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# Fuzzy Control MIMO for Stabilization and attitude of a Cube Sat

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**Abstract.** In the present paper, we design the Multiple Input-Multiple Output (MIMO) fuzzy control algorithm to manipulate the Inertial Mechanical System (IMS) that stabilizes the chaotic movement and attitude the CubeSat in outer space.
The inclination of the CubeSat is obtained by installing two IMS within this, installed on perpendicular faces. Each IMS consists of a reaction wheel and a motor. The torque generated by the IMS causes the angular moment that originates the inclination of the parallel axis to the CubeSat face. We will call this parallel axis a rotation axis. The inclination of each one of the rotation axes is considered a variable $\theta(t)$for each axis. Based on the Control theory, the variable$\theta(t)$is a state variable, simultaneously it is a linguistic variable of fuzzy set theory. Then we developed the Multiple Input-Multiple Output (MIMO) fuzzy control algorithm of the CubeSat's IMS. The information that is needed to build the fuzzy sets and the bases of rules for the design of the control algorithm is obtained through simulations using the Solidworks environment.

**Keywords**: CubeSat, attitude, fuzzy control.

## 1. Introduction

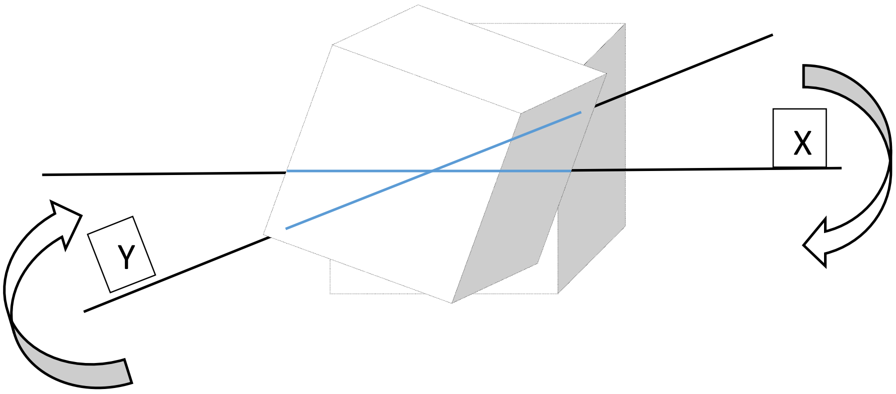
A CubeSat is made up of several subsystems and of the is the Attitude Control System (ACS), which aims to reduce its chaotic movement in outer space and guide it. The ACS has two main components: the actuator and the control algorithm. Systems that use actuators with inertial wheels have been developed, controlled by an algorithm [4]. These systems have as advantages their low cost and reliability.

In this article, we describe the development of a fuzzy control algorithm for the ACS that allows to neutralize the chaotic movement and guides the nanosatellite.

The information obtained in the use of IMS of the ACS based in other types of control using inertial wheels gives us the guideline to propose a fuzzy control applied to a CubeSat in order to make it operate in orbit.

The variables of the fuzzy control algorithm of the IMS in the CubeSat are the following: the variation of the angle of the CubeSat given by the accelerometer. and the torque obtained from the inertial mechanical system.

Control development is based on the information obtained in the simulations performed in the Solid Work environment. Through this, we define the ranges of the variables that are used in the inertial mechanical system (IMS), on which the control actions are carried out. [6],[7] y [8]. An accelerometer measures the variation of acceleration in two axes that is transformed into the inclination of the CubeSat, this information allows to control the torque that IMS must generate. An approximately high of 600 km, where a low-rise satellite is positioned, the gravity force drops by approximately 20%, respect to the earth's surface, it is viable to use accelerometers under these conditions and obtain the necessary information.



Inclinationon axis$x$: $\theta_x(y)$

Inclination on axis$y$: $\theta_y(t)$

Figure 1: inclination of CubeSat over axis.

