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DESIGN CONSIDERATION AND KINEMATIC DEVELOPMENT OF A THRUST VECTOR CONTROL SYSTEM FOR A LIQUID PROPELLANT ROCKET

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Abstract. *This paper presents important considerations and constraints in the design of a thrust vector orientation system for a liquid propellant rocket for low- orbit use to place a meteorological satellite. From a mechanical configuration of the control system of the thrust vector, a method is derived for identifying the kinematic relationships among the commanded angles by the flight inertial unit, the reference elongations of actuators and the position of the orientation system; providing a mathematical representation of the system that can evaluate the performance. Additionally, the dynamic model of the actuators is included in the kinematic model to develop a control strategy. Thus, two control strategies are proposed (on/off control and proportional differential control) and the results are evaluated*

Keywords: *rocket, thrust vector, kinematic model, kinematic control*

1. INTRODUCTION.

Rockets are space vehicles that derive their thrust from solid or liquid fuels. These fuels are burned in a combustion chamber and accelerated in a nozzle, producing gas with high speed that generates the thrust required to counteract the weight and the resistance of the displacement (drag force), allowing the vehicle to follow a position specified in the flight plan.

The Thrust Vector Control (TVC) orients the thrust generated by the combustion, such that forces are added to control the disturbances induced into the system by the misalignment of the propulsion system or by winds perpendicular to the flight path. The TVC allows modifying the flight path in order to deliberately achieve a certain position.

The condition in which a rocket, due to disturbance, creates forces or moments of restitution to take the system to the state of equilibrium or to zero angle of attack is called stability (Department of Defense United States of America, 1997), and it is usually achieved through aerodynamic stabilizers, which are responsible for putting the center of pressure below the center of gravity (Department of Defense United States of America, 1997), thus preventing the rocket from performing unwanted twists that deviate the system from the reference trajectory. When this condition is not achievable by aerodynamic stabilizers, the use of mobile devices, capable of correcting the trajectory based on preset parameters involving a control system, is needed (Aponte Rodrigues *et al*., 2010).

Different mechanisms have been proposed to make the control of the thrust vector. Sutton and Biblarz (2010) reported the main methods used in rocketry to deviate the combustion gases in both solid and liquid propellant rockets. Among the methods proposed, the gimbal mechanisms present a simple mechanic configuration. In addition, it has been proven that this technology produces medium deflection angles, with insignificant losses in the thrust (Sutton and Biblarz, 2010). Additionally, this configuration is considered the best suited from the Colombian technological standpoint regarding the project requirements.

For the thrust vector control with a gimbal type mechanism, various works have been presented (Cova, 2007), (Naguil, 2007), (Modesti, 2007). In these studies, an analytical development of the problem from different viewpoints was considered, such as kinematic, dynamic and control. Experimental prototypes were also developed to validate the results and to formulate important considerations to take into account in pivoting nozzle-type active control systems. For e.g., Jung (1993) proposed obtaining a mathematical model of the control system for a propellant rocket thrust vector, using conventional control strategies, such as linearization and root locus techniques. Lazic and Ristanovic (2007) proposed the development of a device type gimbal whit electrohidraulic actuator, modeling the system as a robotic parallel platform.

However, the design methodology adopted is not clearly discussed. Therefore, our aim is to develop a methodology for system design applied to thrust vector control, setting mechanical design considerations and constraints, establishing appropriate kinematic considerations, and a kinematic control strategy that allows the system to follow the desired path.

The paper is organized into five sections; Section 2 presents the methodological approach and the conceptual development of the mechanism, Section 3 presents a kinematic development of the mechanism, Section 4 presents the dynamic model of actuators, and Section 5 presents the strategy control to be implemented.

2. METHODOLOGY.

The mechanical design of the thrust vector control system begins with the identification of mechanical requirements and constrains of the structure, defining a conceptual design, in which appropriate kinematic constraints are generated. This information collection allows relating the angles commanded by the inertial flight unit, the elongation of the actuators and the system position.

The dynamic model of the system is not presented herein. However, this paper includes the dynamic model of power actuators; this model is used with a kinematic control strategy. All the models are integrated in the simulation of the system. The flowchart proposed for the methodology is presented in Fig.1.

