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CONCEPTUAL DESIGN OF THE THRUST VECTOR CONTROL SYSTEM FOR A HYBRID ROCKET ENGINE

Olexiy Shynkarenko
Luís Guilherme Julião Simões
Lucas Vinicius de Souza Nascimento
Danielle Lima Bezerra
Rodrigo Souza
Mauricio Sá Gontijo
Jungpyo Lee
Artur Elias de Morais Bertoldi
Aerospace Engineering Department - Chemical Propulsion Laboratory, Faculty UnB Gama - FGA, University of Brasilia, Área Especial de Indústria Projeção A, Setor Leste, Gama, 72.444-240, Brasilia - Brazil
olexiy@aerospace.unb.br, lg07js@gmail.com, lucasvgyn@gmail.com, daniellelima5410@gmail.com, rodrigo96.unb@gmail.com, mauricio.sa.gontijo@gmail.com, jpleerocket@gmail.com, artur.bertoldi@aerospace.unb.br

Abstract. *This study focuses on the feasibility of implementing thrust vector control (TVC) in low-thrust hybrid motors developed in the Chemical Propulsion Laboratory (CPL) at the University of Brasilia. The authors examined the compatibility of various TVC methods with hybrid rocket engines (HRE) while considering the required Technology Readiness Level, access to structural materials, manufacturing technology, and cost optimization. They analyzed different types of TVC, including nozzle and combustion chamber gimballing, jet vanes, interceptors, and secondary subsonic and supersonic flow injection. The authors reduced the engine's mass by conducting thermal and structural analyses of the combustion chamber, reducing the thickness of the motor's walls, introducing a new thermal insulation design, and using structural materials with improved characteristics. They also simulated the flow process in the engine using the compressible turbulent model with combustion and validated the engine assembly, gimbal bearing, and test bench structures through numerical analysis. The engine's flexible connections, such as the oxidizer supply hose, gimbal connection, coupling adapters, and sensor cables, were designed according to the requirements of the engine's movement. The analytical and numerical studies allowed the authors to validate the engine with TVC and test stand structures, enabling them to proceed with the system's fabrication and testing in the laboratory.*

Keywords: *hybrid rocket engine, thrust control system, gimbal, thrust vectoring, rocket stability*

1. INTRODUCTION

This paper explores thrust control systems for hybrid rocket engines, focusing on their design and implementation. Derived from established control systems used in solid rocket engines, these hybrid engine-specific control mechanisms are crucial in regulating thrust and ensuring safe and efficient engine performance. Adapting and integrating proven concepts from solid rocket engines makes the potential for enhanced control and maneuverability in hybrid rockets feasible. This paper examines the fundamental principles, design considerations, and safety aspects of developing thrust vector control systems for hybrid rocket engines.

The authors will analyze the compatibility of various thrust vector control (TVC) methods with hybrid rocket engines, considering

- the required Technology Readiness Level,
- access to structural materials,
- manufacturing technology,
- and cost optimization.

The feasibility of employing thrust vector control systems has been considered throughout the development and construction phases of solid rocket motors (SRM). These include the utilization of jet vanes, injection of cold gas or combustion products into the supersonic region of the nozzle, liquid injection, spoilers, shields, deflectors, gimbaled control motors, rotating control motors, and split systems. Among these options, the most prevalent applications in real-world projects are found in TVC systems featuring jet vanes, gimbals, and injection of combustion products into the supersonic section of the nozzle. From a workflow standpoint, considering numerical and experimental modeling methods, all TVC systems can be conditionally categorized into major groups based on the control elements (CE) employed.

The first group encompasses TVC systems where the direction of the thrust vector is regulated by introducing a solid obstruction (gas vanes, peripheral vanes, spoilers) or a jet (transverse jet injection) into the supersonic portion of the nozzle. The flow interacts with the obstruction, forming shockwaves and separation zones, redistributing pressure on the nozzle surface, and generating a lateral control force. The interaction of a high-temperature two-phase or single-phase flow with a solid obstruction or jet causes erosion and chemical reactions, resulting in the ablation of the EC and/or the nozzle wall. When employing gas vanes or spoilers, erosion, ablation, and unstable heating of the ECs can cause changes in their shape. This characteristic makes this group of TVC systems more suitable for single-use engines since, in the case of a reusable system for multiple missions, it would require the substitution of the ECs.

For the first group of TVC systems, the study of flows involving shockwaves, heat transfer, and mass transfer is primarily required in the vicinity of the EC. Two-phase flow calculation methods for nozzles can be employed in the remaining nozzle sections, including subsonic and transonic regions.