## 2. Related literature

CubeSat development, with a mass from 1 to 10 kg, currently has great impact in spatial sciences and engineering. Meanwhile the Nano satellites CubeSat type began to be developed in the early 1999 as a strengthening collaboration among the "University State Politecny of California" and the Stanford University. This collaboration achieved to build and to put as well successfully little and cheap satellites on orbit using economic technology.
As a matter of fact the CubeSat is described as a type of Nano satellites that weighs from 1 kg and its measure is 10 x 10 x 10 cm adding 10 cm of length. Nowadays more than 50 searching groups from all around the world are developing this CubeSat type for technology proofing and for scientific and students league.
[6] In the aeronautical and astronautical department from Massachusetts Institute of Technology describes the Attitude Determination and Control System (ADCS) characteristics.

The next two works describe a Nano Satellites design considering inertia mechanical systems for its attitude. Li, J. et al. [4] uses a fuzzing embedded system and Makovec, K.L. et al. In [5] suggests an algorithm 100% Fuzzy to control a Nano Satellite's attitud. In [4] a Satellite's Attitude Control System design is introduced using cheap hardware and software for a 1U CubeSat. Considering the requirements of price and precision, it is an aspect more difficult for little satellites than have a volume, mass and power limited availability for the Attitude Control System hardware. In this design the embedded Attitude control system is described and proposed for a 1U CubeSat. The aiming can be gotten through a focus of two phases which involves the thick and thin modes. The thin mode may be achieved through using three reaction wheels and magnetorquers. The Attitude control system is designed throughout a control that uses three reaction wheels as actuators. Besides, the actuators hardware and the attitude system control designs attached for the development of prototypes are described. The test results on Earth on this document provide a promising comparison with a regulator on an adaptive fuzzy sliding mode with a common proportional integral derivative controller for a 1U nano satellite CubeSat type.

The project Virginia Tech HokieSat [5] is part of the beginning of the United States AeroSpace Force, no which the students design and build. The mission requieres an attitude determination and control system (ADCS) that supplies an appropriate spaceship control into a satellite formation, although its size is relatively small and limited assumption when using energy for flight operations. This article describes an ADCS development using a simple system, components standardized and unique algorithms that provide a reliable control of the mission. In this project, a control system using a Fuzzy control is proposed. In addition, the attitude design experience is also very relevant.

## 3. Physical analysis of the inertial mechanical system

This section describes the total system torque, considering the CubeSat and the inertial mechanical systems (IMS). The IMS is composed of a DC motor, a reaction wheel and the structure that holds and keeps fix one of the CubeSat faces.

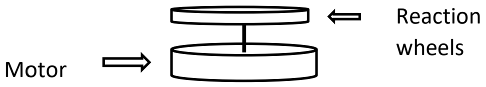


Figure 2: Inertial Mechanical System (IMS)

When the movement describes a circular trajectory, the ability of the force to spin an object is defined as torque, that is the turning capacity that has a force applied to an object

$$T = m\theta r^2 \tag{1}$$

Where $m$ is the object's mass, $\theta$ the angle of force application and $r$ the distance to the turning point.

The inertia moment considering the cubic form of the CubeSat is calculated by using the equation (2) using the mass' information and the length of the sides of the cube, Figure 2 shows the inertia moment of a solid with a cube shape.

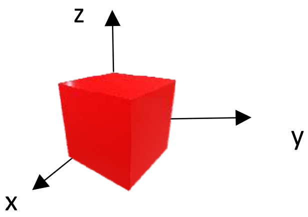
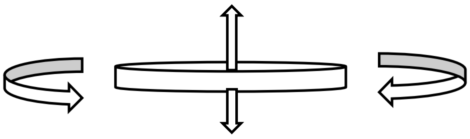


Figure 3: Solid cube

The moment of intertia of the CubeSat whith mass of 1.33 $kgs$, and the length of its sides of 0.10 $cms$, is given by

$$Ic = \frac{1}{6}ml^2 = 2.12 \times 10^{-3} Kgm^2. \tag{2}$$

For a reaction wheel whose axis is in the center with radius $r$ and mass $m$,



The inertia momentum equation is the following

$$I_d = \frac{1}{2}mr^2. \tag{3}$$

The reaction wheel that we considered for the IMS has a mass $m = 0.0229\,kg$, radius $r = 0.04\,m$. when substituting in Equation (3), we get $I_d = 1.832 \times 10^{-5} kgm^2$. From above, we can calculate the moment of inertia of the total system, which is given by $I_t = I_d + I_c$.