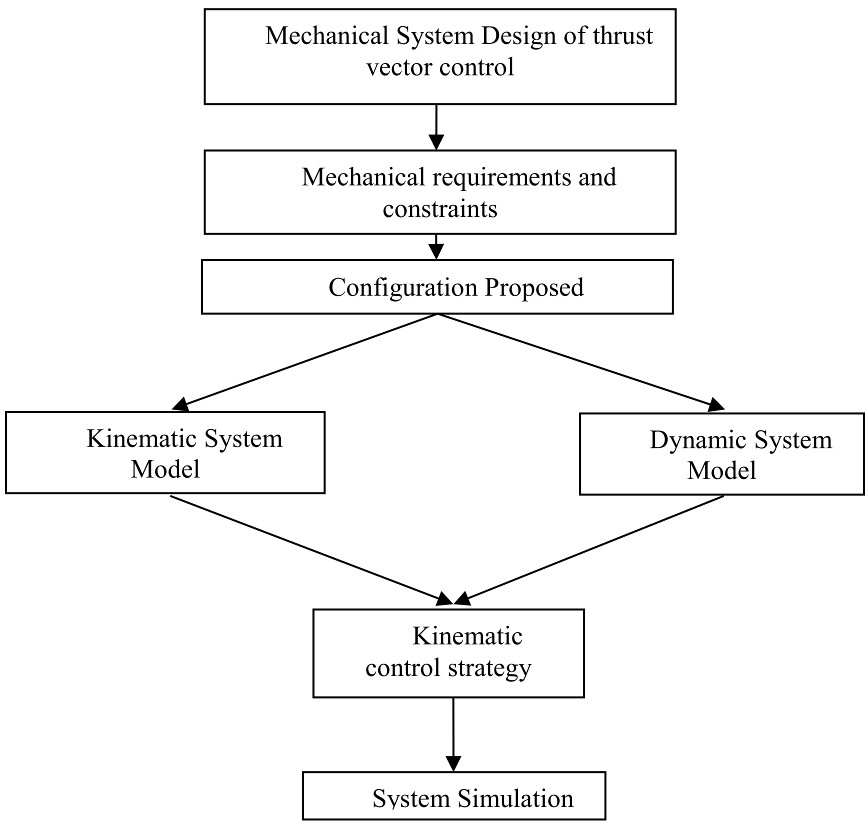

Figure 1. Methodology proposed for the design of the thrust vector control

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2.1. Mechanical requirements

Since the thrust force generated by the combustion gases in the nozzle is exerted in the direction of its symmetry axis, this axis is the one to be manipulated. It has to rotate over the pitch and yaw plane within a sweeping range of ±16°, as show in Fig.2.

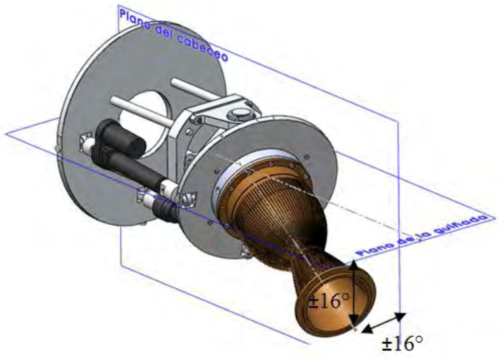

Figure 2.Nozzle angles requirements.

Additionally, the mechanism has to match the internal structure of the rocket, with a diameter of 65cm, and to be integrated with the injector-nozzle system. The latter is presented Fig.3.

Figure 3.Injector-nozzle system

2.2. Mechanical Configuration proposed

The configuration of the system proposed considers different experiences discussed in previous works reported in the literature (Tonguino, 2011; Orozco, 2008). In addition, it collects evaluation of similar configurations (Lazic and Ristanovic, 2007), which were adapted to the specific needs of this project.

The structure consists of a coupling ring with the injector-nozzle assembly, two pairs of bearings, a crosstree which functions as gimbal, an intermediate and an upper support ring, two electromechanical actuators that are responsible for generating movement, and four coupling rods acting as support, in Fig.4, these components are indicated.

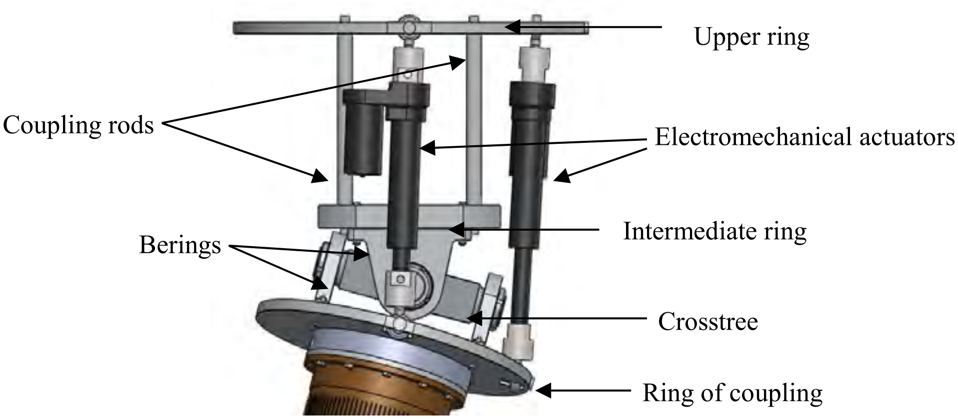

Figure 4.Components of thrust vector control

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3. KINEMATIC ANALYSIS.

The development of the kinematic model is implemented using transformation matrices with Euler angles, obtaining a relationship between command angles of the inertial unit, elongation actuators and system position.

3.1. Direct kinematics

To develop the kinematic model, an internal fixed reference $[X_f ;\ Y_f ;\ Z_f]^T$ is defined, with its origin point at the center of the crosshead, the Z axis coincident with the reference axis of the rocket, and an internal mobile reference $[X_p ;\ Y_p ;\ Z_p]^T$, which has the same origin point as the internal fixed reference, and the Z axis is aligned with the symmetry axis of the nozzle. The set of Euler angles, and, shown in Fig 5, relates the internal fixed reference with the mobile reference by:

$$[X_f; Y_f; Z_f]^T \xrightarrow[T1(\delta_1)]{} [X; Y; Z]^T \xrightarrow[T2(\delta_2)]{} [X_p; Y_p; Z_p]^T \tag{1}$$

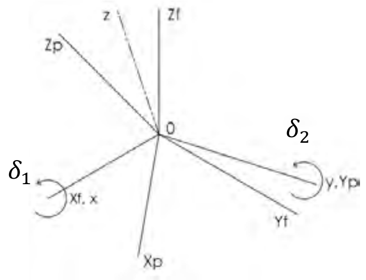

Figure 5. Coordinate system and applied rotations.

