Regulation of an InnoSat by means of evolutionary algorithms

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Abstract

The Innovative Satellite, known as InnoSAT, is a nanosatellite developed by the Malaysian Space Agency (ANGKASA) to carry out dissemination, research and technological development activities, such as the design of regulators that control its behavior in space, especially in the swing and spin axes, which according to their transfer functions have a marginally stable behavior and affect their altitude. a situation that requires a correction through the design and implementation of automatic control techniques such as square linear regulators (LQRs), which are designed through the optimization of a cost function using a weighting matrix. Although this technique ensures system stability, it is often associated with high mean square error and slow setup time. This proposal presents an alternative to improve the design of regulators through evolutionary techniques such as the Genetic Algorithm and the Cuckoo Search. These approaches reduce errors and speed up setup time on the InnoSAT swing and swing axes.

Keywords — Altitude regulation, Cuckoo search, Genetic algorithms, Nanosatellites

1. INTRODUCTION

At the end of the nineties, California Polytechnic University and Stanford University developed the "CubeSat" standard to promote learning and space exploration, this standard allows the development of nanosatellites that have a reduced size, cost and development times compared to regular-sized satellites, with a weight of no more than 1 kg [1]. An example is the Innovative Satellite or InnoSat, a project formed by Sains University Malaysia, Universiti Teknologi Malaysia and Universiti Malaysia Perlis, with the aim of taking photographs of different regions of Malaysia from low orbit, storing them and downloading them once it enters communication with the ground station, however, it is also intended to test altitude systems and solar panel sensors [2]. The InnoSat conceptually is composed of 3 CubeSats of dimensions 10x10x10 cm3 in the shape of a tower with a maximum weight of 1 kg each and a total energy consumption of 15W, in Figure 1 you can see a representation of an InnoSat. [3].

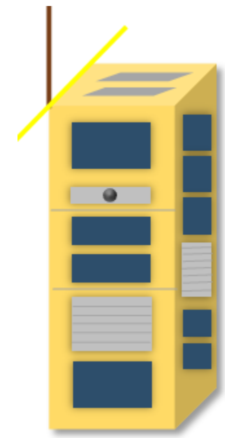

Figure 1. Schematic of an InnoSat.

It should be noted that the dynamic behavior of an InnoSAT is modeled by equations known as Euler's equations that can be transformed into a set of equations written in terms of the complex variable s. This is shown in equations 1,2,3 [2].

$$\varphi(s) = \frac{s^2 - 0.3023s + 0.8088}{s^4 + 1.1050s^2 + 0.1650} \tag{1}$$

$$\theta(s) = \frac{1}{s^2 - 7.1138\,x\,10^{-3}} \tag{2}$$

$$\phi(s) = \frac{s^2 + 0.3015s + 0.240}{s^4 + 1.1050s^2 + 0.1650} \tag{3}$$

InnoSats are susceptible to being affected by environmental disturbances such as gravity, solar wind or radiation, which causes abrupt changes in their positioning, thus interfering with the mission to be performed, especially when a high level of precision is required, as in the case of photographic capture [4]. To compensate for the problem, nanosatellites have an Attitude Control System (ACS), which allows them to regulate their position in orbit and compensate for disturbances derived from the environment.

One way to perform ACS is through classic control techniques such as the use of PID type regulators. An alternative can be intelligent regulators or some modern control techniques, as is the case of Linear Quadratic Regulators, LQR), which are used in a variety of control applications, including aerospace, robotics, electrical engineering, and mechanics. They are also used in stability control, navigation and tracking systems

To understand an LQR regulator, let be a dynamical system defined by state variables such that the state vector, $\dot{x}$ is defined as , $\dot{x} = Ax + Bu$ with an output and described as y=Cx donde $x \in \mathbb{R}^n$ y $u \in \mathbb{R}^m$. From this, a cost function J can be defined which can be written as shown in equation 4, on the other hand the control law $u(t)$ that allows minimizing equation 4 can be written as described in equation 5 [6]

$$J = \int_0^{\infty} [x^T(t)Qx(t) + Ru^T(t)]dt = Cx \quad (4)$$

(5)

