The Eurasia Proceedings of Science, Technology,
Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2023

Volume 23, Pages 50-58

ICRETS 2023: International Conference on Research in Engineering, Technology and Science

Stochastic Longitudinal Autopilot Tuning for Best Autonomous Flight Performance of a Morphing Decacopter

Tugrul Oktay
Erciyes University

Fırat Sal
Iskenderun Technical University

Oguz Kose
Erzincan Binali Yıldırım University

Enes Ozen
Erciyes University and Hasan Kalyoncu University

Abstract: In this conference paper autonomous flight performance maximization of a morphing decacopter is considered by using stochastic optimization approach. For flight controller a PID based hierarchical control system is chosen. In this paper PID controller which is used for pitch angle is considered. In this application only longitudinal flight and longitudinal autopilot is considered where the pitch motion is in primary interest and the used controller is the pitch control. For optimization technique simultaneous perturbation stochastic approximation (i.e., SPSA) is selected. It is fast and safe in stochastic optimization problems when it is not possible to evaluate gradient analytically. At the end a cost function consisting terms that settling time, rise time and overshoot is minimized. A detailed graphical analysis is done in order to better present effect of morphing on longitudinal flight of decacopter flight. Moreover, the cost function consist of rise time, settling time, and overshoot during trajectory tracking.

Keywords: Decacopter, Stochastic optimization, Morphing, Autonomous flight performance.

Introduction

UAVs can be divided into two groups; fixed blades and rotary blades. The fixed-wing vehicle has a long range and a high flight time. On the other hand, rotary wing systems have good maneuverability; they can hover, land and take off vertically (Austin, 2011). Rotary-wing aircraft are named according to the number of rotors they have. Single rotor aircraft are called helicopters. It is the aircraft with the highest payload capacity. It has a swash plate mechanism to move the angle of attack in three-dimensional space. It also has a tail rotor. That's why it has so many mechanical connections. It is disadvantageous in terms of maintenance and manufacturability. Multi-rotor aircraft can control thrust and torque by simply varying the rotational speed of the propellers. It is easy to maintain, but has a lower payload and flight time compared to other types of aircraft. Their propellers are smaller than equivalent helicopter propellers. They can fly in harsh environments with lower risk (Abdelhay et al., 2019).

The main components of a multi-rotor aircraft are the frame, engines and propellers. Frame; carries the controller, sensor, power supply and communication means, carries the motor and propeller, which are located at the end of the frame arm. In a multi-rotor aircraft, the fixed rotors generate thrust vectoring from the ground up. When the multi-rotor aircraft increases the rotational speed of the propellers by the same amount, the vehicle

---

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

lifts. If the thrust vector is equal to the vehicle weight, it maintains its own height. Attitude behavior of the system; controlled by roll, pitch and yaw moments. A positive roll angle is obtained by increasing the speed of the left-hand propellers and decreasing the speed of the right-hand propellers. This causes the rolling moment. It allows the system to rotate around the X-axis. A roll angle is created by the speed differences. The pitching moment between the front and rear propellers is obtained in the same way. In a multi-rotor aircraft, each successive propeller rotates in the opposite direction to balance the drag moments and zero the torque with respect to the total z-axis. A multi-rotor aircraft can create an imbalance by varying the rotational speed of the propellers to achieve a yaw angle, with the total torque reaching a plus or minus value other than 0, yaw occurs (Prisacariu et al., 2016). The system is a system with missing actuators, referring to the fact that the number of inputs is small. The degrees of freedom are greater than the inputs of the system. The multi-rotor aircraft has six degrees of freedom (DOF), but only four inlets. Therefore, the two degrees of freedom depend on the others. When the tilt angles (roll and pitch angle) are changed, a horizontal component of the thrust vector is obtained, which moves the system in the X - Y plane (Alanezi et al., 2022).

