International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Hexarotor Yaw Flight Control with SPSA, PID Algorithm and Morphing

Oguz Kose*[1], Tugrul Oktay[2]

Submitted: xx/xx/202x Accepted : 16/04/2022

Abstract: In recent years, the interest in unmanned aerial vehicles (UAV) has increased. They have penetrated into all areas of life. However, studies on UAV control have been a frequently discussed topic by researchers. In this study, a hexarotor in which yaw flight is tried to be controlled by changing the arm lengths during flight (morphing) is discussed. The hexarotor mathematical model is linearly derived using Newton's equations of motion. The equations of motion are modeled using the state space model approach. Hexarotor has been drawn in Solidworks program in accordance with the reality of all morphing states. Morphing estimation and accordingly proportional-integral-derivative (PID) coefficients were estimated using Simultaneous Perturbation Stochastic Approximation (SPSA). SPSA was preferred because it converged to the optimum result faster than similar algorithms. Hexarotor simulations were performed in Matlab/Simulink environment. Hexarotor yaw flight stability was achieved by minimizing the SPSA generated cost function based on design performance criteria. The cost function converged in 3-4 iterations and approached the optimum result. Accordingly, the design performance criteria have also improved and successfully followed the given trajectory.

Keywords: *Control, Hexarotor, Matlab, Morphing, Newton, PID, SPSA, Solidworks, UAV*

1. Introduction

UAVs are aircraft that can be controlled remotely by the pilot or are automated systems that allow them to fly autonomously or that can fly on a pre-planned route. As UAV technology develops, especially rotary-wing UAVs, which are the main subject of this study, the demands for these devices increase in every field. Today, UAVs are used in every field from entertainment to war, from transportation to the film industry[1-2]. With the presence of UAVs in our lives so much, researchers have focused on research on UAV control. However, in addition to the control, the changing UAV sizes also attracted the attention of researchers. UAVs can vary in size according to the task they do, rather than their standard size. E.g; It is not desirable for a UAV to be used in payload and reconnaissance to have the same dimensions for both missions. Because while exploring, its dimensions need to change while it must enter through a cave or window. This results in changes in the wingspan or arm length of rotary wing UAVs during flight.

In recent years, a lot of work has been done on changing UAV dimensions or arm lengths. Kose and Oktay [3–5] studied the modelling and control of quadrotor, especially quadrotor UAV, as well as the effect of varying arm lengths, namely the morphing state, on flight. In their study, they examined the effect of morphing state on quadrotor longitudinal, lateral and hover flights. They obtained the mass and moment of inertia information by drawing the full model of the quadrotor in Solidworks program in accordance with the reality. The quadrotor model was created linearly using the state space model approach in Matlab/Simulink environment by utilizing Newton's laws of motion. In their studies, the effect of the morphing state was analyzed separately for each flight and shared with graphic and numerical expressions. The rise time, settling time and overshoot values of the simulations in which the arm lengths are assumed to be the same in all three flight conditions are considered as the determining factors. Accordingly, morphing state had no effect on quadrotor longitudinal and hover flight, but had an effect on lateral flight. Rise time, settling time and overshoot values increased in lateral flight. Studies on hexarotor control also find wide coverage in the literature. Leishman et al [6] discussed the navigation and control of a hexarotor equipped with vision based in non-GPS areas. In a platform created, they compared navigation and yaw movement control without hexarotor GPS and by considering cases with EKF and without EKF. They also made navigation with computer vision. Newton's equations of motion and PID algorithms were used for hexarotor modelling and control. Rosales et al. [7] consider a new PID algorithm approach for the hexarotor trajectory tracking task. They considered the non-linear motion of the hexarotor in their work. The stability of the PID controller was developed with an adaptive neural technique and its accuracy was confirmed by Lyapunov discrete theory. A neural description of the dynamical model of the hexarotor is also done for back propagation of output errors to adjust the PID gains to reduce control errors. They showed that the proposed algorithm can be considered as a general solution for the control of nonlinear systems and especially when the dynamics of UAV systems are variable. Arellano-Muro et al [8] discussed the hexarotor dynamic nonlinear model and its control. The control algorithm is based on the backstepping technique and is applied to the trajectory tracking problem. The aerodynamic forces acting on the hexarotor, the wind and other external factor parameters are estimated by the sliding mode. The proposed control technique gave sufficient results due