The second group of TVC systems includes configurations with auxiliary motor rotation (gimbal) or significant portions (GTS, STS). In these cases, the flow becomes predominantly three-dimensional throughout the entire nozzle (starting from the subsonic section for the gimbal). The study of flows, heat transfer, and mass transfer must be conducted along the entire nozzle, ranging from the combustion chamber to the nozzle exit. In this scenario, parameter variations are smoother compared to the first group of ECs, allowing for the utilization of alternative numerical and modeling methods.

The TVC requirements were based on the typical flight program, trajectory, and required angular accelerations.

The authors concluded that chamber gimballing was a Brazilian research institution's only viable TVC method. However, implementing it would require significant modifications to the hybrid motor design, including mass reduction, cost reduction, flexible connections, and modifications to the test bench, which were successfully addressed in this study.

2. DESIGN OF TVC

2.1 Choice of TVC for a small thrust hybrid engine

Choosing the right TVC solution requires careful consideration of various factors, including the specific requirements of university research projects, the differences between hybrid, solid, and liquid rocket propulsion systems, and the availability of materials and manufacturing technologies. It is important to mention that, in this work, TVC systems that require additional engines are not being considered (multiple combustion chambers, extra cold or hot thrusters, etc.).

One alternative for implementing TVC in hybrid rocket engines involves secondary subsonic and supersonic flow injection. However, this approach presents challenges due to the significant nozzle length required to accommodate the inlet device (orifice) and provide sufficient internal surface area for lateral force generation. To address these challenges, certain modifications to the engine design must be considered.

Firstly, extending the nozzle length becomes necessary to increase the surface area available for injection. For example, in the current research project, it has been determined that an adequate supersonic nozzle length without TVC is nearly 20 mm, while with TVC, it should be extended to about 90 mm (Nascimento, 2023). It is important to note that such a design modification increases losses in the nozzle, making it non-isentropic and adding to its weight. Additionally, the non-optimal nozzle shape resulting from the extension may lead to oblique shock waves and excessive heating, potentially impacting nozzle durability.

Secondly, the nozzle supporting structure must be extended to withstand the high thermal stresses experienced during engine operation.

Thirdly, to obtain a reasonable impact on the thrust vector, reactive liquids or combustion gasses are more effective than inert fluids (Sutton and Biblarz, 2016). Since nitrous oxide is used as an oxidizer, it is suitable to suffer thermal decomposition, which could severely damage the nozzle (Karabeyoglu et al., 2008).

Furthermore, the design of a gas bypass system for TVC necessitates the use of reliable, high-temperature resistant pipes and valves capable of controlling injection at temperatures close to stagnation temperatures, which can reach around 3000 K, since the bypass uses gasses from the combustion chamber itself (Fahrutdinov, Kotelnikov, 1987). However, it should be noted that such specialized bypass equipment, incorporating heat-resistant alloys, may not be readily available for university research projects or may be prohibitively expensive. Additionally, thermal expansion of tubing and valves and, in the case of SRMs and HREs, erosion due to solid particles or cloggings could lead to performance losses. Moreover, another possibility of using hot gasses, which is the most effective fluid compared to inert and reactive fluids (Sutton and Biblarz, 2016), is using a gas generator that operates at a lower temperature than the main combustion chamber. However, the complexity is still high, and using a self-pressurizing oxidizer is justified to avoid such additional subsystems. Finally, this system also leads to around 0.2 to 0.8 losses (Gubertov et al., 2004).

Another TVC alternative involves using jet vanes and interceptors to control the exhaust gas flow and adjust its direction as needed. The size of the control surface depends on the engine thrust and determines the length and mass required. In the context of a small engine with a nearly 50 mm diameter exhaust jet, an effective control surface length exposed to supersonic flow could be around 25 mm, with a thickness ranging from 4 to 5 mm. However, implementing this solution presents challenges, as the small thickness of the jet vane and the high loads it experiences make it impractical to implement at institutions such as UnB. In addition, since several firings are required to qualify such systems, the jet vanes would have to be substituted often, increasing the project's overall costs. This solution is more commonly employed in missiles, leading to 1.5 to 2.8 losses due to drag (Gubertov et al., 2004).

Nozzle gimbaling is another alternative that requires the development of reliable bearings capable of operating at or being cooled to temperatures near 3000 K. This solution also necessitates the use of special materials and intricate machining of movable nozzle parts or the development of flexible, thermally resistant nozzle joints (Swain et al. 2018). Additionally, the required actuator forces are relatively high to move the nozzle to counteract the internal, external, and heat shield aerotorques and the flexseal torque. Furthermore, a minimal overshoot, a fast settling time, and a quick acceleration are desirable, making the system more complex (Jung, 1993). Moreover, in general, lower angles are provided by this type of system (Humble et al., 1995; Gubertov et al., 2004).

