using SPSA, they improved the cost index by 46% compared to the initial situation.

2. Quadrotor Working Principle and Modeling

Quadrotor is a type of unmanned aerial vehicles with multi-rotor, vertical landing and take-off, capable of moving in 3 axes, propellers connected to its engines, creating a carrying force and flying, and capable of flying with autonomous or remote control. Hover or flying is done by rotating wings. In standard helicopters, the rotation movement of the helicopter about its axis, which is prevented by the tail rotor, is eliminated by rotating the motors in different directions in the quadrotors. The two of the quadrotor's motors rotating in the same direction and the other two in the opposite direction prevents them from turning uncontrollably around themselves. The rotation directions of the quadrotor motors are shown in Figure 1.

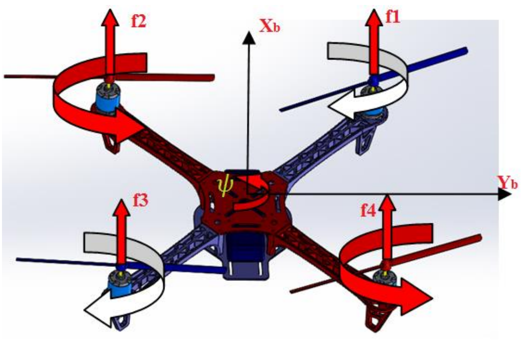


Figure 1. Quadrotor

Quadrotor dynamics are derived from motion equations. These equations are highly complicated. Euler-Lagrange approach is used to create the quadrotor dynamic model. In this approach, the following views are valid:

• Quadrotor structure and propellers are symmetrical and rigid.

• Quadrotor's center of mass and symmetric origin are concentric.

• Quadrotor thrust and drag are proportional to the square of the propeller speeds.

In this study, quadrotor motion equations are used linearly. In this context, quadrotor longitudinal and lateral motion equations are used as follows[12].

$$\dot{x} = u \quad (1)$$
$$\dot{z} = w \quad (2)$$
$$\dot{u} = -g\theta \quad (3)$$
$$\dot{w} = \frac{f_t}{m} \quad (4)$$
$$\dot{q} = \frac{\tau_y}{I_y} \quad (5)$$
$$\dot{\theta} = q \quad (6)$$

Lateral dynamic model:

$$\dot{y} = v \quad (7)$$
$$\dot{v} = g\phi \quad (8)$$
$$\dot{r} = \frac{\tau_z}{I_z} \quad (9)$$
$$\dot{p} = \frac{\tau_x}{I_x} \quad (10)$$
$$\dot{\phi} = p \quad (11)$$
$$\dot{\psi} = r \quad (12)$$

Input signals must be applied for quadrotor to perform its movements in 3 axes. Quadrotor motion input signals are defined as follows.

$$f_t = U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \quad (13)$$
$$\tau_x = U_2 = bl(-\Omega_1^2 - \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \quad (14)$$
$$\tau_y = U_3 = bl(\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \quad (15)$$
$$\tau_z = U_4 = d(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2) \quad (16)$$

Each control input has an effect on quadrotor dynamics. While U1 quadrotor affects altitude, U2, U3 and U4 order have an effect on roll, pitch and yaw movements.

Linear motion equations are shown in the form of the state space model. State space model is the way in which physical systems represented by first order differential equations are expressed in the form of matrices with inputs and outputs. The state space model is shown by the model below.

$$\dot{x} = Ax(t) + Bu(t) \quad (17)$$

$$y = Cx(t) + Du(t) \quad (18)$$

In this study, since longitudinal and lateral movements are examined separately, state space models are also discussed separately. In this case, the longitudinal state space model:

$$\begin{bmatrix}\dot{x}\\ \dot{z}\\ \dot{u}\\ \dot{w}\\ \dot{q}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}0&0&1&0&0&0\\0&0&0&1&0&0\\0&0&0&0&0&-g\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&1&0\end{bmatrix}\begin{bmatrix}x\\ z\\ u\\ w\\ q\\ \theta\end{bmatrix} + \begin{bmatrix}0&0\\0&0\\0&0\\ 1/m&0\\0&1/I_y\\0&0\end{bmatrix}\begin{bmatrix}f_t\\ \tau_y\end{bmatrix} \quad (19)$$

$$y = \begin{bmatrix}0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&1\end{bmatrix}\begin{bmatrix}x\\ z\\ u\\ w\\ q\\ \theta\end{bmatrix} \quad (20)$$