In this study, the distance between the rotors of the ten rotor aircraft and the fuselage center of gravity may vary. While this allows the vehicle to expand in atmospheric disturbances and fly more stable, it has an active morphing feature that allows it to narrow and make aggressive maneuvers and avoid obstacles (Desbiez et al., 2017). In this study, by using the simultaneous perturbation stochastic approximation (SPSA) optimization algorithm, the values that stabilize the lateral and longitudinal flight of the ten rotor aircraft, in which the morphing amount and the best Proportional-Integral-Derivative (PID) coefficients are determined, are obtained (Kose et al., 2022). Decacopter is a rotary-wing aircraft that generates thrust thanks to its 10 propellers and the rotor that drives them. An algorithm and PID controller are being developed to obtain position and attitude control of the active deformable aircraft during flight. As a result, the performance of the ten rotor aircraft was improved and controlled by the SPSA optimization method of metamorphism parameters, PID gain parameters.

Method

Decacopter Design and Proposed Model

A decacopter consists of 10 rotors positioned equidistant from the center of mass. As in quadrotor, hexarotor and octorotor type UAVs, the speed of each rotor is controlled independently to perform decacopter movements. Decacopter has six degrees of freedom (6DOF). 6DOF defines the number of axes that a solid object can move in three-dimensional space. At the same time, 6DOF defines the configuration of a mechanical system with independent parameters. The decacopter also has four control inputs. Control inputs are used to define the movements on the axes. The control inputs are used for hover, longitudinal, lateral and yaw movements. Figure 1 shows the decacopter and its axes.

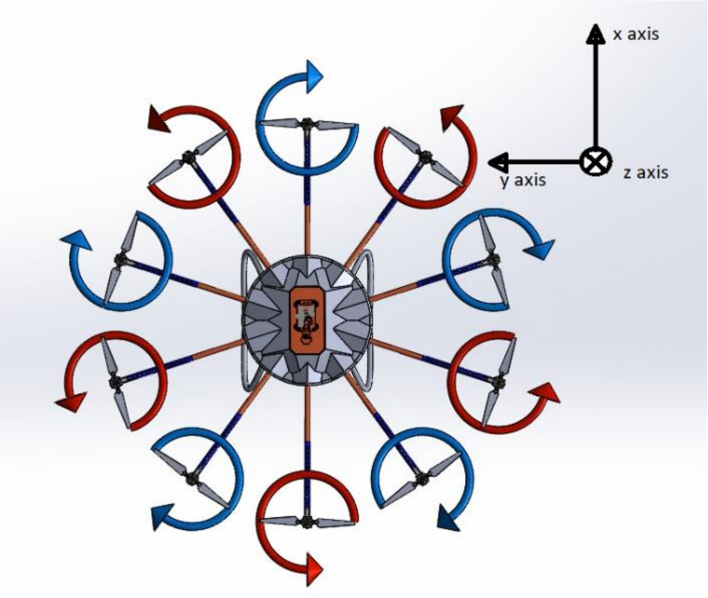


Figure 1. The decacopter and its axes

In Figure 1, there are two axes of the decacopter. These are earth and body frame. The decacopter performs its longitudinal movement on the y axis and this movement is indicated by θ. Longitudinal movement is used for the decacopter to perform forward and backward movement. In addition, in order to perform this movement, the decacopter must increase the speed of the x and y motors and decreases the speed of the k and l rotors according to the rotor sequences shown in Figure 1.

As with quadrotor, hexarotor and octorotor type UAVs, a mathematical model must be obtained for the decacopter type UAV. Newton's laws of motion and Euler's laws are used for the mathematical model of such UAVs (Mustapa, 2015). Accordingly, the mathematical position vectors (x, y and z) of the decacopter are shown in equations 1, 2 and 3 and the Euler angles (θ) are shown in equations 4, 5 and 6.

$$m\ddot{x} = -(T + w_x)\sin\theta \tag{1}$$

$$m\ddot{y} = (T + w_y)\cos\theta\sin\phi \tag{2}$$

$$m\ddot{z} = (T + w_z)\cos\theta\cos\phi - mg \tag{3}$$

$$I_x\ddot{\theta} = \tau_x + w_\theta \tag{4}$$

$$I_y\ddot{\phi} = \tau_y + w_\phi \tag{5}$$

$$I_z\ddot{\psi} = \tau_z + w_\psi \tag{6}$$

Equations 1-6 are nonlinearly expressed equations. In order to facilitate simulations and successful implementation of control algorithms, they are converted into linear form by various approaches. Accordingly, the linear equations of motion of the decacopter can be expressed as follows.