The total torque is composed of the CubeSat torque (cube) $T_c = I_c\dot{\omega}_c$ and the reaction wheel's torque (IMS) $T_d = I_d\dot{\omega}_d$. By taking both movements into account, we get the total torque:

$$I_t\dot{\omega} = T_c - T_d. \tag{4}$$

From Equation (4), we obtain the angular acceleration value

$$\dot{\omega} = \frac{T_c - T_d}{I_t}, \tag{5}$$

throughout it we are able to figure the system rotational kinetic energy total.

The equations that describe the Torque ($T$) and the direct current motor (DC) angular velocity ($\omega$) are given by:

$$T = K\phi_c I_a, \tag{6}$$
$$\omega = \frac{E_t - I_a R_a}{K\phi_c},$$

where $\phi_c$ is the coil flux, $K$ motor's constant, $I_a R_a$ is the loss in the field of the armor and $E_t$ is the back electro-motive force.

Equations (6) indicate the variation of the back electro-motive force, the torque is generated by the motor and the speed of itself, depending on the voltage and field supply. So that, we can control the value of the torque of the IMS, which is generated by the motor.

### 3.1 Physical characteristics of the inertial system

The angular acceleration and angular speed are fundamental to control the CubeSat. The relationship between acceleration and speed is defined by the equation $\ddot{\theta} = \frac{\dot{\theta}}{\rho}$.
where $\ddot{\theta}$ is the angular acceleration, $\dot{\theta}$ the angular velocity and $\rho$ is the time-lapse in milliseconds that we are going to apply voltage to the DC motor to generate the torque on the reaction wheel that is part of the IMS and at the same time provides the torque to the CubeSat to modify its inclination $\theta$.

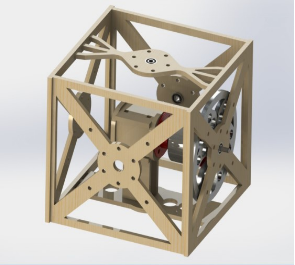


Figure 4: CubeSat with IMS installed.

The motor voltage that we consider in this work is 6 volts, we will leave the voltage fixed to simplify the control algorithm. The rpm range is $[100, 8000]$, that is equal to the angular speed range of $[13.8\ 840]$. The angular speed is generated by applying the time pulse $(\rho)$ given in milliseconds to the motor, it is important to clarify that the acceleration takes the values of $30543\ and\ 61086\ \frac{rad}{s^2}$, the speed range has more values, as described in the following graph.