The transformation matrices are given by Eq. (1) as:

$$T1=\begin{bmatrix}1 & 0 & 0\\ 0 & cos(\delta 1) & \sin(\delta 1)\\ 0 & -sin(\delta 1) & \cos(\delta 1)\end{bmatrix}$$

$$T2=\begin{bmatrix}cos(\delta 2) & 0 & -sin(\delta 2)\\ 0 & 1 & 0\\ sin(\delta 2) & 0 & cos(\delta 2)\end{bmatrix}$$

where:

$T1$= Transformation Matrix 1.
$T2$= Transformation Matrix 2.
$\delta 1$= Euler angle applied on the X axis.
$\delta 2$= Euler angle applied on rotated Y axis.

Due to the fact that the angles commanded by the flight inertial unit are not the same angles at the crosshead, a relationship may be established from Eq.(2), which is obtained by trigonometric relationships according to Fig.6. A vector $[0; 0; -c]^T$ defines the mobile coordinate system.

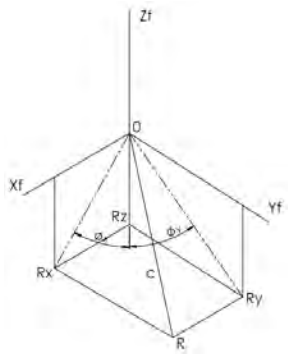

Figure 6. Angles inertial unit commanded by flight

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$$Rz = \frac{-c}{1 + (tan\,\emptyset y)^2 + (tan\,\emptyset x)^2 + (tan\,\emptyset y)\,(tan\,\emptyset x)}$$

$$Rx = \frac{-(tan\emptyset x\,)c}{1 + (tan\,\emptyset y)^2 + (tan\,\emptyset x)^2 + (tan\,\emptyset y)\,(tan\,\emptyset x)} \quad (2)$$

$$Ry = \frac{-(tan\emptyset y\,)c}{1 + (tan\,\emptyset y)^2 + (tan\,\emptyset x)^2 + (tan\,\emptyset y)\,(tan\,\emptyset x)}$$

where:

$\emptyset x$= Commanded Angle *X* by inertial unit of flight (IMU).
$\emptyset y$= Commanded Angle *X* by inertial unit of flight (IMU).
Rx, y, z = Coordinate *X, Y, Z* with respect to the fixed coordinate system.
c= Magnitude of a vector defined with respect to the fixed coordinate system from the origin to the center of the coupling ring.

If the vector [0; 0; -*c*] ^{T} is transformed with respect to the fixed coordinate system and using Eq.(1), is given by Eq.(3):

$$\begin{bmatrix} Rx \\ Ry \\ RZ \end{bmatrix} = \begin{bmatrix} c(sen\delta 2) \\ -c(cos\delta 2 sen\delta 1) = \\ -c(cos\delta 1 cos\delta 2) \end{bmatrix} \quad (3)$$

Replacing the system of Eq.(1) in the system of Eq.(3) are obtained the relationship between the cross angles and commanded angles by the inertial unit of flight by Eq.(4).

$$\delta 1 = \emptyset y \qquad \delta 2 = sin^{-1}(\frac{tan\,\emptyset x}{1 + (tan\,\emptyset y)^2 + (tan\,\emptyset x)^2 + (tan\,\emptyset y)\,(tan\,\emptyset x)}) \quad (4)$$

The elongation in the actuators can be obtained from the distances to the points of coupling between the platform and the actuators (A_p and B_p). these are transformed to fixed coordinate system using Eq.(5), using the mounting distances, Fig.7.

$$d1 = \left\|A_f - Q_f\right\| - A_i d2 = \left\|B_f - P_f\right\| - A_i \quad (5)$$

where:

$d1$= Elongation Actuator 1.
$d2$= Elongation Actuator 2.
A_f= Vector TransformationA_p= $[215.5; 0; -108.071]_p^T$ fixed coordinate system.
B_f= Vector TransformationB_p= $[0; 215.5; -108.071]_p^T$ fixed coordinate system.
Q_f= $[215.50; 0; 408.071]_f^T$
P_f= $[0; 215.50; 408.071]_f^T$
A_i= Initial elongation of the actuator

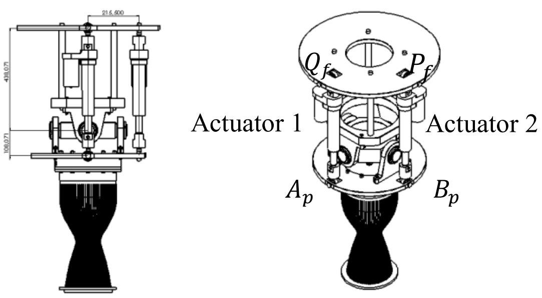

Figure 7. Mounting distances

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Once the relationships to determine the position of the platform due to the elongation in the actuators were made, a code was implemented. This code allows observing all the possible actuator elongations caused by the angles commanded by the inertial flight unit. The flowchart for this task is presented in Fig.7.