$$\ddot{x} = g\theta \tag{7}$$

$$\ddot{y} = -g\phi \tag{8}$$

$$\ddot{z} = -g + \frac{T}{m} \tag{9}$$

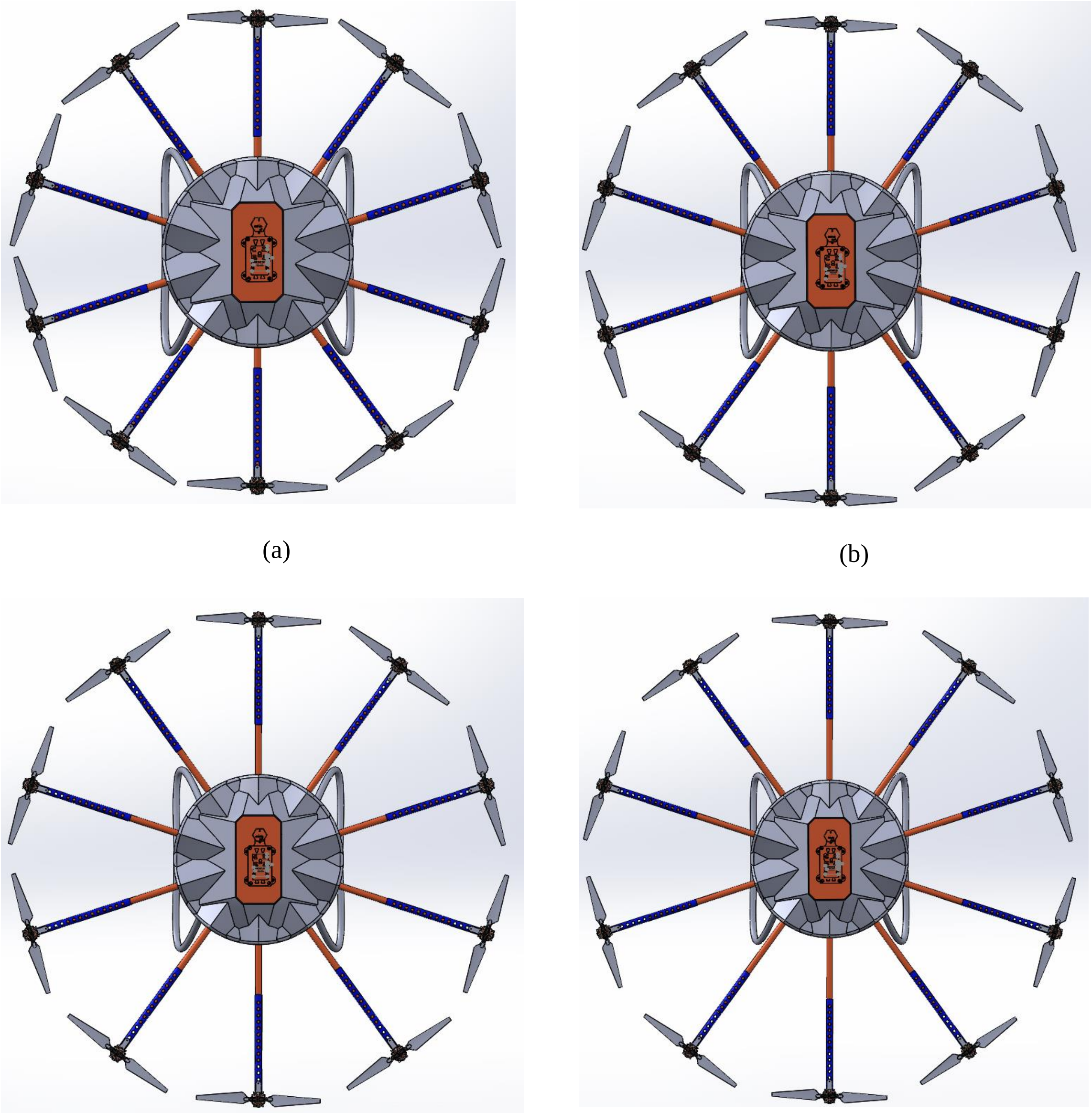
$$\ddot{\phi} = \frac{\tau_x}{I_x} \tag{10}$$