$$u(t) = -Kx(t)$$

Where K is calculable by means of the expression shown in 6 where P is the single positive defined solution of the Riccati equation defined as , $A^TP + AP - PBR^{-1}B^TP + Q = 0$ for $Q = Q^T \geq 0$, in addition to being a real, symmetric and semi-defined positive matrix, while the matrix $R = R^T > 0$, is real, symmetrical and positively defined in such a way that Figure 4 shows a regulation scheme of LQR, where the calculation for K is made by means of expression 6 [6]. The Figure 2 shows a regulation scheme of LQR, where the calculation for K is performed by means of expression 6 [6]

$$K = R^{-1}B^TP \quad (6)$$

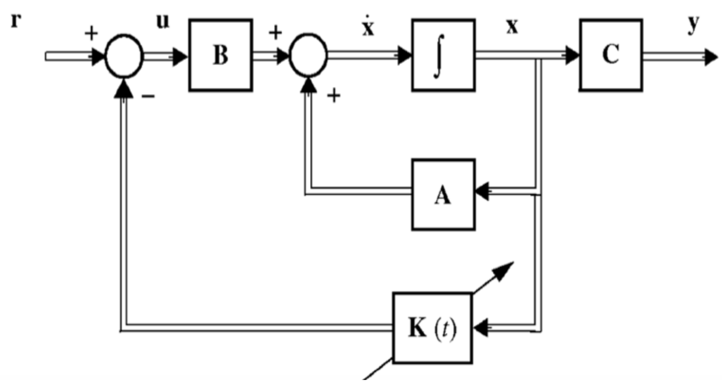

Figure 2. LQR regulation scheme [6]

2. THEORETICAL SUPPORT

A linear squared regulator (LQR) is intended to ensure the stability of a closed-loop system by means of certain feedback gains. This type of control technique belongs to the optimal control methods since they focus on the minimization of a mathematical function called the cost function, defined as the sum of the deviations of the measured values with respect to the desired ones. But in the case of InnoSat, a considerable steady-state error is observed, which in various theoretical positions can be improved by means of optimization techniques such as evolutionary algorithms.

Based on this state of the art of information, this paper proposes to compare the performance of an LQR-type regulator, adjusted by a genetic algorithm with real coding, with respect to a recently developed heuristic called Cuckoo Search, a method mathematically supported in Chaos Theory.

As shown in equation 6, the adjustment of the gains can be made by proposing the matrices and by means of Evolutionary Algorithms (EAs), which are defined as a collection of optimization problem-solving methods inspired by the biological principles developed by Charles Darwin and Gregory Mendel in the book "The Origin of Species". How it works is shown in algorithm 1

Algorithm 1 *Evolutionary Algorithm*

```
Initialize population
Calculate fitness f(x_i)
    While i < maximum number of iterations do
        Select parents
        Recombine pairs of parents
        Evaluate new candidates
        Select individual for the next iteration
        i++
    end
end
```

This allowed David Goldberg and John Holland to propose the first Genetic Algorithm (GA) and Ingo Rechenberg the first evolutionary strategies [7].

The AE's operate from a collection p of vectors , $\vec{x} = \{x_1, x_2, x_3, \ldots, x_n\}$ which constitute the possible solutions to an optimization problem which is modelable by means of a , $f_j(\vec{x})$ mathematical function where x_n represents the n-th variable of a j-th problem, such that , $\vec{x} \in \mathbb{R} \mid\mid \vec{x} \in \mathbb{Z}$ for numerical or combinatorial optimization problems respectively. Some elements of p characterized by having the highest value in $f_j(\vec{x})$ they are subject to several mathematical processes in an iterative manner. In GA, one of the characteristic operations is crossover, which is shown in expressions 7 and 8, it should be noted that the p collection is called chromosomes and each of its components are called genes and represent a variable of the optimization problem to be solved [8]

$$C_n^{H1} = \beta * C_n^1 + (1 - \beta) * C_n^2 \quad (6)$$

$$C_n^{H2} = \beta * C_n^2 + (1 - \beta) * C_n^1 \quad (7)$$

Where $\beta = rand[0,1]$, C_n^1 y C_n^2. are the chromosomes to be recombined, C_n^{H1} y C_n^{H2}. they are the recombined chromosomes. Another of the operators of a GA recombination is mutation, which is a process that aims to change a gene from a chromosome, chosen randomly, through a uniform distribution within an interval defined in the upper and lower limits of said variable, this operator is called a random mutation. The algorithm 2 shows the flow chart of the GA that was implemented in this proposal