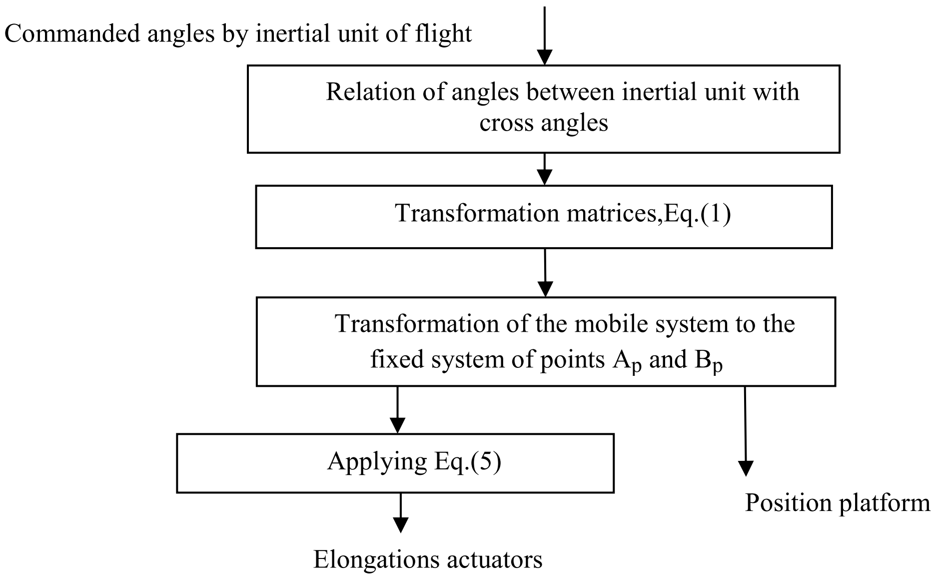

Figure 7. Flow diagram for the direct kinematic model

All the possible elongations achieved are obtained varying the actuators ∅xand∅yfrom 16° to -16°, the results are represented by contour curves shown in Fig.8, the vertical contour lines represent actuator 1elongations and the horizontal contour lines represent actuator 2 elongations.

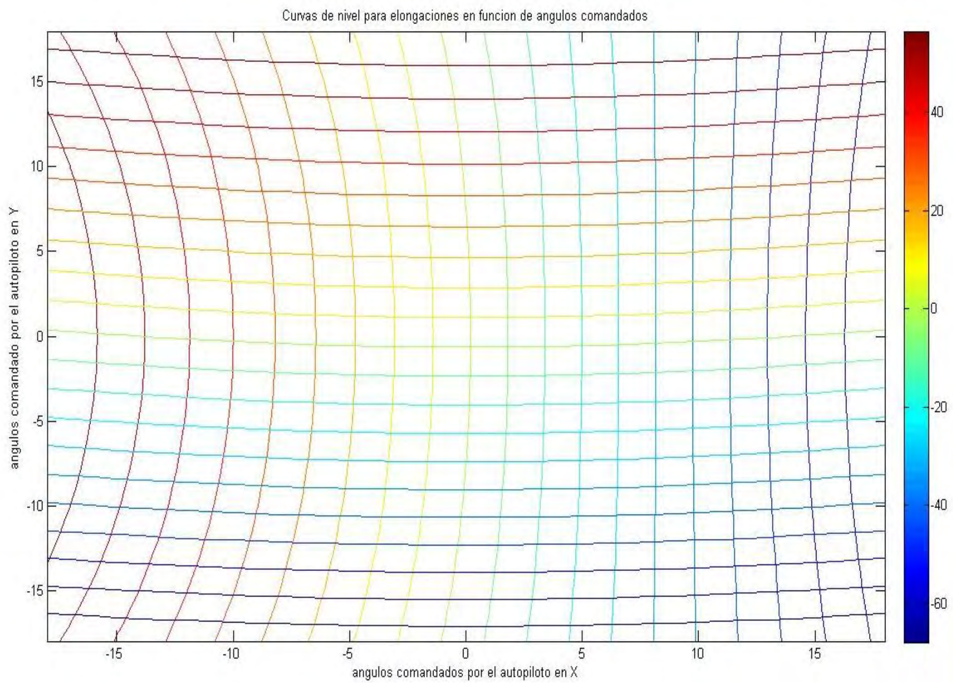

Figure 8: Elongation reached by the actuator.

3.2. Inverse kinematics

Inverse kinematics allows knowing the angles reached by the system according to actuator displacements. This model is used to feedback the autopilot of the rocket, which will help to establish a control strategy.

According to the transformation matrices given by Eq.(1), it may be rearranged as the following expression, Eq. (6).

$$T_1^{-1}A_f = T_2^{"}A_p$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\delta 1) & -sin(\delta 1) \\ 0 & sin(\delta 1) & cos(\delta 1) \end{bmatrix} \begin{bmatrix} Xf \\ Yf \\ Zf \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\delta 1) & sin(\delta 1) \\ 0 & -sin(\delta 1) & cos(\delta 1) \end{bmatrix} \begin{bmatrix} Xp \\ Yp \\ Zp \end{bmatrix} \tag{6}$$

Performing a matrix multiplication and taking separate equations are obtained the set of Eq. (7) given by:

$$X_{Af} = X_{Ap}\, cos(\delta 2) - Z_{Ap}\, sin(\delta 2)$$

$$Y_{Ap} = Y_{Af}\, cos(\delta 1) - Z_{Af}\, sin(\delta 1) \tag{7}$$

$$Z_{Af}\, cos(\delta 1) + Y_{Af}\, sin(\delta 1) = Z_{Ap}\, cos(\delta 2) + X_{Ap}\, sin(\delta 2)$$

where:

X_{Af}= *X* coordinate of point *A* with respect to the fixed system.
X_{Ap}= *X* coordinate of point *A* with respect to the mobile system.
Y_{Ap}= *Y* coordinate of point *A* with respect to the mobile system.
Y_{Af}= *Y* coordinate of point *A* with respect to the fixed system.
Z_{Ap}= *Z* coordinate of point *A* with respect to the mobile system.
Z_{Af}= *Z* coordinate of point *A* with respect to the fixed system.

