Optimal attitude control of a satellite in real orbit using multiple fractional-order controllers

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Abstract

The purpose of this work is to design three optimal fractional-order PI$^{\lambda}$ D$^{\mu}$ controllers for regulating the attitude of a three-axis satellite. The parameter gains of the controllers are tuned with the innovative Harris Hawks Optimizer (HHO). The state-space dynamic model of the satellite system is obtained by linearizing the nonlinear model around the Local Horizontal Local Vertical (LHLV) orbital frame. This allows for the model to be solved in state space. A study in which conventional PID controllers were used as a point of comparison was carried out so that it could be shown how valuable the fractional order is in the design that was proposed.

Keywords— Satellite system, Attitude control, PID Controller, Fractional-order, Harris Hawks Optimizer.

1 Introduction

Satellites are very complex space systems, and have received great attention from researchers and scientists since the turn of the last century [1, 2]. In recent years, attention has been drawn to concentrating focus on the development of very advanced guidance and control algorithms aboard microcomputers deposited at the core of these satellites. These enhancements include more precise aiming, agility, and better resistance to uncertainties and disruptions in the environment. Nevertheless, the majority of these findings are based on the presumption that the spacecraft is actively controlled by a number of actuators that is at least equal to the number of degrees of freedom possessed by the system [3, 6]. Thus, the study of such systems for the purpose of control- ling and directing them is of the utmost importance because of its profound impact on the control of military and civilian technologies [4]. In this regard, we have proposed a sophisticated optimal fractional-order PID controller [11] for satellites based on convex multidimensional optimization techniques [5, 9] especially the Harris Hawks Optimizers [7, 10], and we have provided a comparison study with the classical PID controller.

In this paper, the mathematical model of the attitude motion is described, and the linearization of the satellite model around the Local Horizontal Local Vertical (LHLV) reference frame is performed. Based on this linearized model, three optimal fractional-order PI$^{\lambda}$ D$^{\mu}$ controllers are designed for the stabilization and tracking of attitude trajectory.

2 Harris Hawks Optimizer

The HHO technique is used to find optimal solutions to constrained multidimensional optimization problems in a given set of dimensions [5, 9]. Find the minimal value of the objective function $\left(\min_{x} f(\boldsymbol{x})\right)$ for a given set of constraints. HHO is an evolutionary novel population metaheuristic. HHO was primarily motivated by the cooperative behavior and pursuit strategy of Harris' hawks in nature, which is known as surprise pounce. Multiple hawks work together to ambush their victim by swooping in from all sides. Depending on the scenario and how the prey often escapes, Harris hawks can show a variety of pursuit tactics. See [5, 9, 8]. For a detailed explanation of the various phases of HHO depicted in Fig. 1, including the exploration stage, the transition from exploration to exploitation, the exploitation stage, the pseudo code of HHO, and its computational complexity.

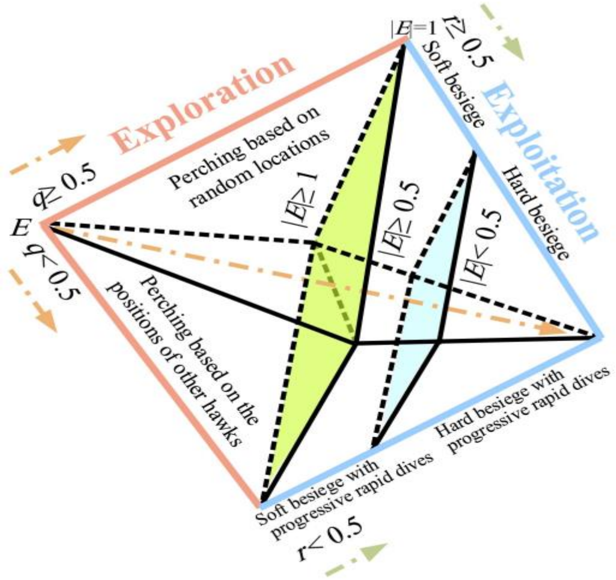


Figure 1: Schematic diagram of different phases of HHO.