Algorithm 2 *Genetic Algorithm*

```
Initialize population
Calculate fitness f(x_i)
    While i < maximum number of iterations do
        Select chromosomes parents
        Cruce new candidates
        Mutate individual for the next iteration
        Replace
    end
end
```

It should be noted that the proposal developed by Holland with the GA's made it possible, subsequently, to develop a variety of bio-inspired methods to solve optimization problems, one of them is the Cuckoo Search Algorithm (CSA), which is theoretically supported by the behavior of the Cuckoo, a predatory bird endemic to Europe and North Africa that has migratory habits towards sub-Africa. sariahana and Southeast Asia. The Cuckoo, in its reproductive cycle, has a parasitic behavior which consists of laying, in nests of other species, its eggs that are incubated when camouflaged. The CSA was proposed in 2019 by She Yang of the University of Cambridge and Suash Deb of C.V. Raman University in India. Basically, this algorithm makes an exploration and update of the nests, which are possible solutions, by means of a random number generator with chaotic distribution, which is carried out by means of a mathematical function called Levy flight in honor of the French mathematician Pierre Lévy, who described bird movements by means of a fractal-type behavior. This is shown in equation 8 [9].

$$\sigma_u = \left[\frac{\Tau(1+\beta) * sin\left(\frac{\pi * \beta}{2}\right)}{\Tau\left(\frac{1+\beta}{2}\right) * \beta * 2^{(\beta+1)/2}} \right]^{\frac{1}{\beta}} \quad (8)$$

Where $\beta = [0.25,3]$, is the size of the step that determines the search space, T is the Gamma function, the dimension of the random number generator is determined by S= $\frac{u}{|v|^{1/B}} \forall\, u \sim N(0, \sigma_u{}^2), v \sim N(0,1)$Based on the above, it is possible to update the nests by means of the expression shown in equation 9 [9]

$$nest_i^{(t+1)} = nest_i^{(t)} + \propto * S\big(\max(nest^t) - min(nest^t)\big) * r \quad (9)$$

Where , $nest_i^{(t)}$ is the current nest, while $nest_i^{(t+1)}$ it is the updated nest, on the other hand r is a random number between 0 and 1, $\propto$ is a parameter between 2 and 4. The CSA randomly selects nests, updates them, and chooses new nests which will be replaced if their value when evaluated in the target function is smaller than that of the original nests. The algorithm 3 shows the flow chart of the CSA that was implemented in this proposal

Algorithm 3 *Cuckoo Search Algorithm*

```
Initialize population
Calculate fitness f(x_i)
    While i < maximum number of iterations do
        Get a cuckoo randomly by Levy flights
        Evaluate its quality/fitness f(x_i) new candidates
        Choose a nest among n (say,j) randomly
        If F_i > F_j then
            Replace j by the new solution
        End if
        A fraction (Pa) of worse nests are abandoned and new
      ones are built
        Keep the best solutions
        Rank the solutions and find the current best
    End While
Postprocess results and visualization
```

3. METHODOLOGY

In this research process, the design of LQR's for axes φ and ϕ is proposed, where the objective functions to be optimized in this research process are shown in equations 10 and 11 for φ and ϕ, respectively. Where ITAE is the integral of the absolute error multiplied by time, IAE is the integral of the absolute error and ISE is the integral of the squared error.

$$f_{obj\varphi} = \frac{1}{\text{ITAE}_\varphi + \text{IAE}_\varphi + \text{ISE}_\varphi} \quad (10)$$

$$f_{obj\phi} = \frac{1}{\text{ITAE}_\phi + \text{IAE}_\phi + \text{ISE}_\phi} \quad (11)$$

According to what has been shown in the section corresponding to the theoretical foundation, it is necessary to represent the transfer functions expressed in 1,2,3 as a system of state matrices, this is shown in the table 1.

On the other hand, given the representation shown in Table 1, it is necessary to configure the possible solutions, $\vec{x} = \{Q_{11}, Q_{22}, Q_{33}, Q_{44}, R_{11}\}$.as shown in Table 2 for the design of the regulators shown in axes φ and φ, which are the object of study in the proposal that is documented in this work. Table 3 shows the operational characteristics of the algorithms used in this proposal, which were the same for the angles φ and ϕ

Table 1. Axis state variables of an InnoSat.

matrix / Angles	A	B	C	D
φ	$\begin{bmatrix} 0 & -1.105 & 0 & -0.1650 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$	$[0 \quad 1 \quad -0.3023 \quad 0.8088]$	$[0]$
θ	$\begin{bmatrix} 0 & 0.0071 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$[0 \quad 1]$	$[0]$
ϕ	$\begin{bmatrix} 0 & -1.105 & 0 & -0.1650 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$	$[0 \quad 1 \quad 0.3051 \quad 0.2040]$	$[0]$

Table 2. Status variables of the axes of an InnoSat.