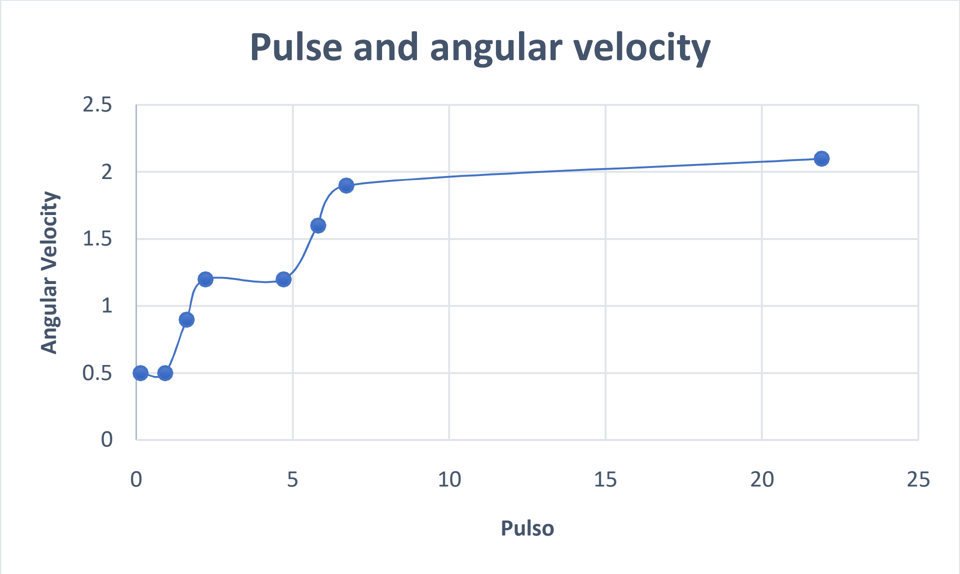


Figure 5 Relation pulse($\rho$)and angular velocity.

Table 1 shows the reaction wheel's parameters. With this information, it is known that the inertia moment generates the necessary torque to provide the CubeSat inclination on the assigned axis.

| Parameters of the Reaction wheel that is part of the inertial system |
|---|
| Density = 0.0027 Kilograms per cubic centimeter |
| Mass = 0.0229 Kilograms |
| Volume = 8.4764 cubic centimeter |
| Surface area = 85.6964 square centimeters |
| Radio = 4 cms. |

Table 1

From Table 1, the inertial moment value of the reaction wheel (see Equation (4)) is given by $I_d = 1.832 \times 10^{-5} kgm^2$. The following graph shows the data obtained by applying a voltage pulse in milliseconds to the inertial system. For each pulse we have as a result a torque value.

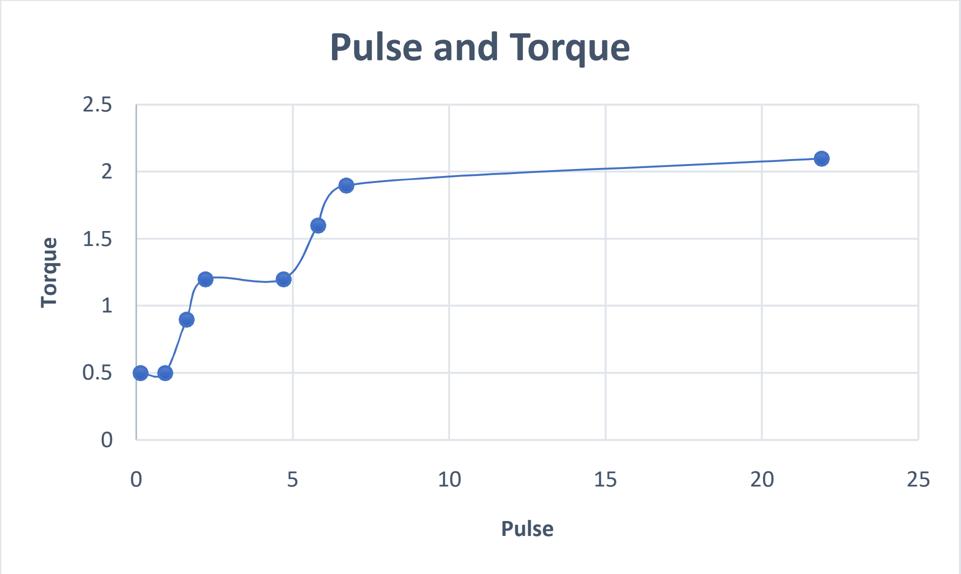


Figure 6: Relation pulse ($\rho$) and Torque (T)

The desired movement in the CubeSat is acquired at the end of the pulse, this action stops the inertial systems inside it, so that the torque is transferred to the CubeSat.
The ranges for each one of the variables are shown.

| |
|---|
| $Pulse \in [0.13, 21.9]$ |
| $Angular\ velocity \in [121.7, 839.96]$ |
| $Torque \in [0.5, 2.1]$ |

*Table 2. Pulse range, angle speed and torque.*

The CubeSat's movement is provided by the MIS force, the pulse $\rho$ is applied to the motor with a constant voltage of 6 volts, this force transfers to the reaction wheel the angular movement that generates the necessary torque.

