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CONTROL OF RIGID-FLEXIBLE SATELLITES USING OPTIMIZATION ALGORITHM FOR PID TUNING

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Abstract: *The satellite attitude control system is considered one of the most critical to guarantee the fulfillment of the functionalities expected in the use of these artifacts. Furthermore, the use of enlarged solar panels in order to support the increasing consumption of energy, and the fact that the restriction imposed on the weight of these items, due to the cost associated with launching them into orbit, results on thinner and more flexible structures. These items are subjected to undesirable vibrations that, if not controlled and maintained within acceptable minimum levels, can impact the accomplishment of the mission. Thus, the objective of this paper is to present the development of a Proportional-Integral-Derivative (PID) controller, using different optimization algorithms to find optimal values for its parameters. Two optimization techniques were tested: bioinspired algorithm (PSO - Particle Swarm Optimization) and fmincon from MATLAB software. The mathematical modeling used for the rigid-flexible satellite was based on the mass-spring method. The results were compared with the ones obtained with the use of a Linear-Quadratic Regulator (LQR). The PID controller using PSO algorithm presented the best performance among the three controllers developed.*
Key words: *Rigid-flexible satellites, PID tuning, optimization algorithm, bioinspired optimization (PSO), fmincon*

1. INTRODUCTION

The current technological development has been greatly benefited by the expansion of the communication capacity provided by the use of satellite networks. Satellite communication virtually eliminates the problems posed by the difficulties of transmitting signals between distant points where the curvature of the Earth begins to act as a limiter. The use of satellites marked the beginning of the space age in the late 1950s with the launch of Sputnik by the former Soviet Union. Since then, this technology has undergone a rapid advance and today it is widely used by governments and private institutions, with applications in remote sensing, meteorological forecasts, signal transmission, safe military communication, navigation through Global Positioning System (GPS), among others.

The Brazilian government, aware of the importance of such topic, has invested considerable resources (running around US$ 800 million), to ensure the implementation of a Geostationary Defense and Strategic Communication Satellite (SGCD), launched on May 04th, 2017, in order to bring improved security to strategic and military communications, as well as being used to fulfill the objectives of the Brazilian National Broadband Program, bringing high-speed internet to isolated regions such as the Amazonian areas (Geraldo and Cossul, 2017).

Due to the amount of investments made in the systems mentioned above and considering the difficulty of performing repairs on satellites in Earth orbit, it is necessary that the attitude control of these artifacts be made as reliably as possible.

Attitude control systems capable of dealing with hybrid spatial structures (rigid body with flexible components) have aroused great interest in the space industry. The use of increasing solar panels in current satellites for the purpose of supporting increasing energy consumption are typical examples of the aforementioned structures. In addition, the limitation on the mass and volume payload of launching vehicles induces the use of thinner and more flexible components (Lopes, 2008). These components are subjected to structural vibrations which, if not properly damped, may affect directly the control system as well as the attitude determination.

There are several possible control techniques to be used in the problem of attitude control of satellites. Among these techniques, one of the most used is the Predictive-Integral-Derivative (PID) controller design (Ogata, 1998, p. 544).

On the present work, the PID controller, mentioned in the previous paragraph, will be designed using a stochastic search technique based on the bio-inspired optimization algorithm named Particle Swarm Optimization (PSO), as presented by Kennedy and Eberhart (1995).

Castro (2009) used a mathematical model for this type of system (mass-spring model) and designed a Linear-Quadratic Regulator (LQR) controller.

This article intends to use the same satellite model described by Castro (2009), for a satellite with a rigid-flexible structure, using a PID controller with two different types of optimization technique (bioinspired optimization and fmincon MATLAB function) and then verify the advantages of using these controllers in comparison to a LQR controller.

Doing so, the question this paper intends to solve is: Which of the three control methods described can be considered more efficient for the attitude control of flexible satellites?

Therefore, the main goal is to compare the three different controllers fore mentioned.