[1] Gumushane University, School of Applied Sciences, Gumushane, Türkiye, ORCID ID : 0000-0002-8069-8749*
[2] Erciyes University, Department of Aeronautical Engineering, Kayseri, Türkiye, ORCID ID : 0000-0003-4860-2230
** Corresponding Author Email: oguzkose24@gmail.com*

to the strength of the backstepping technique, as external winds and external parameters can be controlled. It also confirmed the robustness of the proposed technique in simulations. Studies on UAV morphing have been carried out using different algorithms. In Konar[9], morphing UAV was handled simultaneously with maximum acceleration and endurance ABC algorithm. With the proposed system, various features related to propeller diameter, propeller pitch and battery were accepted as input parameters to the model. Maximum acceleration and endurance are accepted as output parameters. They have shown that the ABC algorithm is an effective method of maximum acceleration and endurance and reduces the cost. Konar et al. [10] used the ABC algorithm to develop the thrust-torque ratio of an unmanned helicopter. The maximum thrust-torque ratio corresponding to the optimum input values was tried to be obtained by using the ABC algorithm. For this, a four-input and single-output model was created. With the proposed model and algorithm, 31% improvement was achieved.

In this study, the yaw flight of the hexarotor, which has six rotors belonging to the rotary wing category, is discussed. Today, it is important for usability that UAVs vary in size for various missions. The proposed method in this study is to ensure that a hexarotor, which starts flying, is prepared for a desired mission during air flight by changing the arm lengths during flight. For the hexarotor modeling, a linear model was created by using Newton's laws of motion. The linear model was simulated in the Simulink environment using the state space model approach[11]. As the control algorithm, the PID control algorithm, which is frequently used in the industry and is easy to use, is used. The change of hexarotor arm length can be termed as morphing. In addition, when the arm lengths change, the moment of inertia values also change because the distance from the axis of rotation changes. Drawings of 20 different arm lengths of hexarotor were drawn in Solidworks program and moment of inertia values were obtained from the drawings. The length of the arm was determined by SPSA. Proper determination or estimation of the parameters that play an active role in the control of the UAV is important for the stable flight of the UAV. Various parameters are estimated using many optimization algorithms in the literature. However, the important thing here is to be able to converge to the optimum result quickly and within satisfactory limits, depending on the cost function. Since SPSA makes only two predictions in each iteration, it is preferred because it converges faster than similar algorithms. The arm length varies between 0.37 m and 0.65 m. The moments of inertia of the nearest arm length are taken according to the arm length estimated by SPSA. The moments of inertia obtained from the drawings are sufficient since the gap value is low. In addition, PID gain values, which are the control algorithms, vary depending on the morphing rate. PID gains are also estimated by SPSA according to the morphing rate. With the proposed method, hexarotor yaw flight was tried to be controlled according to different arm lengths.

2. Hexarotor Model, Morphing and Control Algorithm

2.1. Hexarotor Model

The Hexarotor is a six-rotor aircraft, as shown in Figure 1. The Hexarotor has six degrees of freedom and is an under-actuated system. The six degrees of freedom consist of translational and rotational motion in the three-dimensional axis.

Hexarotor uses earth and body frame to define position and orientation on the three-dimensional axis($x, y, and\ z$). Earth frame is a fixed frame that does not move. Body frame is used to control angel orientation.

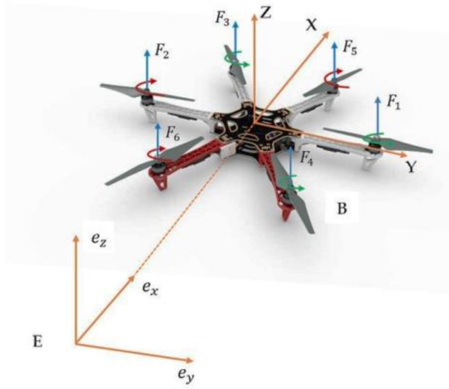


Fig. 1. Hexarotor model [12]

The hexarotor needs to vary the rotor speeds in order to perform its basic movements. The yaw(ψ) motion considered in this study is the motion that takes place on the z axis. Here, the yaw motion occurs with clockwise or counterclockwise rotation. While 3 of the rotors rotate clockwise, the other 3 rotate counterclockwise. The speed of the rotors rotating in the direction in which the yaw motion is desired is increased and the speed of the reverse rotating rotors is decreased.