3 Satellite Attitude Model

The orientation of the body frame *(x, y, z)* Â (coincident with the three principal axes of inertia) with respect to the orbital reference frame *(x_r, y_r, z_r)*, also known as Local-Vertical-Local-Horizontal (LVLH), will be used to define the satellite's attitude in this work. The three principal axes of inertia will be used to determine the orientation of the body frame. The point of origin of the orbit reference frame will move along with the center of mass of the satellite as it travels through orbit. The z_r axis is directed toward the center of mass of the Earth, whereas the x_r axis is in the plane of the orbit, perpendicular to the z_r axis, and in the direction of the spacecraft's velocity. The *y* y_rÂ axis is perpendicular to the plane in which the orbit is viewed locally, so completing a three-axis right-hand orthogonal system. Figure 2 provided a visual representation of the LVLH reference frame [1].

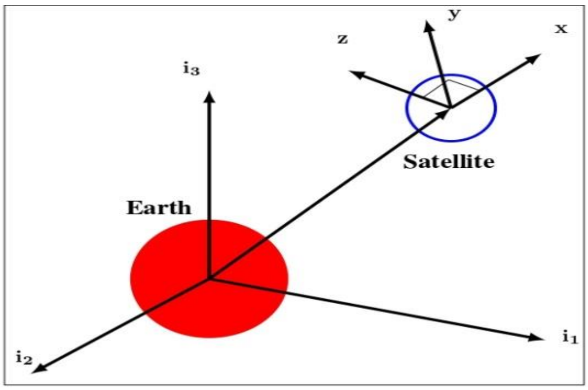


Figure 2: LVLH axis representation.

The dynamic model of the attitude model can be represented in the state space form [1]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \quad (1)$$

with states $x = [\varphi, \theta, \psi, \dot{\varphi}, \dot{\theta}, \dot{\psi}]^T$, and inputs $u = [\tau_x, \tau_y, \tau_z]^T$. A is the state matrix, B is the input matrix, C is the output matrix, and D is the direct transmission matrix, their characteristic parameters values is mentioned in Table 3. The dynamical model is given by [1]:

$$B = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{J_x} & 0 & 0 \\ 0 & \frac{1}{J_y} & 0 \\ 0 & 0 & \frac{1}{J_z} \end{pmatrix}, \quad C^T = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$A = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{4\omega_0^2(J_z - J_y)}{J_x} & 0 & 0 & 0 & 0 & \frac{4\omega_0(J_x -}{J_x} \\ 0 & \frac{3\omega_0^2(J_x - J_z)}{J_y} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\omega_0^2(J_x - J_y)}{J_z} & \frac{\omega_0(J_y - J_x - J_z)}{J_z} & 0 & 0 \end{pmatrix} \quad (2)$$

4 Main results

The formulation of the fractional-order $\mathrm{PI}^{\lambda}\mathrm{D}^{\mu}$controller is given as [12]:

$$C(s) = \left(K_p + K_i \frac{1}{s^{\lambda}} + K_d s^{\mu}\right) e(s) \tag{3}$$

To find a optimal parameters gains of the three controllers $(K_p, K_i, K_d, \lambda, \mu)$ which achieve the best tracking of attitude trajectory, we formulated to a convex minimization problem which can be solved by HHO optimizer [5], where the objective
function $f(x)$ is given as follows:

$$f(x) = \left\| \int (y_{\mathbf{ref}} - y_{\mathbf{real}})^2 dt \right\|_{\infty} = \left\| \int e^2 dt \right\|_{\infty} \tag{4}$$

Find x which minimize the objective function

$$\min_{x} \left\| \int e^2 dt \right\|_{\infty} \tag{5}$$

5 Results with interpretations

The figures Fig. 3, Fig. 4, Fig. 5 and Fig. 6 shown the evolution of the optimization process in term of the number of iterations, in the case of classical PID controller Num-iter = 500, and the search space of parameters gains = [0.001 200]. In the case of PI^{λ} D^{μ} Num-iter = 10 and the search space of parameters gains = [0.001 200]. In the Table 1 and Table 2 we found the optimal parameters gains of the both classical and fractional-order PID controllers of the three axes, which are obtained based optimization HHO tools. Based on the obtained results shown in Fig. 7 and Fig. 8 respectively, we see that the fractional-order controller gives best tracking than the classical one, the parameters gain of the proposed PI^{λ} D^{μ} is small compared with the classical PID controller, which mean ensuring a good tracking with minimum control energy.