Matrix / Angles	Q	R
φ	$\begin{bmatrix} Q_{11} & 0 & 0 & 0 \\ 0 & Q_{22} & 0 & 0 \\ 0 & 0 & Q_{33} & 0 \\ 0 & 0 & 0 & Q_{44} \end{bmatrix}$	$[r_{11}]$
ϕ	$\begin{bmatrix} Q_{11} & 0 & 0 & 0 \\ 0 & Q_{22} & 0 & 0 \\ 0 & 0 & Q_{33} & 0 \\ 0 & 0 & 0 & Q_{44} \end{bmatrix}$	$[r_{11}]$

Table 3. Characteristics of the proposed algorithms

	GA y CSA
Population size (possible solutions)	100
Population Range	$Q_{11} = rand[0,10]$ $Q_{22} = rand[0,10]$ $Q_{33} = rand[0,10]$ $Q_{44} = rand[0,10]$ $R_{11} = rand[0,10]$

4. RESULTS

For the research process documented in this proposal, comparisons were made between the ψ and φ axes since, according to the specialized literature, they present a greater difficulty for the design of regulators compared to the θ angle, which is characterized by being a second-order function. Tables 4 and 5 show the performance criteria: time of establishment,t_s over impulse, M_p. and steady-state error, E_{SS}. in addition to the errors described in the objective function for the φ and ϕ angles respectively. The best values obtained by the algorithms are highlighted in red

Table 4. Angle Performance Criteria ϕ

Performance criteria	Adjustment with GA	Adjustment with CSA
t_s	10	10
M_p	1.0422	1.0422
ITAE	0.0169	0.0186
IAE	1.6888	1.8557
ISE	0.9888	0.9748
E_{SS}	0.0089	6.2960e-04

Table 5. Angle Performance Criteria φ

Performance criteria	Adjustment with Ga	Adjustment with Cuckoo Search
t_s	20	16
M_p	1.2720	1.124
ITAE	0.0333	0.0343
IAE	3.3342	3.4324
ISE	2.0249	2.2465
E_{SS}	-3.51e-04	-2.6530e-04

The matrices Q and R that are obtained by means of a GA used in this proposal are shown in table 6 for the axes ϕ and φ

Table 6. Matrices Q and R obtained with a GA

	Q	R
φ	$\begin{bmatrix} 0.0097 & 0 & 0 & 0 \\ 0 & 1.6210 & 0 & 0 \\ 0 & 0 & 0.0018 & 0 \\ 0 & 0 & 0 & 7.2515 \end{bmatrix}$	$[11.5666]$
ϕ	$\begin{bmatrix} 21.9797 & 0 & 0 & 0 \\ 0 & 0.0037 & 0 & 0 \\ 0 & 0 & 0.0035 & 0 \\ 0 & 0 & 0 & 0.3889 \end{bmatrix}$	$[27.0171]$

The Q and R matrices that are obtained by means of a CSA used in this proposal are shown in table 7 for the axes ϕ and φ

Table 7. Matrices Q and R obtained with a CSA

	Q	R
φ	$\begin{bmatrix} 0.0494 & 0 & 0 & 0 \\ 0 & 0.0221 & 0 & 0 \\ 0 & 0 & 0.0107 & 0 \\ 0 & 0 & 0 & 0.5945 \end{bmatrix}$	$[0.9483]$
ϕ	$\begin{bmatrix} 3.9271 & 0 & 0 & 0 \\ 0 & 0.0003 & 0 & 0 \\ 0 & 0 & 0.0098 & 0 \\ 0 & 0 & 0 & 0.0422 \end{bmatrix}$	$[4.5016]$

Figures 3 and 4 show the responses to the unit step for the ϕ y ϕ axes respectively. On the other hand, the convergence of the GA and CSA algorithms, i.e. their responses, is shown in Figures 5 and 6 for the axes ϕ and φ