Considering the first two equations of the set of Eq.(7) which are linearly independent, it is possible to calculate the values of δ_1 and δ_2. These values represent the angles at the crosstree from point *A* or *B,* which have to be previously known, in both fixed and mobile coordinate systems. The relations obtained for the angles at the crosstree are presented in Eq. (8).

$$\delta 1 = -2tan^{-1}\left(\frac{Z_{Af} \pm \left(\mathrm{Y}_{\mathrm{Af}}^2 - \mathrm{Y}_{\mathrm{Ap}}^2 + \mathrm{Z}_{\mathrm{Af}}^2\right)^{\frac{1}{2}}}{\mathrm{Y}_{\mathrm{Af}} + \mathrm{Y}_{\mathrm{Ap}}}\right)$$

$$\delta 2 = -2tan^{-1}\left(\frac{Z_{Ap} \pm \left(-\mathrm{X}_{\mathrm{Af}}^2 + \mathrm{X}_{\mathrm{Ap}}^2 + \mathrm{Z}_{\mathrm{Ap}}^2\right)^{\frac{1}{2}}}{\mathrm{X}_{\mathrm{Af}} + \mathrm{X}_{\mathrm{Ap}}}\right) \tag{8}$$

The resulting relationships show a set of solutions in the cross angles depending on the position of the platform, the solution depends on the quadrant in which the mechanism is positioned and need to be considered to establish the control strategy.

The angles in the inertial flight unit from the crosshead angles may be obtained by algebraic inversion of Eq.(4) to obtain Eq.(9).

$$\emptyset y = \delta 1 \qquad \emptyset x = tan^{-1}\left(\frac{\left(1 - 4\, sin^2\delta 2 - (4\, sin^2\delta 2 * 2\, tan^2\, \delta 1)\right)^{\frac{1}{2}} + 1}{2sin\delta 2}\right) \tag{9}$$

A systematic approach was adopted to obtain the inverse kinematics of the system; the code flow diagram is displayed in Fig.9. The actual commanded angles achieved by the inertial unit are obtained from the platform position using Eq.(8) and Eq.(9), sequentially.

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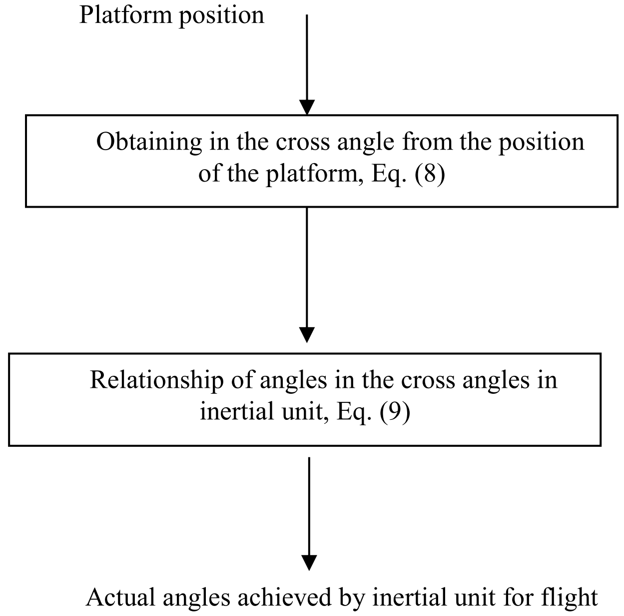
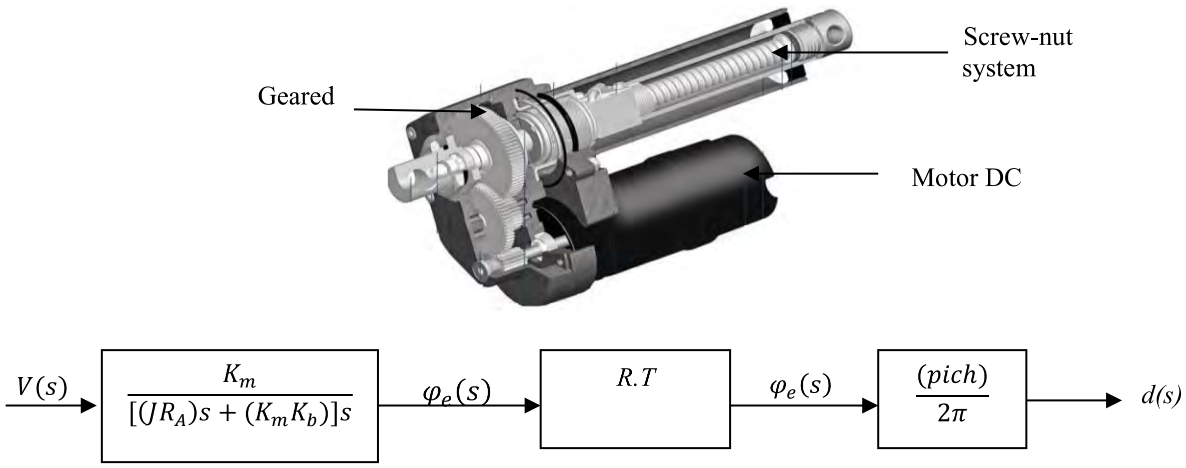


Figure 9. Flow diagram for the inverse kinematics.