## 4. Diffuse Control Algorithm Development

The design of a Fuzzy control algorithm based on Fuzzy logic is named Fuzzy Control (FC). And now let's introduce the elements that make it up.

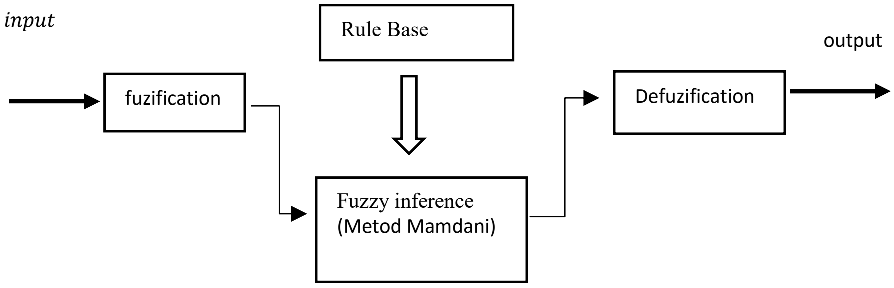


Figure 7: Fuzzy Control

In our work, the Fuzzy control is of the MIMO type, two input and two output variables, the following diagram shows the steps to consider for the Control Algorithm and subsequently for the Simulation.

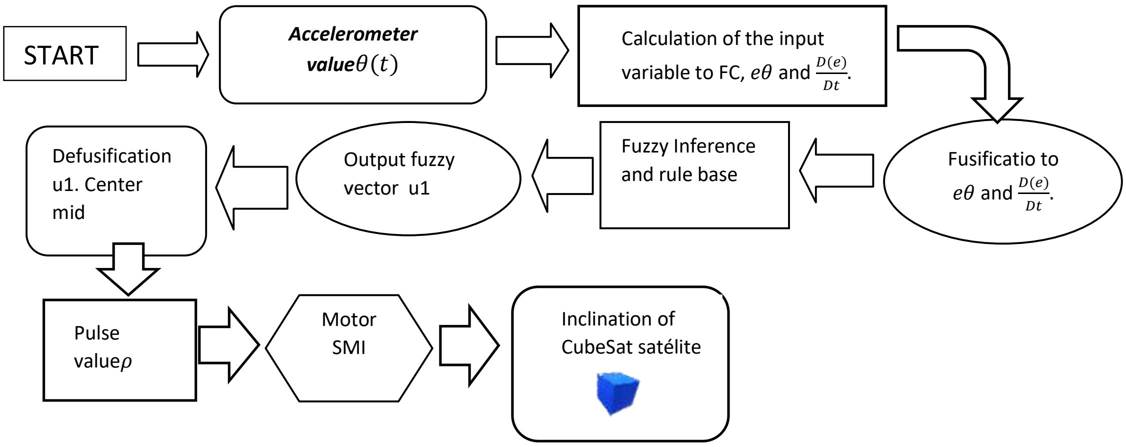


Figure 8: Control Fuzzy of Cube Sat

From Figure 8, the range of the input-output variables that we consider are:
Input variable $e_\theta \in [-30,30]$ and $\frac{D(e)}{Dt} \in [-600,600]$ and output variable $\rho \in [0.13,21.9]$.

The states of the variables and ranges of the fuzzy sets are:

| Variable | States and ranges of variable | | |
|---|---|---|---|
| $e\theta$ | NEG<br>[-30,-10] | CEN<br>[-20, 0, 20] | POS<br>[10, 30] |
| $\frac{D(e)}{Dt}$ | NEG1<br>[-6, -2] | CEN1<br>[-5, 0, 5] | POS1<br>[2, 6] |
| $\rho$ | B<br>[0.13, 1.13] | M<br>[0.16, 0, 2.16] | A<br>[1.19, 2.16] |

Table 3: Ranges of the fuzzy sets of each state variable

### 4.1 Steps of the Fuzzy Control Algorithm

1. We set the input variables $\theta_x$ and $\theta_y$, are provided by the accelerometer, the inclination for each axis of rotation established on the CubeSat. The range of the variables is: $[-30,30]$ degrees.