$$\ddot{\theta} = \frac{\tau_y}{I_y} \tag{11}$$

$$\ddot{\psi} = \frac{\tau_z}{I_z} \tag{12}$$

T is the total thrust generated by the 10 rotors. τ_x, τ_y and τ_z are the roll, pitch and yaw torques respectively. These torques and total thrust are the inputs required to control the desired motion of the decacopter. I_x, I_y and I_z are the moments of inertia of the decacopter.

The decacopter performs morphing by changing the arm lengths during its flight. Morphing is a developmental feature that has recently started to be applied in UAVs. Morphing is a change in the geometry of the UAV before or during flight (Oktay and Kose, 2020). If the UAV changes its geometry before flight, such as changing the length of the arm or changing another geometric feature, this is characterized as passive morphing (Oktay and Coban, 2017). If the UAV performs this while in the air during flight, this is called active morphing (Kose and Oktay, 2021). In this study, the decacopter performed morphing by simultaneously lengthening and shortening the arm lengths during flight. With morphing, the arm length of the decacopter can be shortened by a minimum of 65 cm and lengthened by a maximum of 80 cm. Examples of the morphing situation are shown in Figure 2.



(a) (b)

(c) (d)

Figure 2. (a) 65 cm arm length, (b) 70 cm arm length, (c) 75 cm arm length, (d) 80 cm arm length

With morphing, the distances of the arms to the axes of rotation will change. However, there will also be changes in the values of the moments of inertia. Since moments of inertia are divisors in equations 10, 11 and e12, they will have an effect on the equations of motion and therefore on longitudinal flight. The new moment of inertia calculation for each morphing condition is shown below:

$$I_x = \frac{1}{3} * \frac{m}{10} * 4 * (L * \sin(\alpha 1))^2 + \frac{1}{3} * \frac{m}{10} * 4 * (L * \sin(\alpha 2))^2 \tag{13}$$

$$I_y = \frac{1}{3} * \frac{m}{10} * 4 * (L * \sin(\alpha 1))^2 + \frac{1}{3} * \frac{m}{10} * 4 * (L * \sin(\alpha 2))^2 + \frac{1}{3} * \frac{m}{10} * 2 * L^2 \tag{14}$$

$$I_z = \frac{1}{3} * m * L^2 \qquad (15)$$

SPSA and Control Algorithm

There are several unknown parameters in decacopter control. These parameters are control algorithm coefficients and morphing ratio. The unknown parameters need to be obtained quickly and reliably (Spall, 1998). For this purpose, SPSA algorithm is preferred. SPSA algorithm is an algorithmic method used to optimise systems with multiple unknown parameters(Maryak et al., 2001). SPSA is a global minimisation search method. No matter how large the size of the optimization problem is, SPSA makes only two predictions in each iteration(Ko et al., 2008). This feature distinguishes it from similar algorithms.

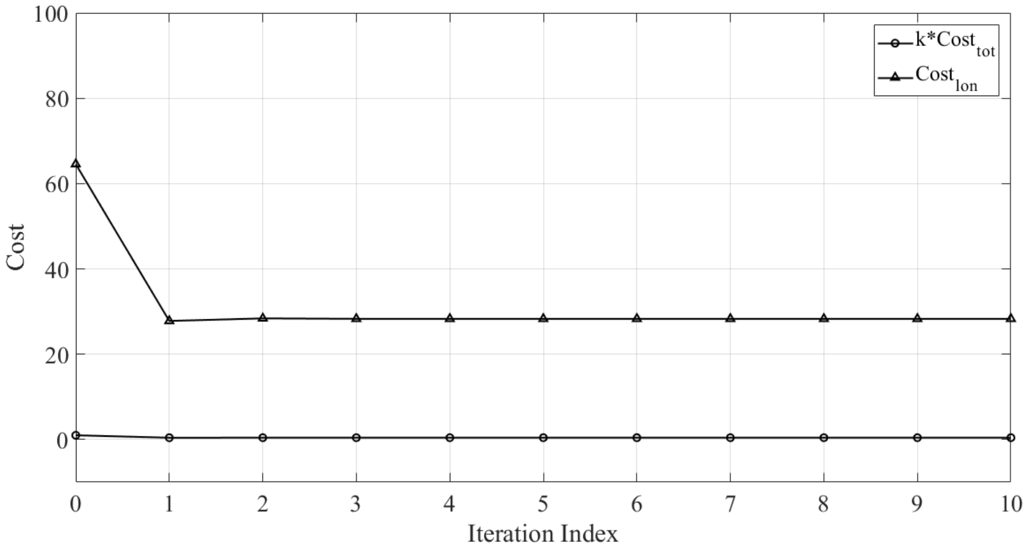
Since there is a complex relationship between the decacopter control algorithm parameters and morphing, it is difficult to calculate or obtain these values. For this purpose, the following cost function is generated simultaneously for the decacopter longitudinal flight.