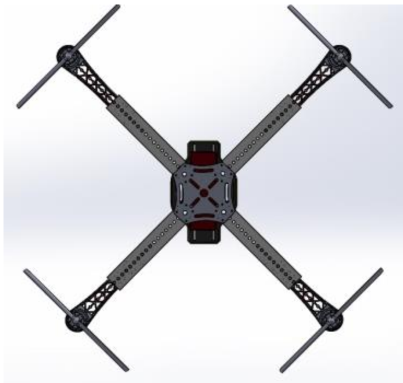
The lateral state space model is as follows.

$$\begin{bmatrix}\dot{y}\\ \dot{v}\\ \dot{p}\\ \dot{r}\\ \dot{\phi}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}0&1&0&0&0&0\\0&0&0&0&g&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&1&0&0&0\\0&0&0&1&0&0\end{bmatrix}\begin{bmatrix}y\\ v\\ p\\ r\\ \phi\\ \psi\end{bmatrix} + \begin{bmatrix}0&0\\0&0\\ 1/I_x&0\\0&1/I_z\\0&0\\0&0\end{bmatrix}\begin{bmatrix}\tau_x\\ \tau_z\end{bmatrix} \quad (21)$$

$$y = \begin{bmatrix}0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&1&0\\0&0&0&0&0&0\end{bmatrix}\begin{bmatrix}y\\ v\\ p\\ r\\ \phi\\ \psi\end{bmatrix} \quad (22)$$

3. Quadrotor Differential Morphing System

Generally, morphing can be described as changing the quadrotor geometry. Conventionally, the quadrotor has two types of geometric structures, plus-style and x-style. It is possible to do morphing by changing the lengths of the quadrotor arms or the angle of intersection of the arms. In this study, morphing was done by changing the arm lengths. In unmanned aerial vehicles, morphing is divided into two as active and passive morphing[13]. Active morphing is defined as minor physical changes that are performed continuously in the quadrotor geometry during flight, aiming to improve flight performance. Passive morphing is defined as small physical changes that occur once in the quadrotor geometry prior to flight, aiming to improve flight performance. Two types of active morphing, collective and differential, occur in the arm length change process. In the previous study[14] collective morphing was discussed. Differential morphing can be described as the quadrotor arms not being extended by the same amount at the same time. Figure 2 shows the quadrotor differential morphing states.



(a)

(b)

(c)

(d)

Figure 2. (a) Initial situation (b) 37.5% Differential morphing (c) 62.5% Differential morphing (d) 87.5% Differential morphing

While the mass remains constant due to varying arm lengths, the moments of inertia around the x, y and z axes also change[15]. Inertia moments and mass information of differential morphing are given in Table 1.

Table 1. Quadrotor moments of inertia

	$m(kg)$	I_x	I_y	I_z
Fig 2.(a)	0.60292	0.08437	0.08482	0.02146
Fig 2.(b)	0.60292	0.08428	0.08494	0.02148
Fig 2.(c)	0.60292	0.08434	0.08514	0.02175
Fig 2.(d)	0.60292	0.08450	0.08543	0.02220

4. Optimization Design

The optimization algorithm is a procedure that changes parameters that can be adjusted step by step from the initial value to a value developed by the objective function[16]. Various gradient based algorithms have been implemented and developed. However, it was not effective for problems with many and uncertain values[17]. Therefore, gradient-free stochastic algorithms have been the basis for many studies in recent years.

Since there is a very complex relationship between the objective function and optimization variables, it is not possible to derive derivatives of the objective function according to these parameters analytically. This situation brings to mind the use of certain random optimization methods. In this article, a random optimization method called SPSA (Simultaneous Perturbation Stochastic Approximation) has been chosen to solve this problem. This method has been used successfully in similar complex optimization problems. SPSA is also economical because calculating the gradient of the objective function only needs to calculate it twice. In addition, this method is also successful in limited optimization problems.