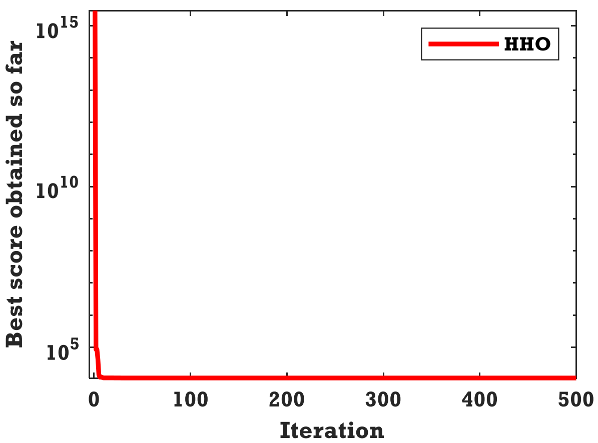


Figure 3: The objective function of classical controller.

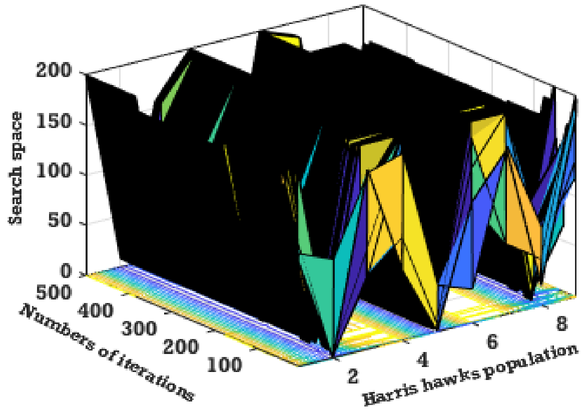
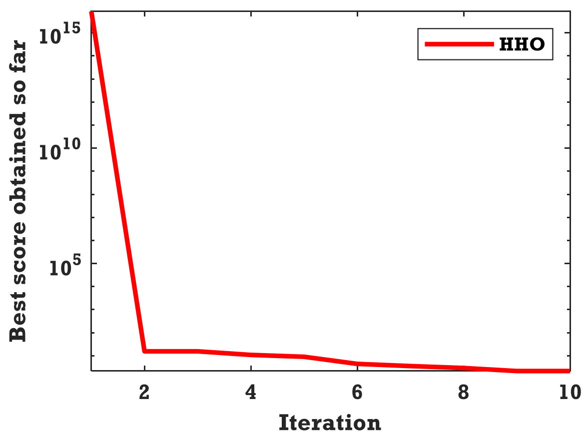


Figure 4: The evolution of HHO population of classical



Controller.

Figure 5: The objective function of Fractional-order Controller.