$$J_{long} = T_{rt_{long}} + T_{st_{long}} + OS_{long} \qquad (16)$$

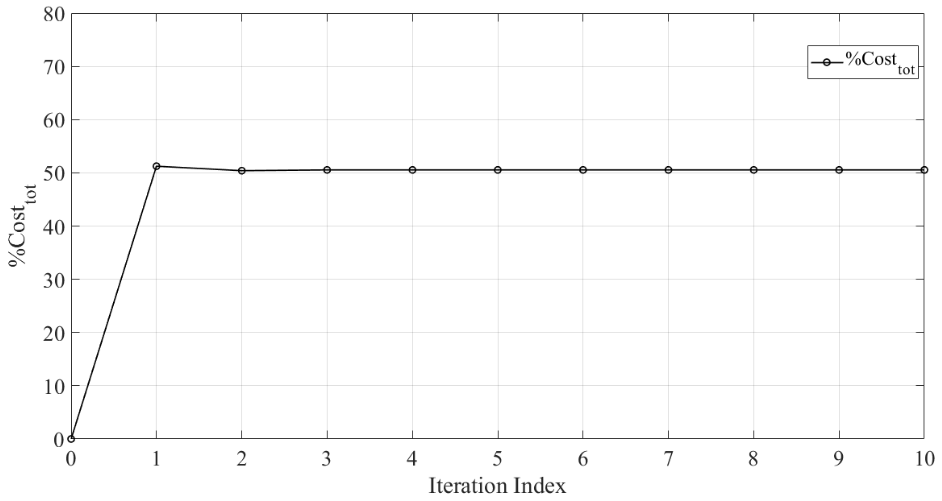
The cost function is a function of decacopter rise time, settling time and overshoots values. The control algorithm coefficients estimated by SPSA are effective in longitudinal control of the decacopter. PID control algorithm is used for longitudinal control of the decacopter. PID is a feedback control loop mechanism widely used in industrial systems(Haddadi et al., 2015) . The PID control algorithm continuously calculates an error value. The error value consists of the difference between the set point of the system and the feedback value. The error value is multiplied by K_p proportional, K_i integral and K_d derivative terms and transferred to the system output. In this study, the SPSA algorithm estimated the K_p, K_i ve K_d values required for the control algorithm.

Conclusion

In this study, the longitudinal flight control of a decacopter type UAV with morphing is implemented using SPSA and PID control algorithms. The full model of the decacopter was drawn in Solidworks and the mass and arm length information of the decacopter were obtained. The mathematical model of the decacopter was created using the Newton-Euler approach. Linear equations of motion were used for the state space model approach. Determination of the decacopter morphing rate and control algorithm coefficients were used for longitudinal flight. Here, the SPSA optimization method was used to estimate the parameters. As shown in Figure 3, the cost index and total cost index were minimized by SPSA.



(a)



(b)

Figure 3. (a) Cost index, (b) Total Cost index

As can be seen in Figure 3, the cost index was improved by 50% and the total cost index was improved by 50%. The arm length values predicted by the SPSA optimization method in each iteration, which was run for 11 iterations in total, are shown in Figure 4.