For the rest of this paper, important to say that it is organized in sections, as followed described: the rigid-flexible satellite model used to perform the simulations of this study and the computational procedure to be implemented is shown in the section called "Computational Procedure"; in the section "Results and Discussions", the results of the simulations carried out will be presented, with the pertinent discussions. Finally, the "Conclusion"section will present the conclusions of the article.

2. COMPUTATIONAL PROCEDURE

This section will show the procedures adopted to describe the problem and to implement the controllers. So, it will be presented in the two subsections that follows.

2.1 Mathematical Model

The satellite used in the simulations to be presented is constituted by a servomotor, responsible for rotating a rigid cylindrical body coupled to a flexible arm, according to Fig. 1.

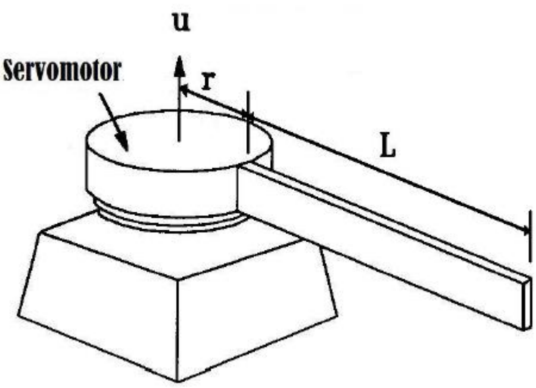

Figure 1: **Schematic representation of the satellite type being analyzed (CASTRO, 2009).**

As shown above, the satellite is constituted by a servomotor, which was considered as a rigid body, responsible for providing the angular displacement of the L length rod, by the application of a voltage u that will result in a torque on the system. The rod will be considered as a flexible body and, therefore, will be subjected to vibrations.

The angular displacements imposed on the satellite are shown in Fig. 2.

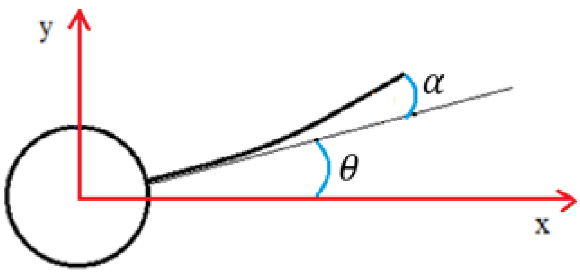

Figure 2: **Satellite upper view showing rigid (θ) and flexible (α) body displacements. (CASTRO, 2009)**

The mathematical model to be used will be represented on the state space, by means of the following equations:

$$\dot{X} = A.X + B.u \quad (1)$$

$$Y = C.X \quad (2)$$

Where X is the state vector of the system, given by Eq. (3) below, A is the state matrix, B is the input matrix, u is the applied voltage in the servo system, Y is the output vector, and C is the output matrix which, in this case, will be considered to be the identity matrix 4x4, so that the output vector is equal to the state vector.

$$X = \begin{bmatrix} \theta \\ \alpha \\ \dot{\theta} \\ \dot{\alpha} \end{bmatrix} \tag{3}$$

In order to obtain the state matrix, the mass-spring method will be used. The detailed development of the model can be found in Castro (2009).

Thus, one obtains a system in the state space, given by the following equation:

$$\begin{bmatrix} \dot{\theta} \\ \dot{\alpha} \\ \ddot{\theta} \\ \ddot{\alpha} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 591.9 & -31.9 & 0 \\ 0 & -947.2 & 31.9 & 0 \end{bmatrix} \cdot \begin{bmatrix} \theta \\ \alpha \\ \dot{\theta} \\ \dot{\alpha} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 56.2 \\ -56.2 \end{bmatrix} .u \tag{4}$$

With the mathematical model presented, it was possible to use the control techniques and optimization strategies described on the following section.