4. ACTUATOR DYNAMICS.

The actuators used in the project are electromechanical. They use a DC motor, a gearbox, and a set of screw nuts, with which the rotational movement is transformed into linear movement; the overall configuration of actuators and their block diagram, expressed in the Laplace domain, allow relating the voltage applied to the motor to the rod displacement, thus obtaining a control signal. Its configuration and the transfer function of the system can be visualized in Fig.10.



where:

$V(s)$= commanded voltage
K_m= Motor torque constant
K_b= Motor voltage constant
R_A= Resistance motor armature
J=Motor inertia
$R.T$ = Transmission ratio gearbox
d(s) =Elongation reached by the actuator

Figure 10. Electromechanical actuator configuration and block diagram.

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To estimate the constants in the transfer function of the actuators, data reported by the manufacturer is used (Wander Linear, 2013), obtaining the block diagram shown in Fig.11, from the position reached, the velocity and acceleration can be derived.

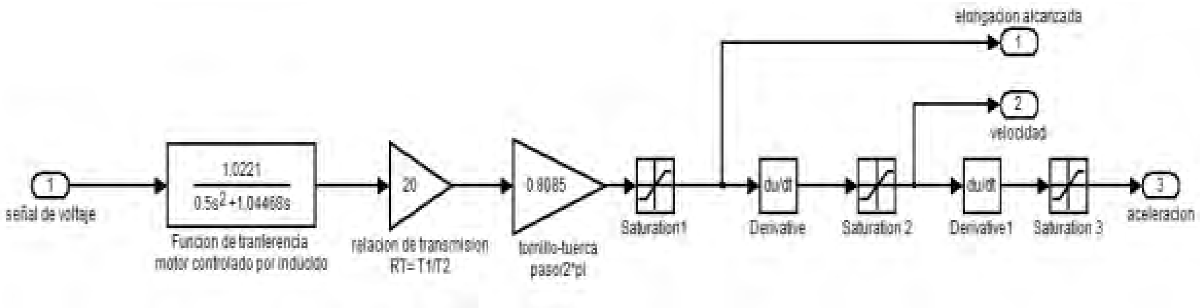

Figure 11. Block diagram parameters in the constants

5. CONTROL STRATEGY

A kinematic control was developed as a control strategy. This control allows locating the platform position from the actuator position. The control loop was implemented changing the actual elongation obtained with the dynamic model of the actuators in a voltage signal. This signal is compared with a reference voltage generated from the direct kinematic model; the flowchart of the system is shown in Fig.12.

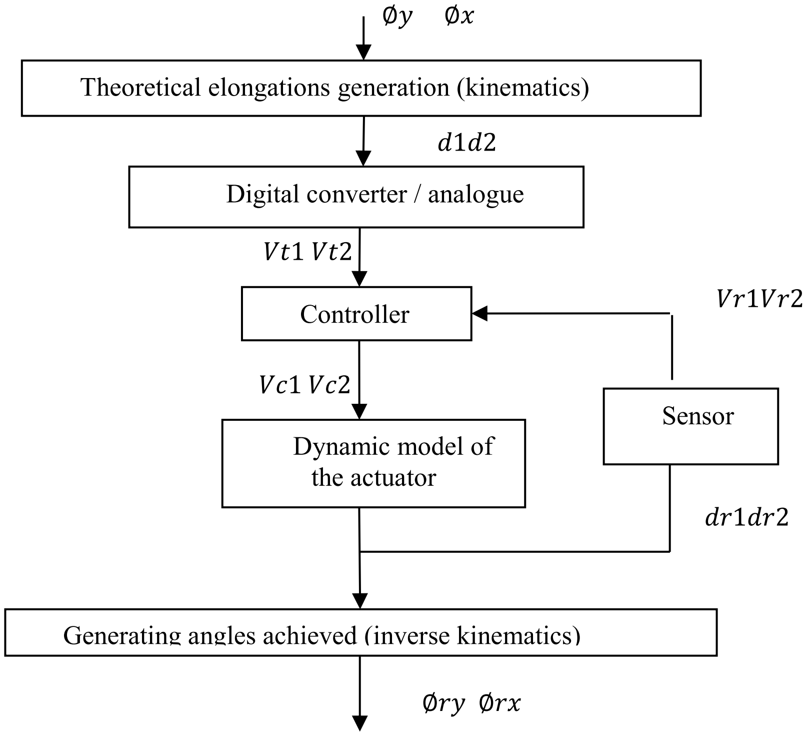

Figure 12. Flowchart of the system

The first control strategy was implemented with a two-position controller (on/off), where the voltage needed to produce the elongation of the actuator is compared with the voltage needed to produce the commanded elongation. In this regard, it calculates an error rate and establishes a control signal for two states, 12V and -12V, which represent maximum forward gear and backwards gear, respectively.