Multivariate stochastic optimization plays an important role in the control and analysis of many engineering systems[18]. Since analytical solutions are rarely available, it is necessary to use mathematical algorithms for optimization problems in the real world. SPSA method has been developed for the solution of difficult multivariate optimization problems. SPSA is used in areas such as static parameter estimation, feedback control, signal processing and image processing and experimental design[19].

In this article, SPSA was used to design quadrotor differential morphing and PID coefficients. SPSA is useful for getting optimum and fast results. Getting optimum results is important for differential morphing and quadrotor control. SPSA is used the cost index for optimum results. Below is the cost index.

$$J = T_{rt} + T_{st} + OS \tag{23}$$

Cost index consists of rise time, settling time and overshoot values. Both longitudinal and lateral flight cost indexes are divided as follows.

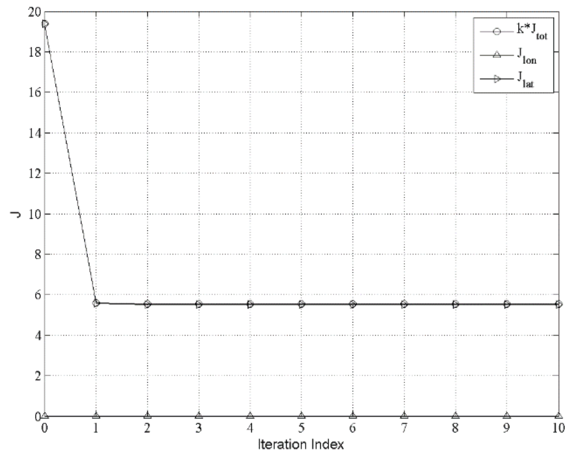
$$J_{long} = T_{rt_{long}} + T_{st_{long}} + OS_{long} \tag{24}$$

$$J_{lat} = T_{rt_{lat}} + T_{st_{lat}} + OS_{lat} \tag{25}$$

The total cost index is calculated as follows.

$$\%J_{tot_i} = J_{long_i} + \frac{J_{long_0}}{J_{lat_0}} + J_{lat_i} \tag{26}$$

The longitudinal and lateral flight control system is handled together for differential morphing. In our application, trajectory tracking of 1 degree for longitudinal flight and pi / 2 degree for lateral flight was applied. Cost index is considered together for longitudinal and lateral flight. The longitudinal and lateral flight control system is handled together to determine optimal coefficient values. A total of 8 values are determined with SPSA. Of these, 3 PID coefficients for longitudinal controller, 3 PID coefficients for lateral controller, and 2 differential morphing parameters of quadrotor. In Figure 3, cost function values, total cost, both longitudinal and lateral flight PID coefficient changes are given.



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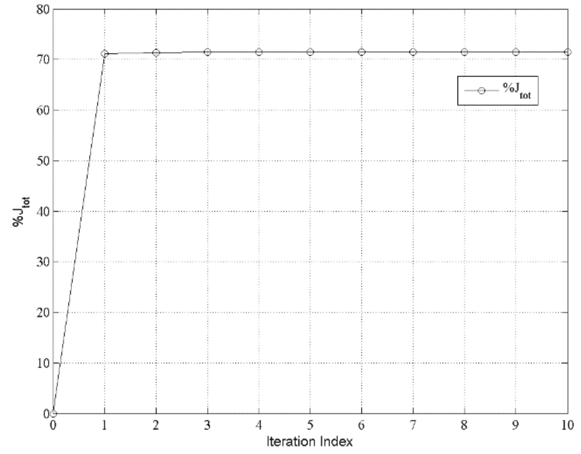

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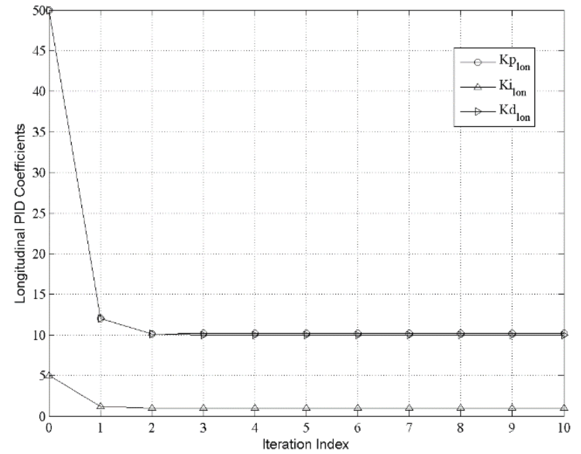