To describe the hexarotor dynamic model, the structure is assumed to be symmetrical and rigid. Accordingly, the hexarotor mathematical model can be put forward with the Newton Euler approach[13]. In this study, linear motion equations for hexarotor deflection motion are discussed. Accordingly, the complete mathematical model of the hexarotor can be written as follows.

$$\ddot{x} = g\theta \tag{1}$$

$$\ddot{y} = -g\phi \tag{2}$$

$$\ddot{z} = -g + \frac{U_1}{m} \tag{3}$$

$$\ddot{\phi} = \frac{U_2}{I_x} \tag{4}$$

$$\ddot{\theta} = \frac{U_3}{I_y} \tag{5}$$

$$\ddot{\psi} = \frac{U_4}{I_z} \tag{6}$$

g gravitational acceleration, m hexarotor mass, I_x, I_y and I_z respectively hexarotor moment of inertia, U_1, U_2, U_3, U_4 represent the hexarotor control inputs[14]. Since yaw flight is considered in this study, only the U_4 input will be used.

$$U_4 = d(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2 - \omega_5^2 + \omega_6^2) \tag{7}$$

2.2. Hexarotor Morphing

Morphing is called as changes made in the shape of aircraft during or before flight[15]. Morphing may vary depending on the design of the aircraft[16 - 17]. E.g; while changing the arm angles or changing the arm lengths in quadrotor type aircraft[18], it can be done by changing the wing lengths in fixed-wing aircraft[19]. In the hexarotor, on the other hand, morphing is performed by changing the arm lengths simultaneously. Hexarotor arm length was determined to be 0.5 m in flight starting condition. With

Morphing, the arm length was changed between 0.37 m and 0.65 m. Since morphing takes place during flight, it is considered as active morphing. Examples of hexarotor morphing states are shown in Fig 2.

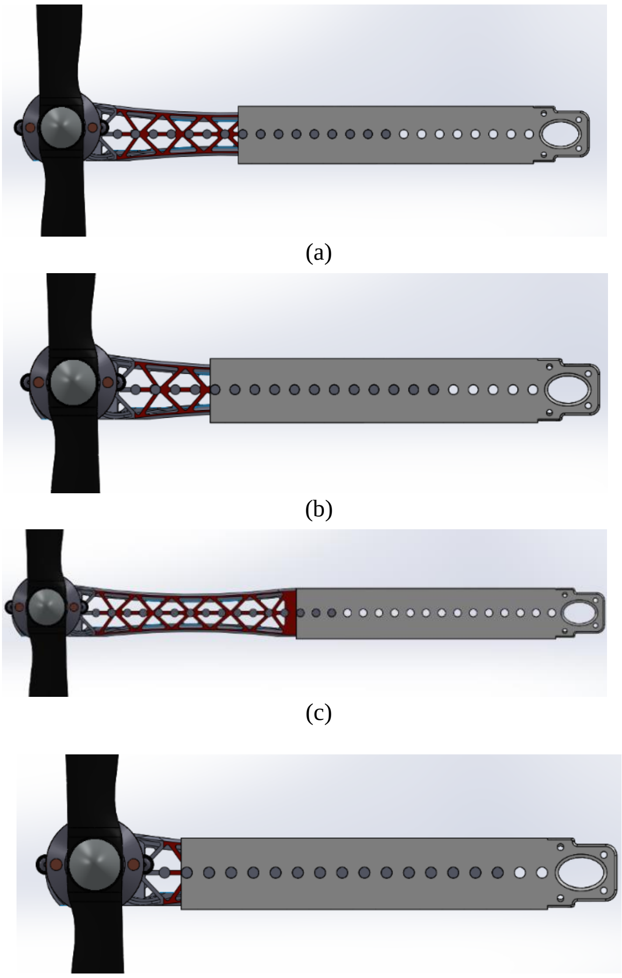


Fig. 2. (a) Initial condition, (b) Morphing 1, (c) Morphing 2, (d) Morphing 3

Table 1. Moment of inertia

Arm Length(m)	$I_x(kg*m^2)$	$I_y(kg*m^2)$	$I_z(kg*m^2)$
0,37	2,93	2,95	0,22
0,38	1,89	1,88	0,22
0,4	1,89	1,89	0,22
0,41	1,9	1,94	0,28
0,43	2,96	2,96	0,26
0,44	1,92	1,92	0,28
0,46	2,98	2,98	0,3
0,47	2,99	3,02	0,35
0,49	1,95	1,97	0,36
0,5	3,01	3,02	0,37
0,52	1,97	1,97	0,39
0,53	3,03	3,04	0,41
0,55	3,05	3,05	0,43
0,56	2,02	2,01	0,47
0,58	2,02	2,02	0,49
0,59	2,04	2,03	0,51
0,61	2,05	2,05	0,55
0,62	2,07	2,08	0,59
0,64	3,13	3,14	0,61
0,65	3,15	3,15	0,63

In the case of morphing, while the arm lengths change, the hexarotor mass remains constant, changes occur on the moments of inertia where the arm lengths change their distance from the axis of rotation. Moments of inertia were obtained from the models of morphing states drawn in Solidworks program. The moments of inertia obtained from the models drawn in the Solidworks program are given in Table 1.