2.2 Parameters description

The restriction parameters used in the development of the controllers were: (i) the maximum voltage supplied by the torque motor of Fig. 1; and (ii) the maximum acceptable angular deflection of the flexible body (α), as described in Tab. 1.

Table 1: **Restrictions to the system.**

	Parameter	Restriction
Flexible Displacement (°)	α	[-2,2]
Voltage supplied by the motor (V)	u	[-24,24]

2.2.1 LQR Controller

The Linear-Quadratic Regulator controller developed on this paper was solved using the associated Riccati's equation to the problem, minimizing the cost function presented on the Eq. (5):

$$J = \int_0^{\infty} (\mathbf{X'QX} + u'Ru) \tag{5}$$

where Q, as presented on Eq. (6), and R are the weighting matrices of the system.

$$Q = \begin{bmatrix} Q_1 & 0 & 0 & 0 \\ 0 & Q_2 & 0 & 0 \\ 0 & 0 & Q_3 & 0 \\ 0 & 0 & 0 & Q_4 \end{bmatrix} \tag{6}$$

The solution of the problem gives the optimum gain matrix showed on Eq. (7).

$$K = \begin{bmatrix} K_1 & K_2 & K_3 & K_4 \end{bmatrix} \tag{7}$$

2.2.2 PID Controller using fmincon

For the PID controller with optimization using the MATLAB fmincon function, the following parameters were used:

- Sequential quadratic programming (SQP) algorithm;
- Initial controller parameters = [0.1 1 1]; and
- Maximum controller parameters = [100 10 10].

2.2.3 PID Controller using PSO

For the PID controller with PSO bio-inspired optimization, the following parameters were used:

- Swarm size = 20;
- Number of iterations per experiment = 50;
- Momentum or inertia varying linearly from 0.9 to 0.1;
- Cognitive coefficient = Social coefficient = 2.05;
- Number of experiment = 32; and
- Maximum velocity = 30.

In all cases, the following general parameters were used:

- Reference: step function of 30 degrees;
- Time of simulation varying from 0 to 50s with 0.01s per each step; and
- Cost function for the PID optimization: ITAE + 1000.abs(Max. flexible displacement – 0.0349), where the first term is the Integral of Time multiplied by the Absolute value of Error and the second term takes into account the restriction on the flexible angle (2 degrees = 0.0359 rad).

3. RESULTS AND DISCUSSIONS

3.1 LQR controller

Various simulations were made using the mathematical model, changing the parameters of the Q and R weighting matrices and adjusting then in order to assure the restriction on the maximum flexible angle displacement, as presented on Tab. 1, has been met. Table 2 below shows the results (Maximum Flexible Angle displacement, Settling Time considering 2% and the overshooting) for the simulations where the restriction mentioned above was respected.

Table 2: **LQR controller response varying Q and R weighting matrices.**

Q_1	Q_2	Q_3	Q_4	R	K_1	K_2	K_3	K_4	Max. Flex. Angle (°)	T_{sd}, 2% (s)	Overshooting
1000	1	1	1	522.55	1.3834	0.0347	0.1070	0.0630	-2.0000	1.6698	0.0000%
1000	10	1	1	522.5	1.3834	0.0338	0.1070	0.0630	-2.0000	1.6697	0.0000%
1000	100	1	1	522	1.3841	0.0252	0.1071	0.0628	-2.0000	1.6690	0.0000%
1000	1000	1	1	517.25	1.3904	-0.0613	0.1080	0.0611	-2.0000	1.6619	0.0000%
1000	363	1	1	520.6	1.3860	0.0000	0.1074	0.0623	-2.0000	1.6669	0.0000%
10000	1	1	1	5270	1.3775	0.0686	0.1051	0.0651	-2.0000	1.6724	0.0000%
100000	1	1	1	52745	1.3769	0.0719	0.1049	0.0653	-2.0000	1.6726	0.0000%