2. The values that enter the CD are the inclination error and the numerical derivative, respectively

$$e\theta = K - \theta \text{ and } \frac{D(e)}{Dt} = \frac{e\theta_i - e\theta_{i-1}}{0.01}.$$

3. For each input value to the CD, three membership functions are considered Triangular. The states we consider are: negative (NEG), center (CEN), positive (POS), negative 1 (NEG1), center 1 (CEN1), positive 1 (POS 1), for the inclination error ($e\theta$) and its numerical derivative($\frac{D(e)}{Dt}$), respectively.

Rule base

4. To meet the objective of the control, it is necessary to describe the rule base of the fuzzy control algorithm, we use the linguistic variables that represent the input and output variables. The rule base that represents the expert system is developed based on 7 rules of the form; IF____*THEN*____. The form of the rules in this case is as follows;

$$IF\ e\theta\ is\ NEG\ and\ \frac{D(e)}{Dt}\ is\ NEG1\ THEN\ \rho\ is\ A.$$

The rule base aredescribed below;

**Rule base**

| $\frac{D(e)}{Dt}$ $e\theta$ | NEG | CEN | POS |
|---|---|---|---|
| NEG1 | B | B | M |
| CEN1 | B | M | A |
| POS1 | M | M | A |

5. To Defusify we use center-average, we obtain the value of the output variable ($\rho$).

The pulse value is applied to the SMI, the necessary Torque for the angular motion of the CubeSat is obtained.

## 5. Fuzzy Controller Algorithm simulation to attitude the CubeSat facing the chaotic movement

The computer simulation program to simulated the CubeSat movements on an axis, $K = 0$. it is shown in the flowchart (diagram)
The input of simulation program is inclination angle $\theta(t)$ obtained by the accelerometer. The input variables of the fuzzy control algorithm, $e\theta$ y $\frac{De}{Dt}$, are obtained through $\theta(t)$ y $K = 0$, the output variable is $\rho$.

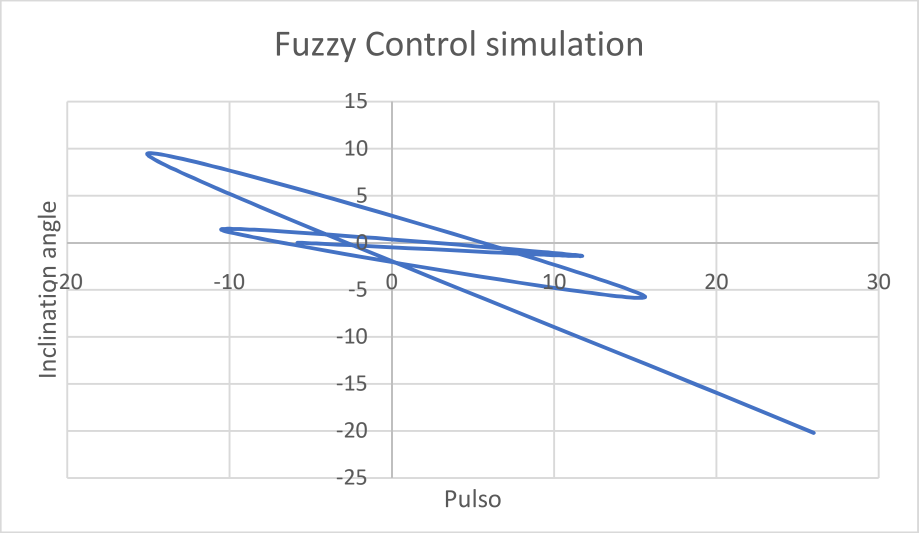


Figure 9 Fuzzy Control simulation results.

Figure 10 depict the feedback controller simulation response. Six iterations are required for the angle and pulse to converge to zero.