2.3. Control Algorithm

PID control algorithm is a widely used algorithm in control applications and industrial systems. It can be easily applied to linear control mechanisms. PID control algorithm coefficients (k_p, k_i and k_d) are preferred because of their easy adjustment, design simplicity and robustness. When applied to highly complex systems such as the Hexarotor, the model can produce poor results if not simplified properly[20].

PID control includes proportional-integral-derivative terms. These three terms represent PID basic elements. These three elements each do a different job and have different effects on the system. Proportional control deals with current control error, integral control deals with estimation of future errors, while derivative effect deals with past errors. With the sum of these three effects, PID control emerges. PID control can be shown as in Fig 3.

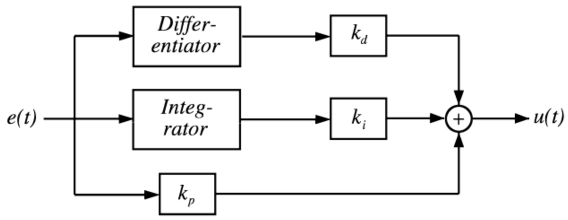


Fig. 3. PID controller[21]

The system error $e(t)$ is tried to be minimized for $u(t)$ by passing through three effects. The mathematical expression for the PID controller for yaw flight can be shown as follows.

$$u(t) = K_p\, e(t) + K_i \int_0^t e(t)d(t) \; + K_d\, de(t)/d(t) \tag{8}$$

Here, the coefficients k_p, k_i and k_d are important parameters for PID to be effective. If these parameters are not selected properly, PID control may not give the desired results. Since the PID coefficients change according to the arm lengths in this study, the coefficients were determined by SPSA.

3. SPSA Based Solution

SPSA is an optimization algorithm that uses only the measures of the objective function to search for solutions[22]. SPSA is used in many areas such as modelless predictive control[23], air traffic control[24] signaling timing for vehicles[25]. In this study, the estimation of arm length and PID coefficients in case of hexarotor morphing was performed with SPSA.

When SPSA seeks a solution, it starts with guess first and updates iteratively to improve performance. The problem solved with SPSA can be expressed as follows.

$$min\ (f(\theta)) \tag{9}$$

where $f(\theta)$ is the objective function. θ is the parameter vector of length D. θ consists of real numbers and is a vector with upper and lower limits for each element. The SPSA general recursive form is as follows.

$$\hat{\theta}_{k+1} = \hat{\theta}_k - a_k \hat{g}_k(\hat{\theta}_k) \tag{10}$$

where, $\hat{g}_k(\hat{\theta}_k)$ is the estimation of the gradient vector $g(\theta)$ at k iterations based on the measurements of the objective function. $\hat{g}_k$

is the estimate of the gradient and a_k is a positive number. The gradient estimation in each iteration of SPSA is as follows.

$$\hat{g}_{ki}(\hat{\theta}_k) = \frac{y(\hat{\theta}_k + c_k\Delta_k) - y(\hat{\theta}_k - c_k\Delta_k)}{2c_k\Delta_{ki}} \tag{11}$$

where, c_k is a positive number and Δ_k is the perturbation vector. Morphing rate and PID coefficients are obtained simultaneously with SPSA for yaw flight. Optimum results are important for stability and performance of yaw flight. SPSA determines the optimum results based on the design performance criteria of rise time, settling time and overshoot. This depends on minimizing the cost index. Then, depending on the design performance criteria, the cost function can be written as follows.

$$J = T_{rt} + T_{st} + OS \tag{12}$$

The cost index for the yaw flight would be as follows. In this study, since the smallest cost index belongs to T_{st}, it is tried to minimize the cost index by approximating all the values that make up the cost index.

$$J_{yaw} = a/b * T_{rt_{yaw}} + T_{st_{yaw}} + c/d * OS_{yaw} \tag{13}$$

The aim of optimization algorithms is to minimize the cost index. The total cost index is subtracted from the first cost index and divided by the first cost index. Since the output value is very small, it is multiplied by 100 to obtain the total cost index[26]. The total cost calculated for the yaw flight can be calculated as follows.

$$\%J_{tot} = \left(\frac{Cost(1) - Cost(i)}{Cost(1)}\right) * 100 \tag{14}$$

The a, b, c, and d weights are derived from the design performance criteria and are used to minimize the function. a, b, c, and d weight values were obtained by taking the rise time, settling time, overshoot and peak values in the first iteration, respectively.