From Tab. 2, the parameters for the weighting matrices Q and R that led to the best performance and met the restrictions of Tab. 1 were as follows on Eq. (8) and (9):

$$Q = \begin{bmatrix} 1000 & 0 & 0 & 0 \\ 0 & 363 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

$$R = [520.6] \tag{9}$$

Using these matrices to solve the LQR problem, one will obtain the optimum gain matrix showed on Eq. (10).

$$K_{LQR} = \begin{bmatrix} 1.3860 & 0.0000 & 0.1074 & 0.0623 \end{bmatrix} \tag{10}$$

Simulating the response of the system to a step function of 30°, with the designed LQR controller, Fig. 3 and 4 show the results for the rigid and the flexible angle displacements.

The simulated value for the tension on the servomotor using this controller was obtained using the model on simulink showed on Fig. 5. The results for the tension are presented on Fig. 7.

The performance values for this controller, such as the 2% settlement time (Tsd), overshooting, ITAE and maximum tension on the servomotor are presented on Tab. 3.

3.2 PID controller using fmincon

Using the fmincon function for the optimization, the parametes K_p, K_i and K_d obtained are:

$$K_{fmincon} = \begin{bmatrix} 0.3428 & 0.0000 & 0.0611 \end{bmatrix} \quad (11)$$

Figures 3 and 4 also show the results of the simulations for the gain values of the PID controller obtained with the MATLAB fmincon function optimization for the satellite's rigid and flexible displacements, respectively.

The simulated value for the tension on the servomotor using this controller was obtained using the simulink model showed on Fig. 6. The results for the tension are presented on Fig. 8.

The performance values for this controller, such as the 2% settlement time (Tsd), overshooting, ITAE and maximum tension on the servomotor are presented on Tab. 3.

3.3 PID controller using PSO

Using bioinspired (PSO) algorithm for the optimization, the parameters K_p, K_i and K_d obtained are:

$$K_{PSO} = \begin{bmatrix} 1.2384 & 0.0000 & 0.0000 \end{bmatrix} \quad (12)$$

Figures 3 and 4 also show the results of the simulations for the gain values of the PID controller obtained with PSO bio-inspired optimization for the satellite's rigid and flexible displacements, respectively.

The simulated value for the tension on the servomotor using this controller was obtained using the simulink model showed on Fig. 9, below. The results for the tension are presented on Fig. 8 that follows.

The performance values for this controller, such as the 2% settlement time (Tsd), overshooting, ITAE and maximum tension on the servomotor are presented on Tab. 3.