The results are shown with respect to time for positions, velocities and acceleration and for the actual angles reached at operating points $\emptyset y = 16$ and $\emptyset x = -16$.

The results showed that the response forms of the system (Fig.15) are similar to the ones of the actuators (Fig. 13 and 14). Therefore, the system response can be improved with a better actuator control. Regarding this, linear control can be used. As is typical for on/off control strategies, the system always presents oscillation. This can cause considerable wear of the power transmission and structural components. In addition, the thrust system can present unwanted movements due to this oscillation, such that the system cannot be oriented as desired.

The results show saturation in position, velocity and acceleration, which represent extremes operation values. This condition is not advisable for any mechanical or electronic component.

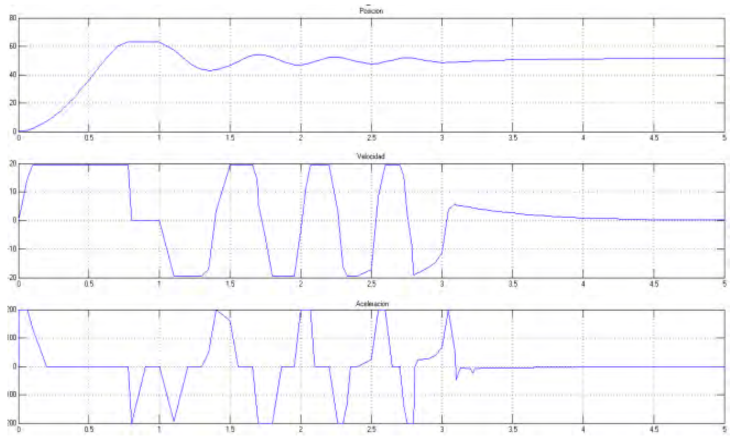

Figure 13. Results from the on/off control strategy for actuator 1.

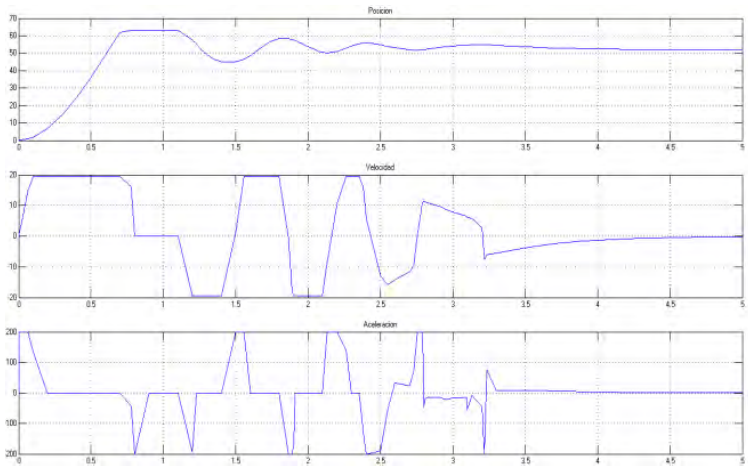

Figure 14. Results from the on/off control strategy for actuator 2.

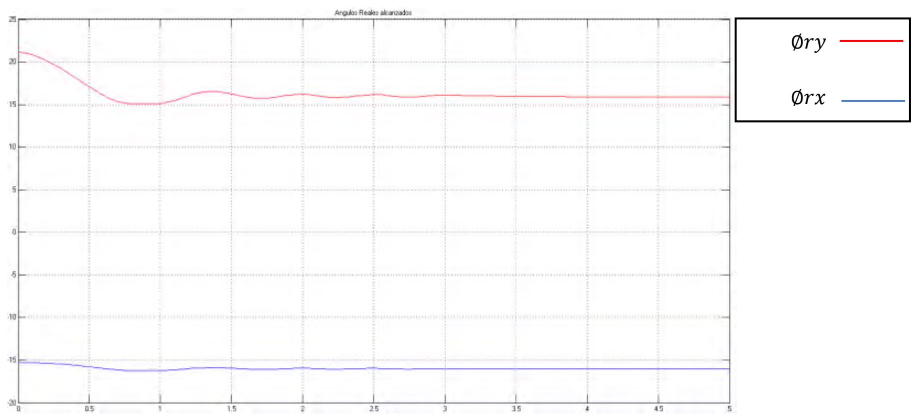

Figure 15. Actual angles achieved with the on/off control strategy

The settling time is achieved in 4s, condition that must be improved to correct any misalignment before submitting a total path loss. Thus, a different control strategy to improve the behavior of the system is required.

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Representative improvement in system performance was achieved by implementing a second control strategy, using a proportional differential controller (PD), which takes the voltage for a commanded elongation, and by means of using an adder compares this with the voltage for the reached elongation. The controller parameters were tuned in manual form with 1/4 decay criterion. The best results were achieved with values *Kp* = 10 and *Td* = 2. The results for the actuators are shown in Fig.16 and 17, and for the system in Fig.18.