Table 2. Weight of values in SPSA

Weight	Values
a	0.0128
b	0.0702
c	0.0128
d	23.7

The improvement in the cost index and the cost of yaw flight are shown in Fig 4.

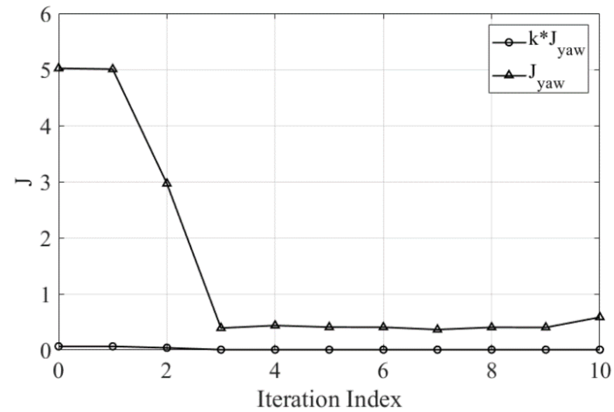


Fig. 4. Improvement in cost index, yaw flight cost index

The main purpose of SPSA is to improve the cost in each iteration. This is possible by calculating $\%J_{tot}$ in each iteration. The $\%J_{tot}$ calculated at each iteration is given in Fig. 5.

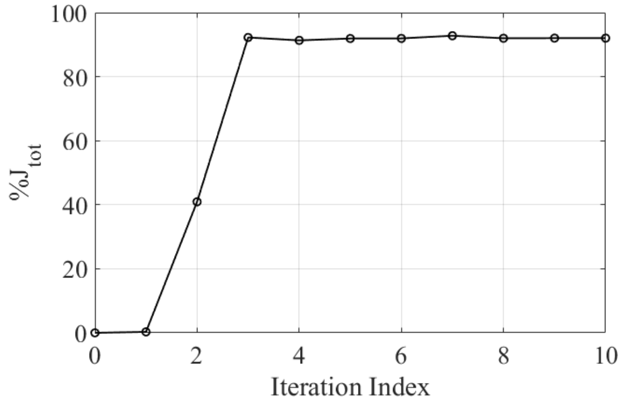


Fig. 5. Total cost improvement in each iteration

Morphing ratio was determined as 0.5 m at the beginning of SPSA. The best morphing rate was obtained by estimating different morphing values in each iteration. Morphing rate can be minimum 0.37 m and maximum 0.65 m. Accordingly, the estimated morphing rates in each iteration are given in Figure 6.

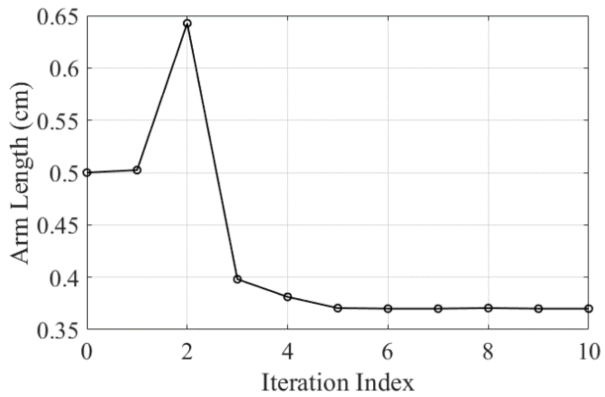


Fig. 6. Morphing ratio(arm length) in each iteration

For yaw flight, the PID coefficients also vary according to the morphing ratio estimated at each iteration. Since there is a change in the hexarotor solid body model in each estimated morphing ratio, the PID coefficients should be updated as well. At the beginning of SPSA, the PID coefficients were given as 50, 5 and 50, respectively. The estimated PID coefficients according to the morphing ratio in each iteration are given in Figure 7.

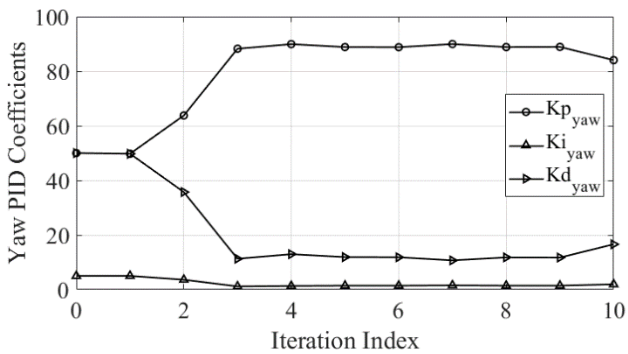


Fig. 7. PID coefficients in each iteration

The stability of yaw flight depends on the design performance criteria of rise time, settling time and overshoot obtained from the PID structure. The better the PID coefficients are selected, the better the design performance criteria will yield. The design performance criteria according to the estimated PID coefficients in each iteration are given in Fig 8.