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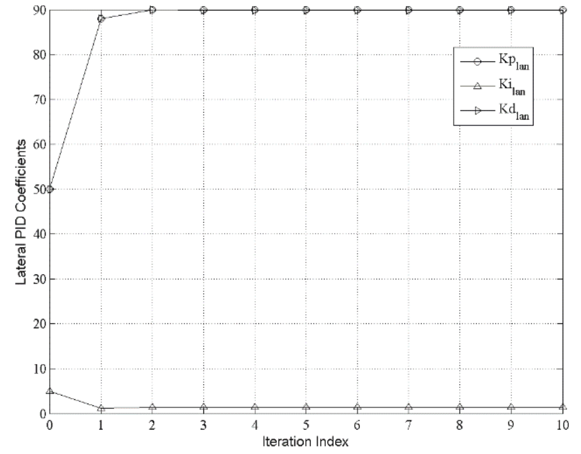
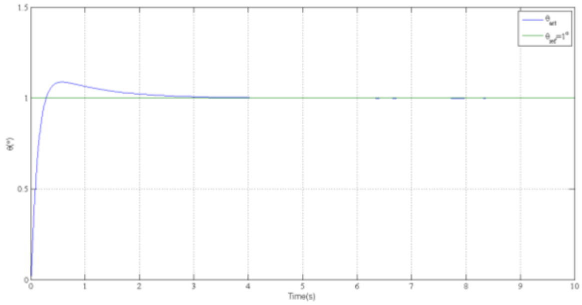


(d)

Figure 3. (a) Cost function (b) Total cost (c) Longitudinal flight PID (d) Lateral flight PID

Both longitudinal and lateral flight simulation in atmospheric turbulence are given in Figures 4 and 5. Figures 4 and 5 shows the desired trajectories for both longitudinal and lateral flight. In this study, since the hover flight was not considered, the related outputs were not taken into consideration. Linear and angular velocity simulation results did not show catastrophic behaviours.



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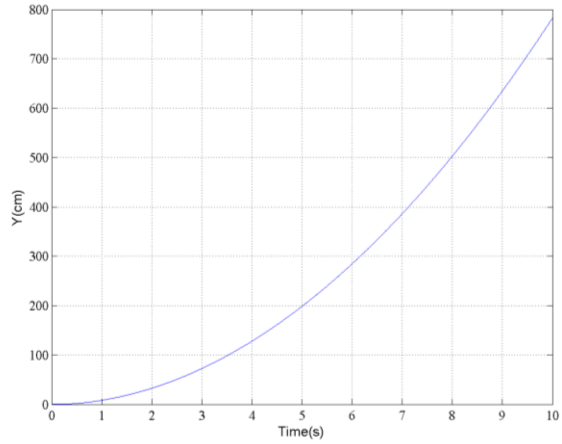

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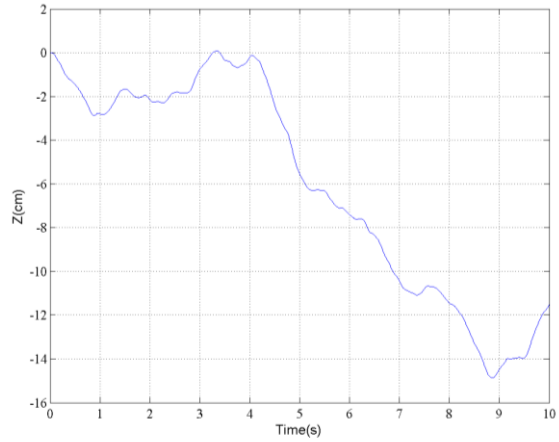