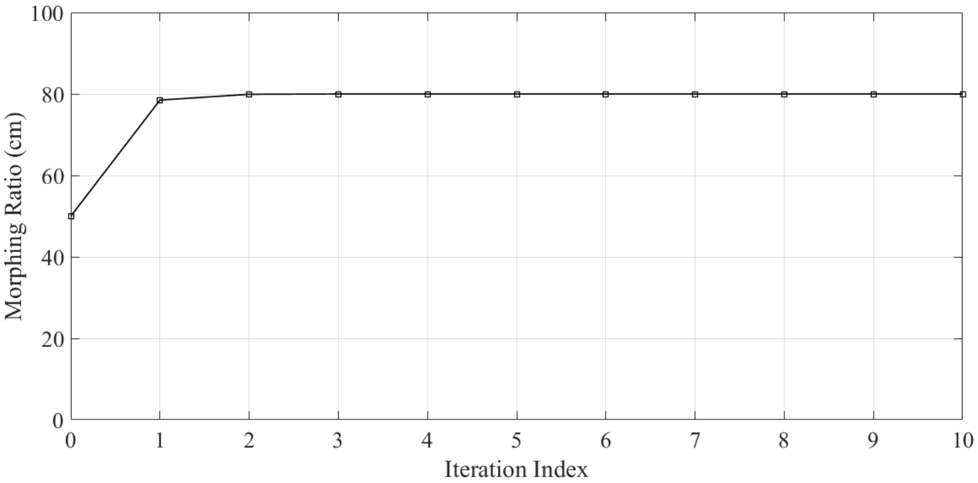


Figure 4. Morphing rate at each iteration

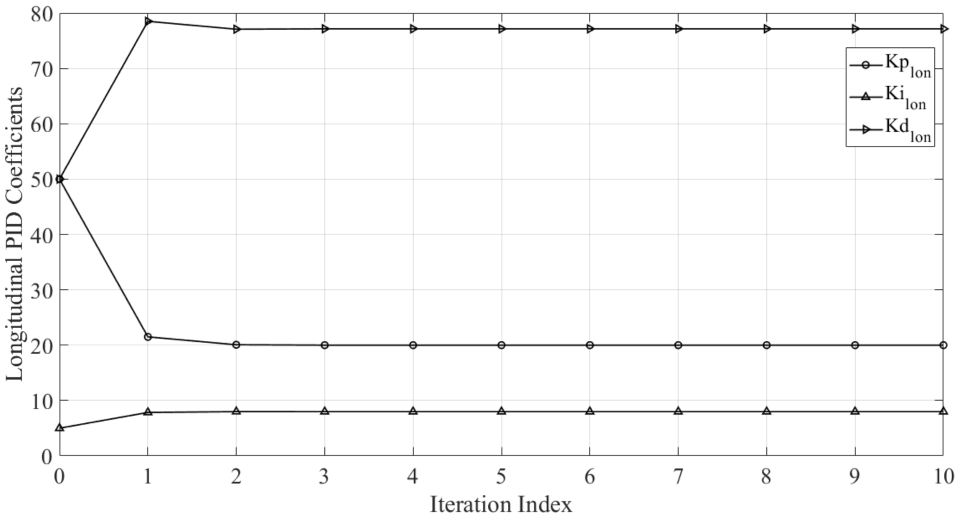


Figure 5. PID coefficients

The PID coefficients obtained in 11 iterations are shown in Figure 5. The rise time, settling time and overshoot values, which are the design performance criteria in the simulations performed at each iteration, are shown in Figure 6.