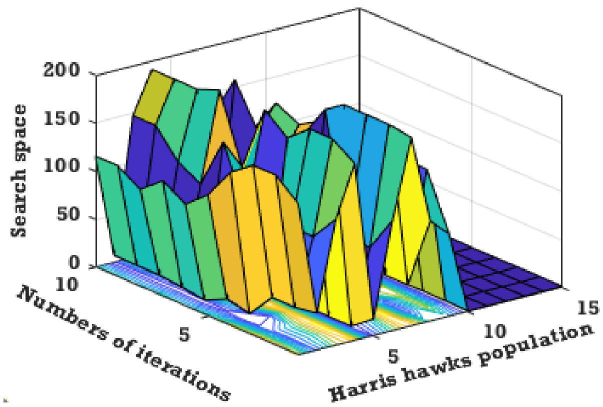


Figure 6: The evolution of HHO population of Fractional-order Controller

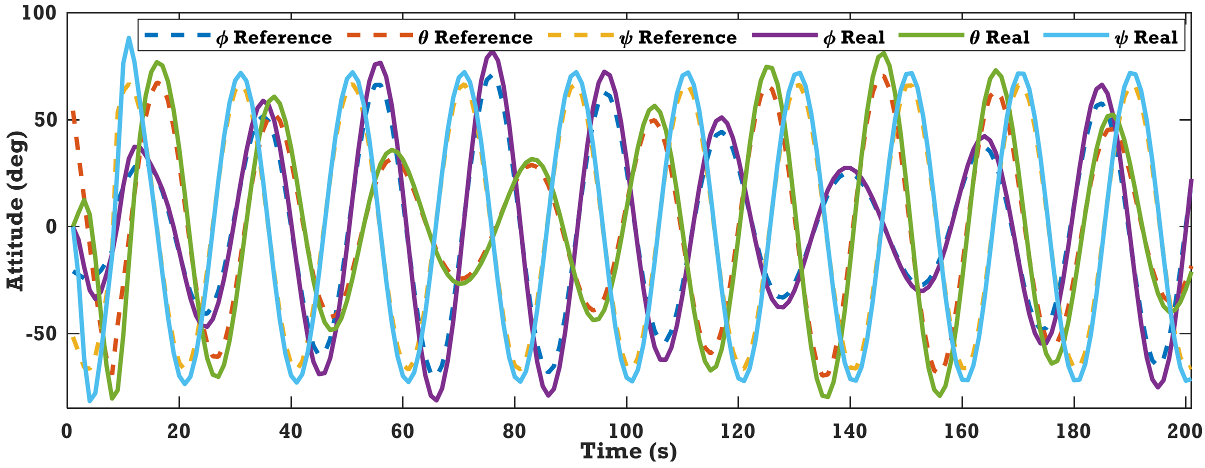


Figure 7: Attitude satellite control real and reference: Classical PID controllers.

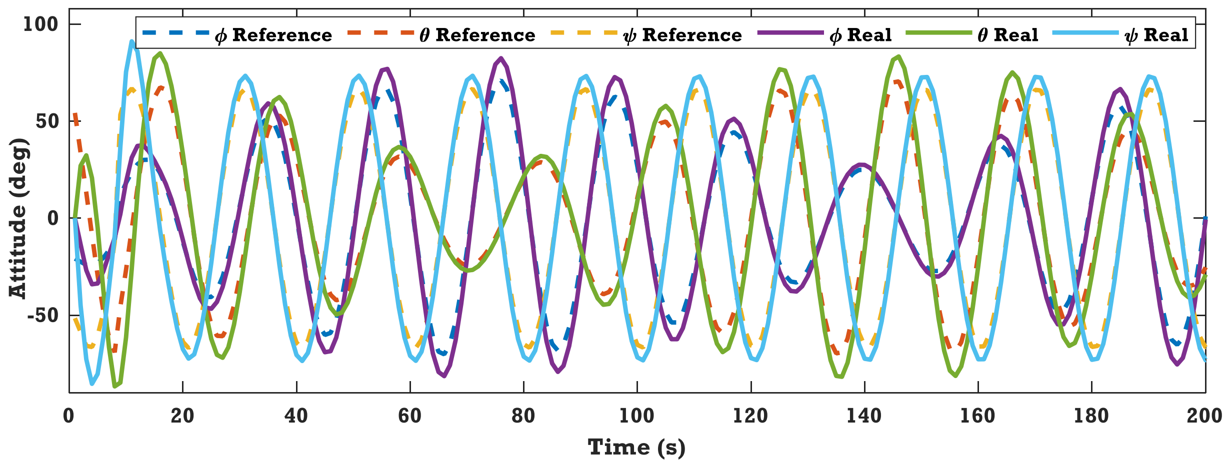


Figure 8: Attitude satellite control real and reference: Fractional-order $PI^{\lambda} D^{\mu}$ controllers.

Table 1: Parameters gains of classical PID controllers

Controller	K_p	K_i	K_d
PID φ	200	7.641	156.531
PID θ	200	0.001	200
PID ψ	187.092	7.963	161.060

Table 2: Parameters gains of $PI^{\lambda} D^{\mu}$ controllers

Controller	K_p	K_i	K_d	λ	μ
$PI^{\lambda} D^{\mu}$ φ	115.82	7.32	147.78	0.983	1.018
$PI^{\lambda} D^{\mu}$ θ	190.68	3.85	142.12	1.5	1.273
$PI^{\lambda} D^{\mu}$ ψ	145.66	40.31	76.99	1.004	1.339

6 Conclusion

In this work, an optimal control attitude of satellite system has been achieved, based on three fractional-order PI$^{\lambda}$ D$^{\mu}$ controllers, using a new HHO optimizer. The fractional-order action in the both integral and derivative made the difference, by giving the controller a considerable degree of freedom to select the precise parameters to the proposed controller, counter to the classical PID controller with integer- order. Further studies focus on the design of one optimal fractional-order compensator, which can be smoother than the proposed controller.

7 Appendix

Table 3: Simulation satellite system parameters values

Param	Value
Principal momentum of inertia without payload kgm^2	$J_x = 305.89126$ $J_y = 314.06488$ $J_z = 167.33919$
Torque arm (m)	$l = 1.0$
Mean orbital motion (rad/s)	$\omega_0 = 0.001$
Mass (kg)	578.05239
Orbit altitude (km)	750
Maximum force (N)	5
Eccentricity	$\cong 0$

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