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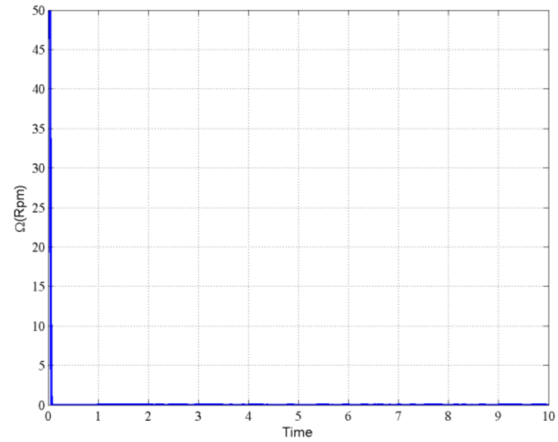
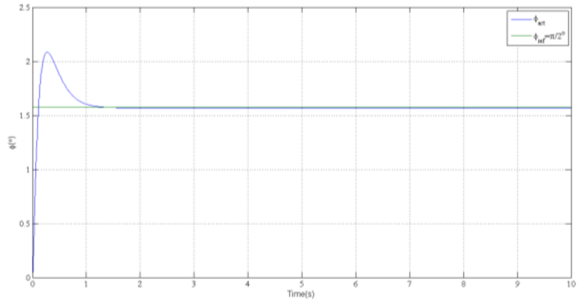


(d)

Figure 4. Responses of longitudinal movement



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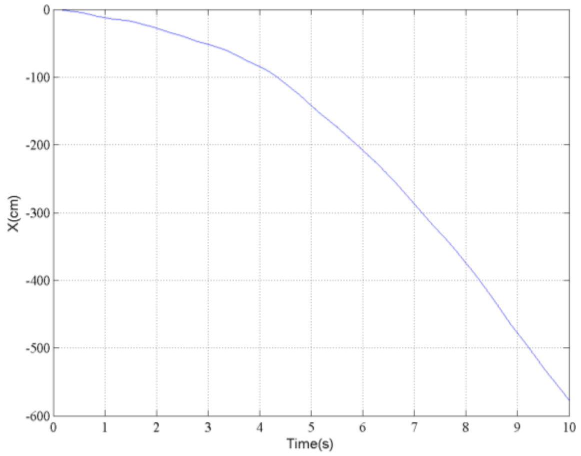

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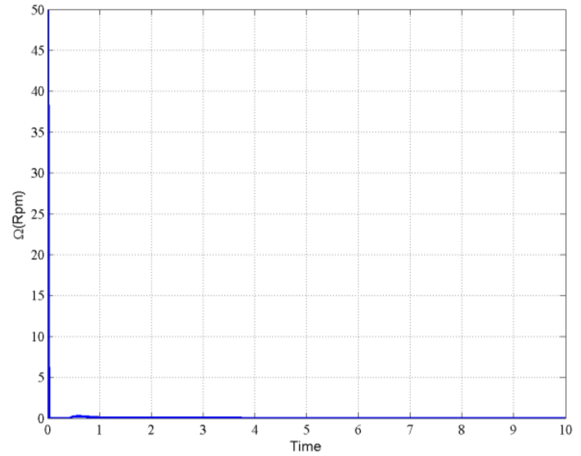

(c)

Figure 5. Responses of lateral movement

5. Conclusion

In this article, differential morphing is discussed for longitudinal and lateral flight. The quadrotor dynamics was created using the Newton-Euler approach. Quadrotor full model and morphing models were drawn in Solidworks program. Simulations were made in Matlab / Simulation environment by using state space model approach. PID algorithm was used as control algorithm. Using SPSA, morphing parameters and PID were determined.

With SPSA, the total cost index was improved by 71% compared to the quadrotor initial situation. Total cost index was sufficient for longitudinal and lateral flight. In the initial state, the PID coefficients selected for P = 50, I = 5 and D = 50 for longitudinal flight were determined as P = 10, I = 1 and D = 10 after SPSA. In the initial state, the PID coefficients selected for P = 50, I = 5 and D = 50 for lateral flight were determined as P = 90, I = 1 and D = 90 after SPSA. According to simulation results (Figure 8-a and Figure 9-a), PID coefficients did not show catastrophic behaviour and succeeded in following the desired trajectory. The differential morphing has been successfully integrated into the autopilot system and the desired results have been successfully achieved.

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Ethical Approval
Not applicable

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