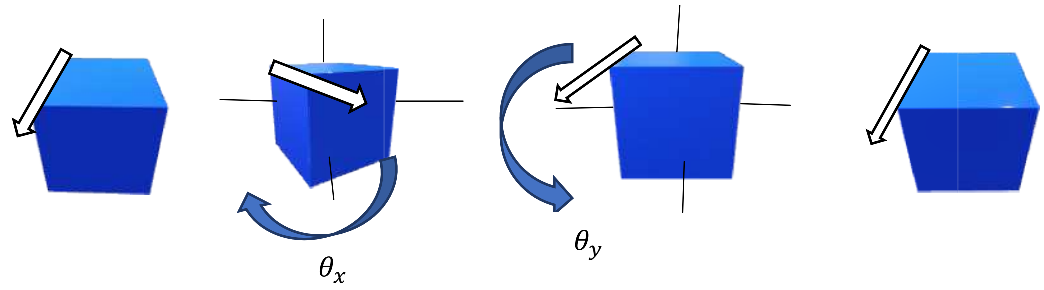


Figure10 Graphic description of the movement caused by the IMS to the Cube Sat, in both axes, to return to their initial position.

### 5.1 ACS CubeSat

In outer space, the CubeSat must be oriented towards the Earth with different tilt angles for distinct position in the orbit it describes.
To achieve this goal, we propose that $K$ belongs to the closed interval [0.5], for each of the axes. The proposed range considers a small variation in orientation. We do not have analyzed what happens if $K$ does not belong to [0.5].
In the next experimental tests, we change the $K$ value from 0 to 0 since we wish a non-zero tilt angle. It should be note that value $K$ can modified in both axes.
The graphic simulation converges to $K = 2$, over the inclination angle axis and to 0 for the pulse.

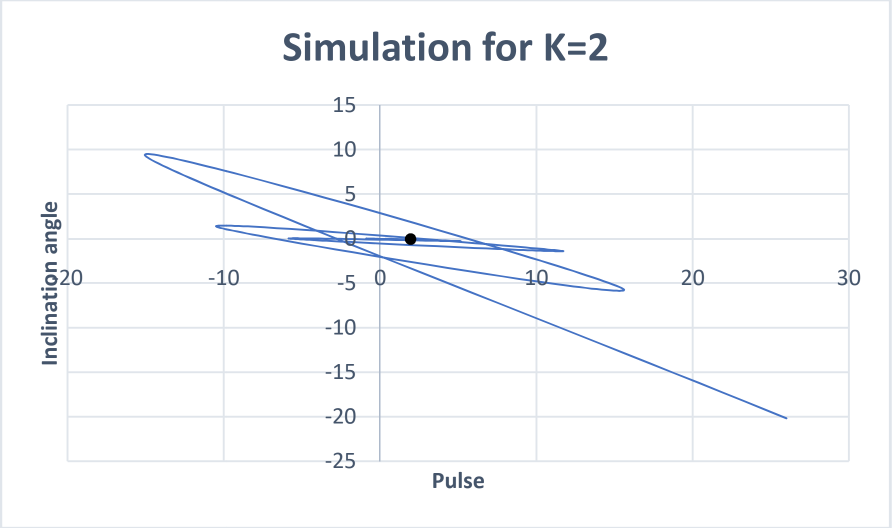


Figure 11: Results of the simulation program for $K$=2

## Conclusion

The Fuzzy control algorithm was developed to counteract the chaotic movement of a CubeSat. The algorithm let us locate it in a accurate way into the outer space. We consider that this algorithm works correctly and achieves its targets considered, to prove this, we based on the results gotten from the algorithm simulation. The data generated has their limitations, since the MIS is not able to provide results into the outer space. In the further work, we can stand by the next targets, prove the MIS with the control algorithm assembled to a base to release the CubeSat and to carry out our tests into an environment like the outer space.

A CubeSat into the outer space requires a work of an attitude system, the torque is measured in milinewtons-meters (mNm), during the simulation we noticed the torque values were bigger, but, the control system can be rebuilt to accomplish its targets in a real case. The voltage consumption should also be considered, since in a CubeSat it is limited.

As we mentioned before, when a CubeSat is in orbit it needs to modify its orientation depending on the position. This work can be adapted to the satellite's condition in orbit.

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