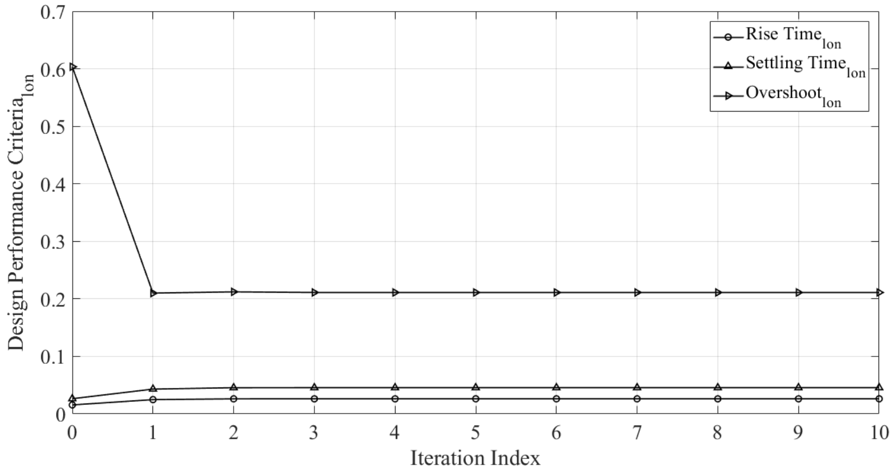
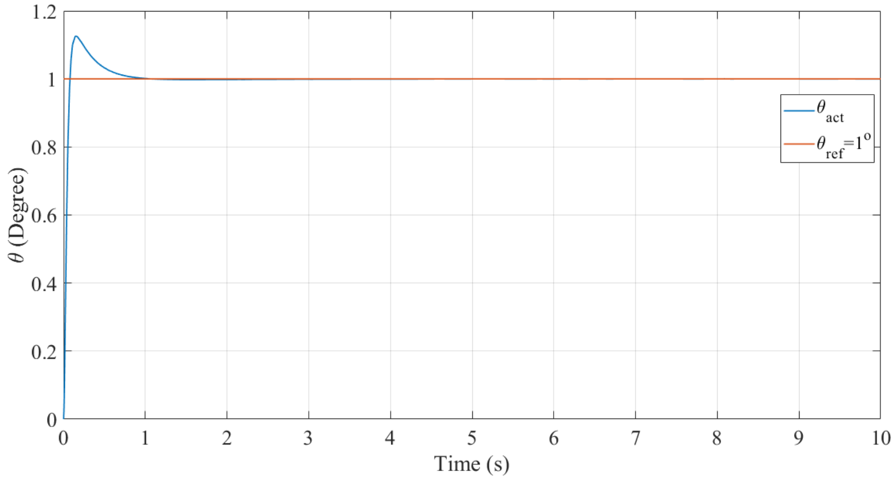
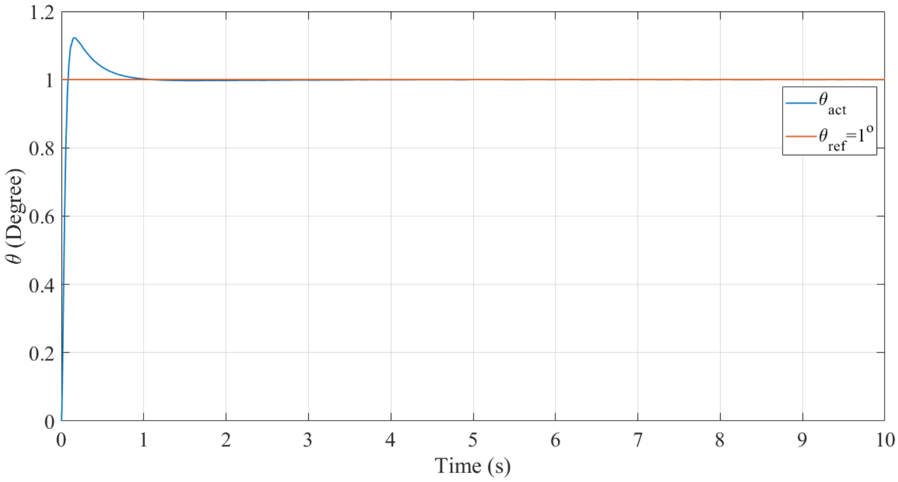


Figure 6. Design performance criteria

The second and fifth iteration simulations were performed with all the data obtained. In the simulation, the decacopter was asked to follow a 1° trajectory for longitudinal flight. Figure 7 shows the simulation outputs.



(a)



(b)

Figure 7. (a) Simulation 2, (b) Simulation 5

The decacopter successfully followed the given trajectory. However, when the design performance criteria were examined, it was found that there was no excessive behavior in the settling and rise time values while there was a serious decrease in the ascent value. This showed that longitudinal flight with morphing was successfully implemented in the decacopter.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

*This article was presented as an oral presentation at the International Conference on Research in Engineering, Technology and Science (www.icrets.net) held in Budapest/Hungary on July 06-09, 2023.