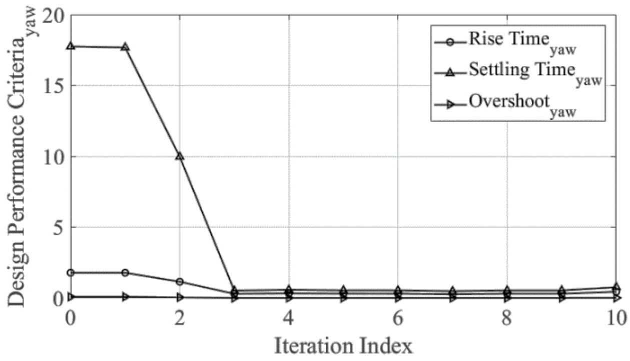
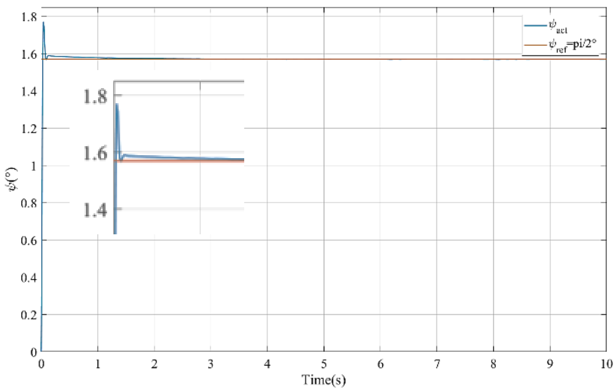
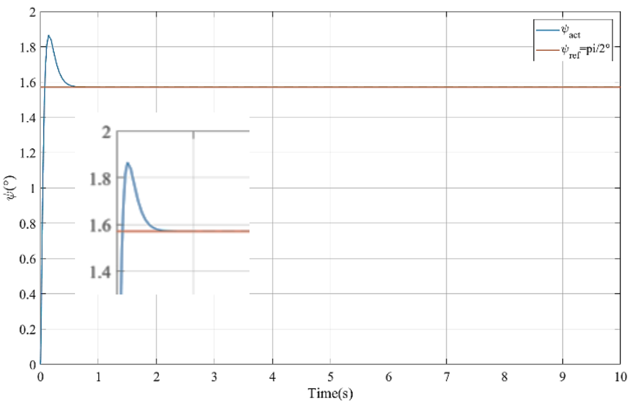


Fig. 8. The design performance criteria in each iteration

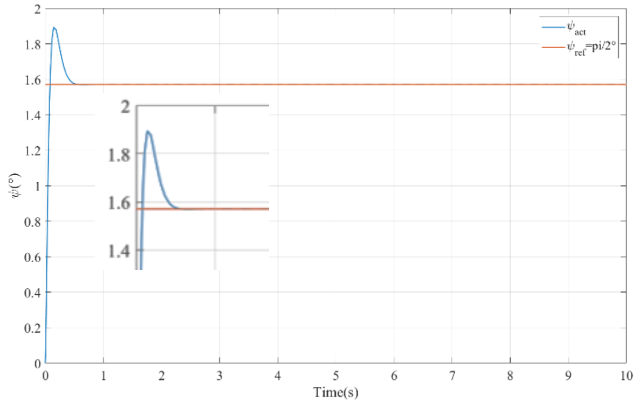
Closed-loop responses for yaw flight were obtained by performing simulations based on the morphing ratio and PID coefficients using SPSA. Moments of inertia according to the morphing ratio obtained in each iteration were extracted from the data set and simulated with PID coefficients. Simulations were carried out for the $pi/2°$ angle. The flight initial state, fifth iteration and final iteration simulation results are shown below.



(a)



(b)



(c)

Fig. 9. Simulations results (a) Initial iteration, (b) Fifth iteration, (c) Final iteration

As can be seen from the simulation results, the hexarotor successfully followed the given trajectory. Design performance criteria remained within satisfactory limits.

4. Conclusion

Proper selection of morphing rate and PID coefficients is important for hexarotor yaw flight stability. The hexarotor solid body model will change as the arm length becomes longer or shorter according to the estimated morphing rate. Since this change changes the distance from the rotation axis, it will also have an effect on the moments of inertia.