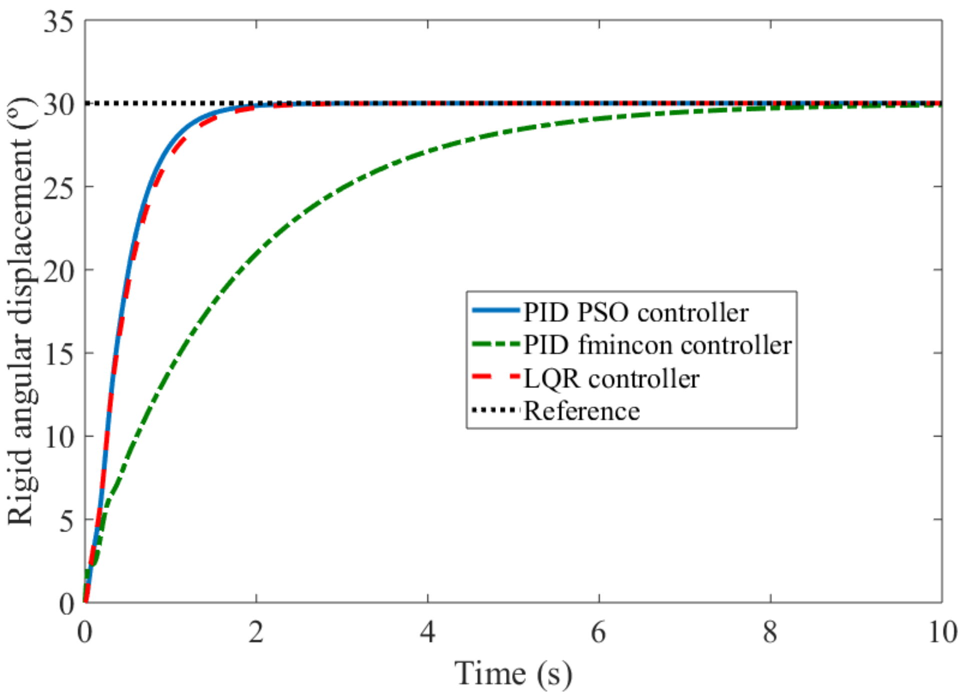

Figure 3: **Response to the 30°step for the satellite rigid displacement (θ)**

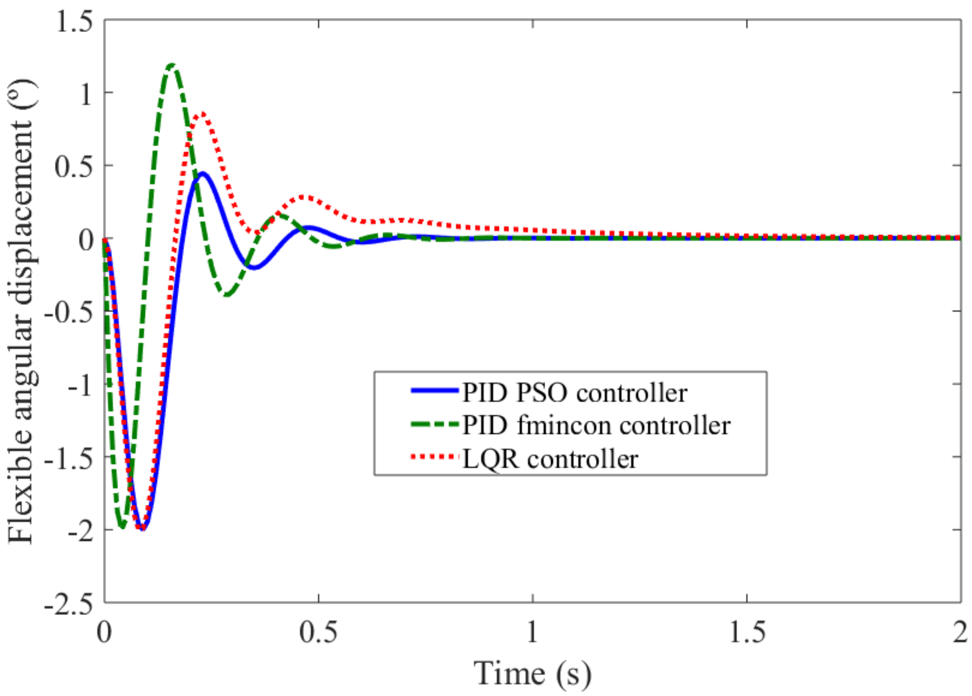

Figure 4: **Response to the 30°step for the satellite flexible displacement (α)**