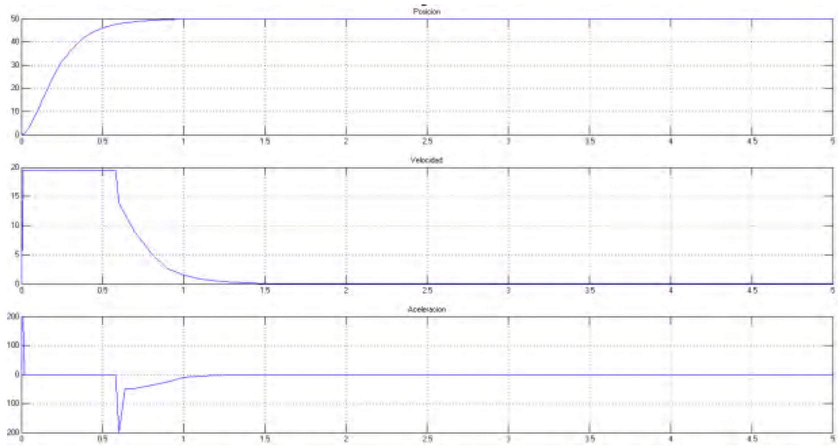

Figure 16. Results from the PD strategy for actuator 1.

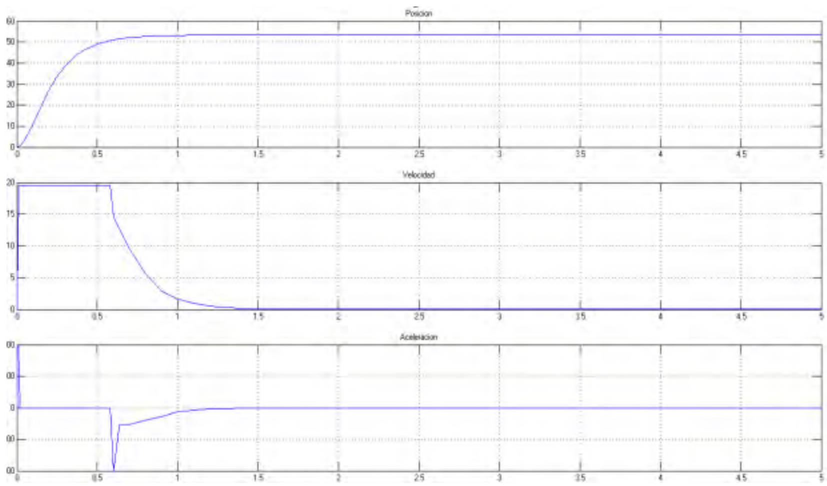

Figure 17. Results from the on/off control strategy for actuator 2.

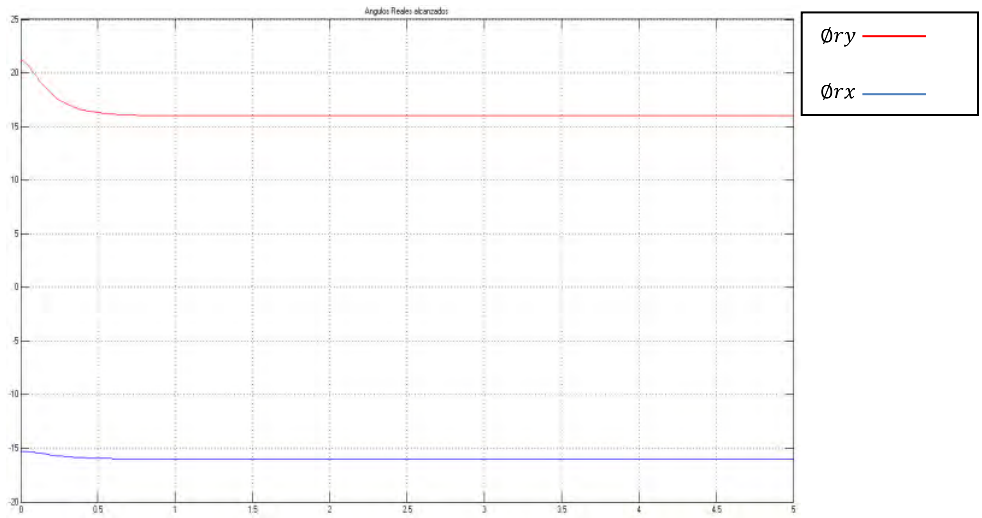

Figure 18: actual angles reached with the PD control strategy

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The PD control strategy implemented showed representative improvement in the system performance, reducing the system oscillations, and generating a damped system. Saturation points in position for this configuration were removed, preventing the actuators from working at their maximum range. The settling time was also reduced to 1s.

Manually adjusted parameters for the controller showed good performance, but improvements in the path of the nozzle axis to fit a minimal path could be achieved through the use of adaptive control to obtain the controller parameters for each operating point. Control strategies of this type are proposed as this project future work.

6. CONCLUSIONS

The development of this project allowed contributing to the Colombian aerospace development in the field of rocketry for active control mechanisms, proposing a system which allowed the manipulation of the vector thrust generated by combustion, in a sweeping range from -16° to 16° in pitch and yaw planes, obtaining an appropriate response in the system for positions, velocities and accelerations. The use of the mathematical formulation can provide a set of relationships that will allow for the evaluation of the system for different control strategies.

The direct kinematic model developed provides the elongations of the actuators to a commanded angle, allowing the generation of the reference point for control. The generation of inverse kinematics yielded a plant model, with which the system response can be observed. Comparing the two control strategies implemented: on/off control, and PD control, the latter showed representative improvements in the system response, making it possible to reduce oscillations, settling time and steady-state error. These control strategies allow the plant to be brought to a desired position, but not to have control over the path described by the symmetry axis of the nozzle.

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