In this study, active morphing condition is considered for yaw flight. Active morphing was carried out during hexarotor flight. SPSA optimization method was used to determine the PID coefficients depending on both the morphing ratio and the ratio during active morphing. Moment of inertia values changing with morphing ratio were obtained from full models drawn in Solidworks program.

In yaw flight performed using SPSA, 92% improvement was obtained when the initial state and final state were compared. This improvement is obtained from the cost function formed by the yaw flight design performance criteria. The PID coefficients k_p, k_i and k_d are given as 50, 5 and 50 in the initial state, respectively. In the final state, the values were 89, 2 and 12, respectively, and remained within satisfactory limits. The arm length was determined as 0.5 m in the initial state and 0.38 m in the final state, and managed to stay within the limits given for optimization.

When the simulation results were examined, the $pi/2°$ trajectory given for the yaw flight was successfully followed by the values predicted by the hexarotor SPSA. When the graphs given in Fig 9 are examined, in the last iteration, the hexarotor successfully followed the trajectory with the final value determined by SPSA. When the design performance criteria were examined, the rise time decreased from 1.7 s to 0.44 s. Settling time value decreased from 18 s to 0.76 s. Overshoot value has been reduced from 0.0875% to 0.0132%. When these values are examined, SPSA's ability to make effective and fast optimization emerges. Here, genetic algorithms could be preferred instead of SPSA, but while genetic algorithms perform 2^n calculations in each iteration, SPSA also minimizes the optimization time since it only performs 2 calculations in each iteration. In addition, when the graphs are examined, it is seen that SPSA approaches the optimum result in 3 or 4 iterations. In addition, SPSA showed faster convergence and stability when compared to other hexarotor control studies in the literature, for example [27], [28], especially when the morphing state is included.

References

[1] T. OKTAY and Y. ERASLAN, "Numerical Investigation of Effects of Airspeed and Rotational Speed on Quadrotor UAV Propeller Thrust Coefficient," *J. Aviat.*, vol. 5, no. February, pp. 9–15, 2021, doi: 10.30518/jav.872627.

[2] İ. H. Güzelbey, Y. Eraslan, and M. H. Doğru, "Effects of Taper Ratio on Aircraft Wing Aerodynamic Parameters: A Comperative Study," *Eur. Mech. Sci.*, vol. 3, no. 1, pp. 18–23, 2019, doi: 10.26701/ems.487516.

[3] T. Oktay and O. Kose, "The Effect of Collective Morphing on the Longitudinal Flight in Quadcopter," *MAS INTERNATIONAL EUROPEAN CONGRESSON MATHEMATICS, ENGINEERING, NATURAL ANDMEDICAL SCIENCES-III*. Şanlıurfa, 2019.

[4] T. Oktay and O. Kose, "The Effect of Collective Morphing on the Lateral Flight in Quadcopter," *Umteb6. UluslararasiMesleki ve Teknik Bilimler Kongresi*. Iğdır, 2019.

[5] T. Oktay and O. Kose, "The Effect of Collective Morphing on the Vertical Flight in Quadcopter," in *MAS INTERNATIONAL EUROPEAN CONGRESSON MATHEMATICS, ENGINEERING, NATURAL ANDMEDICAL SCIENCES-III*, 2019, pp. 1–10.

[6] R. Leishman, J. Macdonald, T. Mclain, and R. Beard, "Relative Navigation and Control of a Hexacopter," *2012 IEEE Int. Conf. Robot. Autom.*, pp. 4937–4942, 2012, doi: 10.1109/ICRA.2012.6224983.

[7] C. M. Soria and F. G. Rossomando, "Identification and adaptive PID Control of a hexacopter UAV based on neural networks," *Int. J. Adapt. Control Signal Process.*, vol. 33, no. March 2017, pp. 74–91, 2019, doi: 10.1002/acs.2955.

[8] C. A. Arellano-muro, L. F. Luque-vega, and A. G. Loukianov, "Backstepping Control with Sliding Mode Estimation for a Hexacopter," in *2013 10th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE)*, 2013, pp. 31–36.

[9] M. Konar, "Simultaneous determination of maximum acceleration and endurance of morphing UAV with ABC algorithm-based model," *Aircr. Eng. Aerosp. Technol.*, vol. 92, no. 4, pp. 579–586, 2020, doi: 10.1108/AEAT-11-2019-0229.