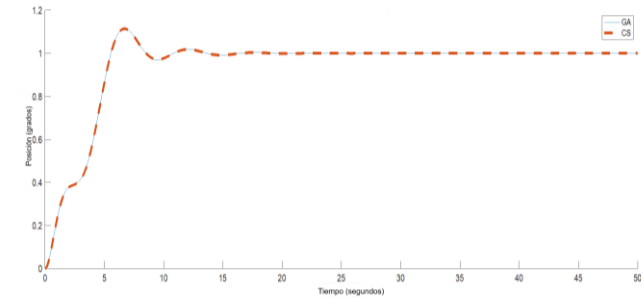

Figure 3. LQR-regulated response to the unit step of the ϕ axis

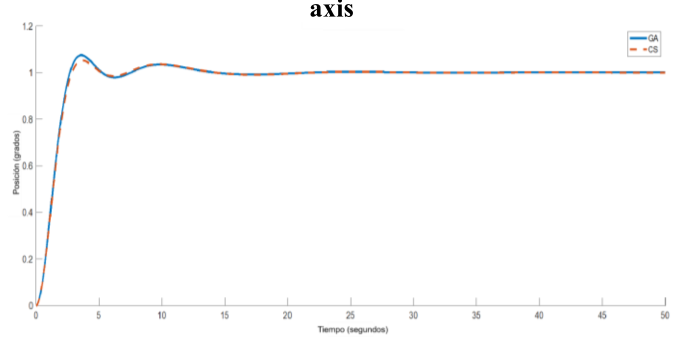

Figure 4. LQR-regulated response to the unit step of the φ axis

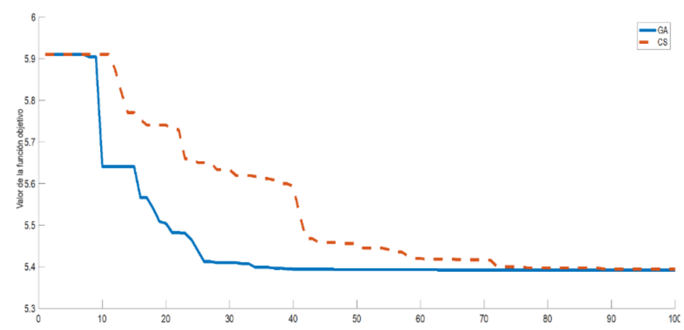

Figure 5. Axis convergence ϕ

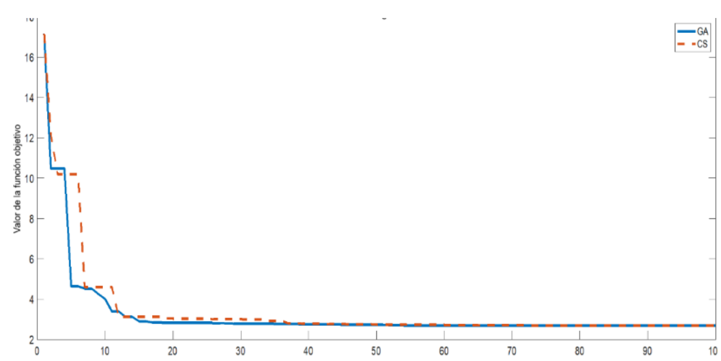

Figure 6. Axis convergence φ

5. CONCLUSIONS

As can be seen in the figures shown in the previous sections of this research process, the behavior of controllers with GA and CSA is similar, but it can be observed that the percentage of error in the steady state presents a wide improvement with respect to the adjustment made by means of a GA.

Based on the results shown, it is possible to establish future lines of action such as those described below:

1. Perform an inferential statistical analysis, which will determine if there are statistically significant differences
2. Testing new heuristic methods
3. To propose a representation of the rotation of the InnoSAt as a MIMO, multiple input, multiple output model

Efforts are currently being made in Mexico to insert the country into space exploration, efforts made by public universities in coordination with the Mexican space agency, such as the one documented in this proposal, are aimed at developing their own technology.

The axis that benefits the most from the application of the Cuckoo Search algorithm is the φ axis where it is possible to observe that the variations of the establishment time, t_s. and the percentage of overdrive , M_p. they are reduced by 20% and 11.64%. Therefore, it is necessary to study more broadly the effects of the Cuckoo Search algorithm on its variations, applied to the design of innoSat's.

For this reason, as a future work it would be necessary to hybridize both methods of solving an optimization problem such as the one raised in this proposal

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