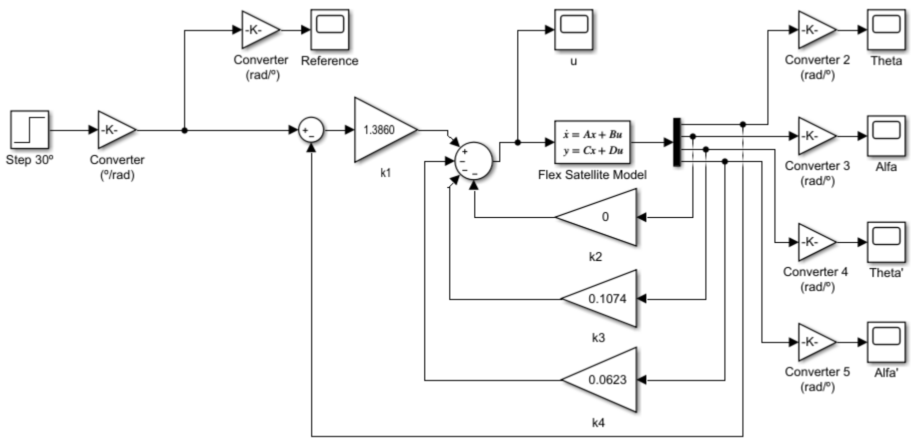

Figure 5: **Simulink model for the LQR controller**

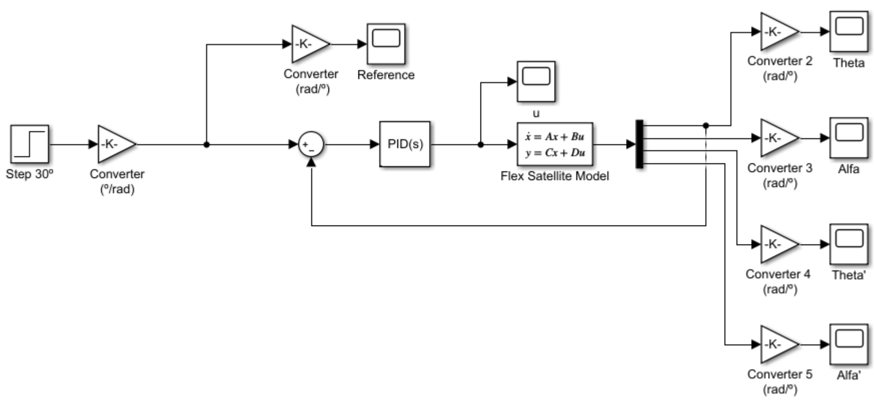

Figure 6: **Simulink model for the PID controllers**

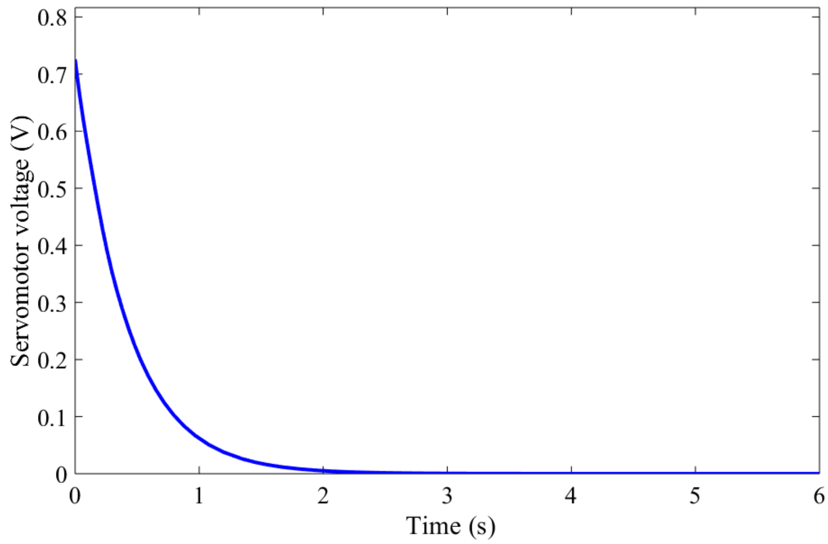

Figure 7: **Tension on the servomotor for the LQR controller to a 30°step**

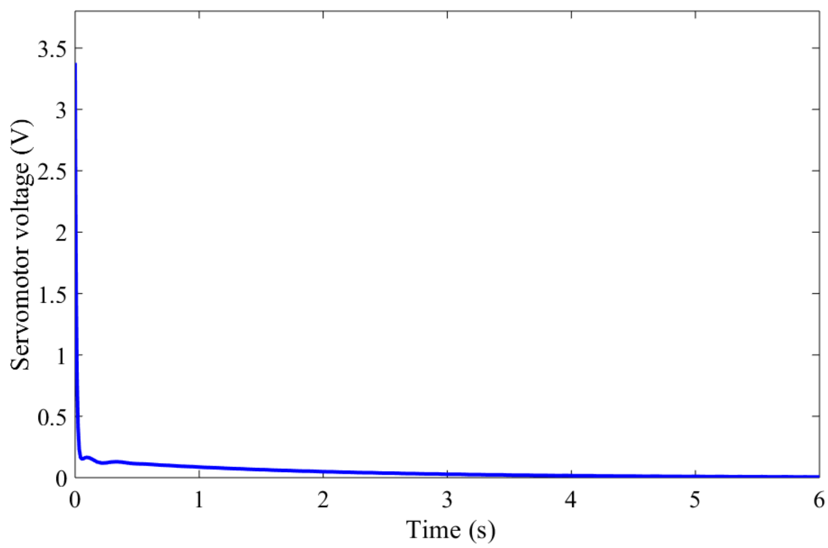

Figure 8: **Tension on the servomotor for the PID fmincon controller to a 30°step**

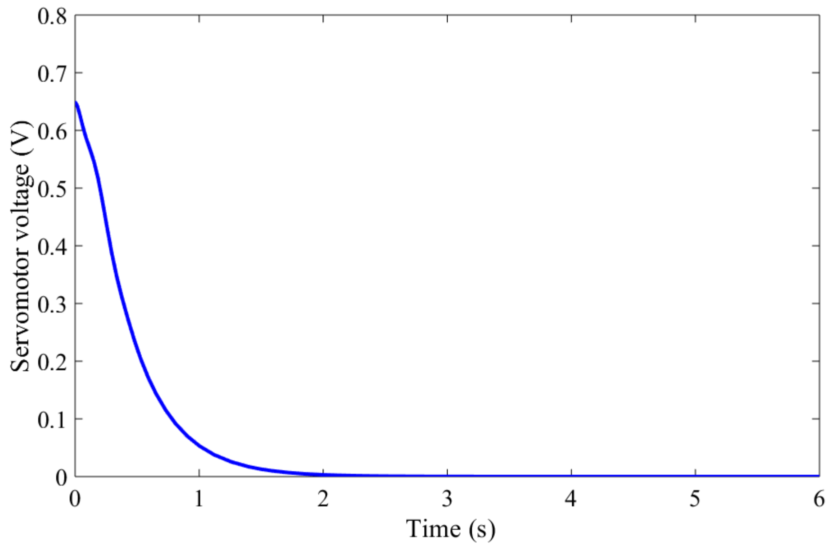

Figure 9: **Tension on the servomotor for the PID PSO controller to a 30°step**

Table 3: **Performance of the controllers.**

	T_{sd} (s)	Overshooting	ITAE	Maximum Voltage (V)
LQR controller	1.6669	0.0000%	609	0.73
PID fmincon controller	6.7585	0.0000%	8499	3.43
PID PSO controller	1.4963	0.0000%	515	0.64

4. CONCLUSIONS

Bringing back the question this paper intends to solve: Which of the three control methods described can be considered more efficient for the attitude control of flexible satellites?

One can see, from Tab. 3, that the PID controller using PSO algorithm for te tuning optimization shows a better performance than the other two, once the settlement time, Integral of Time multiplied by the Absolute value of Error (ITAE) and the the maximum voltage on the servomotor are smaller than the results the other 2 presented.

This result is also important when considering the economy one can have with the use of a PID controller, instead of a LQR, once the PID uses less feedback information than LQR, so it needs less sensors.

5. REFERENCES

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6. AUTHORAL RESPONSABILITY

The authors are solely responsible for the content of this work.