[10] M. Konar, A. Turkmen, and T. Oktay, "Improvement of the thrust-torque ratio of an unmanned helicopter by using the ABC algorithm," *Aircr. Eng. Aerosp. Technol.*, vol. 92, no. 8, pp. 1133–1139, 2020, doi: 10.1108/AEAT-03-2020-0057.

[11] T. Oktay, M. Konar, M. Onay, M. Aydin, and M. A. Mohamed, "Simultaneous small UAV and autopilot system design," *Aircr. Eng. Aerosp. Technol.*, vol. 88, no. 6, pp. 818–834, 2016, doi: 10.1108/AEAT-04-2015-0097.

[12] N. P. Nguyen, N. X. Mung, and S. K. Hong, "Actuator fault detection and fault-tolerant control for hexacopter," *Sensors (Switzerland)*, vol. 19, no. 21, 2019, doi: 10.3390/s19214721.

[13] J. Fogelberg, "Navigation and Autonomous Control of a Hexacopter in Indoor Environments," *MSC Thesis*, pp. 1–75, 2013.

[14] R. S. Rodriguez, "UAV mission planning based on Prognosis & Health Management," Universit'e de Lorraine, 2020.

[15] G. O. Vargas, C. Hintz, L. R. G. Carrillo, F. Munoz Palacios, and E. S. Espinoza Quesada, "Dynamic modeling of a multi-rotorcraft UAS with morphing capabilities," *2015 Int. Conf. Unmanned Aircr. Syst. ICUAS 2015*, no. December, pp. 963–971, 2015, doi: 10.1109/ICUAS.2015.7152385.

[16] F. Sal, "Analysis of combined passively and actively morphing blade root chord length and blade taper for helicopter control," *Aircr. Eng. Aerosp. Technol.*, vol. 92, no. 2, pp. 172–179, 2020, doi: 10.1108/AEAT-04-2019-0077.

[17] F. Sal, "Effects of the actively morphing root chord and taper on helicopter energy," *Aircr. Eng. Aerosp. Technol.*, vol. 92, no. 2, pp. 264–270, 2020, doi: 10.1108/AEAT-08-2019-0165.

[18] T. Oktay and O. Kose, "Simultaneous quadrotor autopilot system and collective morphing system design," *Aircr. Eng. Aerosp. Technol.*, vol. 92, no. 7, pp. 1093–1100, 2020, doi: 10.1108/AEAT-01-2020-0026.

[19] T. Oktay and S. Coban, "Simultaneous longitudinal and lateral flight control systems design for both passive and active morphing TUAVs," *Elektron. ir Elektrotechnika*, vol. 23, no. 5, pp. 15–20, 2017.

[20] D. Kotarski, Z. Benic, and M. Krznar, "Control Design for Unmanned Aerial Vehicles with Four Rotors," *Interdiscip. Descr. Complex Syst.*, vol. 14, no. 2, pp. 236–245, 2016, doi: 10.7906/indecs.14.2.12.

[21] P. J. P. P.G. Howlett, *Advances in Industrial Control*. 2006. [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Advances+in+Industrial+Control#0

[22] J. C. Spall, "Simultaneous Perturbation Stochastic Approximation," *Introd. to Stoch. Search Optim.*, vol. 19, no. 5, pp. 176–207, 2005, doi: 10.1002/0471722138.ch7.

[23] N. Dong and Z. Chen, "A novel data based control method based upon neural network and simultaneous perturbation stochastic approximation," *Nonlinear Dyn.*, vol. 67, no. 2, pp. 957–963, Jan. 2012, doi: 10.1007/s11071-011-0039-x.

[24] J. C. Spall and D. C. Chin, "Traffic-responsive signal timing for system-wide traffic control," *Transp. Res. Part C Emerg. Technol.*, vol. 5, no. 3–4, pp. 153–163, 1997.

[25] N. L. Kleinman, S. D. Hill, and V. A. Ilenda, "SPSA/SIMMOD optimization of air traffic delay cost," in *Proceedings of the 1997 American Control Conference (Cat. No. 97CH36041)*, 1997, vol. 2, pp. 1121–1125.

[26] T. Oktay and S. Coban, "Simultaneous longitudinal and lateral flight control systems design for both passive and active morphing TUAVs," *Elektron. ir Elektrotechnika*, vol. 23, no. 5, pp. 15–20, 2017, doi: 10.5755/j01.eie.23.5.19238.

[27] K. Singh, "Modelling and Controls of a Hexacopter." Texas A&M University-Kingsville, 2018.

[28] H. S. Saini, "System Modeling and Simulation of Hexacopter," Punjabi University, 2016.