*This work has been supported by Erciyes University Scientific Research Projects Coordination Unit under grant number FBA-2022-12375.

References

Abdelhay, S., & Zakriti, A. (2019). Modeling of a quadcopter trajectory tracking system using PID controller. *Procedia Manufacturing*, *32*, 564–571.

Alanezi, M. A., Haruna, Z., Sha'aban, Y. A., Bouchekara, H. R. E. H., Nahas, M., & Shahriar, M. S. (2022). Obstacle avoidance-based autonomous navigation of a quadrotor system. *Drones*, *6*(10), 1–19.

Austin, R. (2011). *Unmanned aircraft systems: UAVS design, development and deployment*, 54. John Wiley & Sons.

Desbiez, A., Expert, F., Boyron, M., Diperi, J., Viollet, S., Ruffier, F., Desbiez, A., Expert, F., Boyron, M., Diperi, J., Viollet, S., Desbiez, A., Expert, F., Boyron, M., Diperi, J., Viollet, S., & Ruffier, F. (2017). *X-Morf : a crash-separable quadrotor that morfs its X-geometry in flight To cite this version : HAL Id : hal-01644528*.

Haddadi, S. J., Emamagholi, O., Javidi, F., & Fakharian, A. (2015). Attitude control and trajectory tracking of an autonomous miniature aerial vehicle. *2015 AI and Robotics, IRANOPEN 2015 - 5th Conference on Artificial Intelligence and Robotics*.

Ko, H.-S., Lee, K. Y., & Kim, H.-C. (2008). A simultaneous perturbation stochastic approximation (SPSA)-based model approximation and its application for power system stabilizers. *International Journal of Control, Automation, and Systems*, *6*(4), 506–514.

Kose, O., & Oktay, T. (2021). *Combined quadrotor autopilot system and differential morphing system design*. *Journal of Aviation*, *5*(2), 64–71.

Kose, O., & Oktay, T. (2022). Hexarotor yaw flight control with SPSA , PID algorithm and morphing. *International Journal of Intellıgent Systems and Applıcatıons ın Engıneerıng*, *10*(2), 216–221.

Maryak, J. L., & Daniel, C. C. (2001). *Global random optimization by simultaneous perturbation stochastic approximation*. In *Proceedings of the 2001 American control conference.(Cat. No. 01CH37148) (Vol. 2, pp. 756-762). IEEE.*

Mustapa, M. Z. (2015). Altitude controller design for quadcopter UAV. *Jurnal Teknologi*, *74*(1), 187–194.

Oktay, T., & Coban, S. (2017). Simultaneous longitudinal and lateral flight control systems design for both passive and active morphing TUAVs. *Elektronika Ir Elektrotechnika*, *23*(5), 15–20.

Prisacariu, V., Air, R., & Academy, F. (2016). *Introductıon morphıng technology ın unmanned aırcraft vehıcles* In *International Conference of Scientific Paper, AFASES.*

Spall, J. C. (1998). An overview of the simultaneous perturbation method for efficient optimization, *Johns Hopkins Apl Technical Digest*, *19*(4), 482-492.

Oktay T. & Kose. O. (2020). Simultaneous quadrotor autopilot system and collective morphing system design. *Aircraft Engineering and Aerospace Technology*, *92*(7), 1093–1100.

Author Information

Tuğrul Oktay
Erciyes University
Kayseri, Turkey
Contact e-mail: *tugruloktay52@gmail.com*

Fırat Şal
Iskenderun Technical University
Iskenderun, Turkey

Oğuz Köse
Erzincan Binali Yıldırım University
Merkez / Erzincan, Turkey-

Enes Özen
Erciyes University and Hasan Kalyoncu University
Kayseri, Turkey and Gaziantep, Turkey

To cite this article:

Oktay, T. Sal, F. Kose, O. & Ozen, E. (2023). Stochastic longitudinal autopilot tuning for best autonomous flight performance of a morphing decacopter. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 23*, 50-58.