On the other hand, Chamber gimballing involves developing a robust gimbal mechanism capable of supporting the engine's weight under the applied thrust force. Additionally, powerful actuators must be designed to facilitate the movement of the entire combustion chamber. To reduce design requirements, the combustion chamber should be relatively lightweight, with an optimized center of mass and minimized moment of inertia, ensuring a compact configuration. It is important to note that the moving parts in such a TVC system are not exposed to high temperature or pressure forces, which simplifies the material requirements.

Table 1 compiles some of the main characteristics of each TVC system discussed above:

Table 1. Main characteristics of TVC systems.

TVC type	**Materials availability**	**Losses (1)**	**TVC angles [°] (2)**	**Main application**
Secondary injection (cold)	Available	0.2	± 5	Experimental SRM
Secondary injection (hot)	Unavailable	0.8	± 10	Ballistic missiles
Jet vanes/interceptors	Available	1.5 ~ 2.8	± 10	Missiles
Gimbal (nozzle)	Unavailable	0	± 6	Launch vehicles / ballistic missiles
Gimbal (chamber)	Available	0	± 12	Launch vehicles

(1)Compiled from (Gubertov et al., 2004)

(2)Compiled from (Gubertov et al., 2004; Humble et al., 1995; Sutton and Biblarz, 2016)

In conclusion, selecting an adequate TVC solution for hybrid rocket engines involves evaluating various alternatives and considering factors such as nozzle length, supporting structures, material availability, and engine size. Each alternative presents its challenges and trade-offs. Based on the current research, a TVC system based on combustion chamber gimballing appears to be the most promising solution for a compact hybrid rocket engine. However, further research and development are necessary to address university research projects' specific requirements and limitations.

2.2 Mechanical design

2.2.1 Engine

The prototype engine for the current development is the so-called SARA v.1 hybrid rocket engine (Shynkarenko, 2015) of 1 kN thrust working on nitrous oxide - paraffin propellants. The main characteristics of the engine are shown in Table 2. The first generation of this engine had a modular structure composed of injection, pre-chamber, chamber, post-chamber sections, and nozzle. The section parts are replaceable to study the effect of the engine geometry on its performance and stability. In such a way, replacing the design of the parts, the most optimal engine design was found experimentally.

Table 2. The main propulsion characteristics of the SARA engine.

Parameter, units	**Value**
Thrust, kN	0.963
Specific impulse, s	230.0
Oxidizer mass flow rate, kg/s	0.379
Fuel mass flow rate, kg/s	0.048
Drag efficiency	0.965

Based on the previous engine design, the authors reduced the engine's mass by conducting thermal and structural analyses of the combustion chamber, reducing the thickness of the motor's walls, introducing a new thermal insulation design, and using structural materials with improved characteristics. They also simulated the flow process in the engine using the compressible turbulent model with combustion and validated the engine assembly. Figure 1 shows the engine profile and temperature distribution in the combustion chamber after 6 seconds of operation. Here (1) is the chamber section, (2) is the nozzle, (3) is the nozzle insert, (4) is the injection plate, (5) is the oxidizer closure, (6) is the fuel grain, and (7) is the heat insulation.

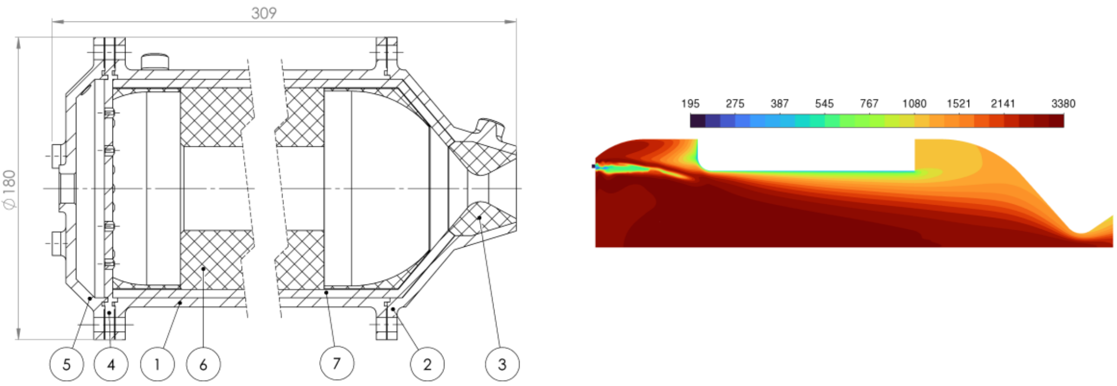

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Figure 1. Design of SARA v.2 engine: a - engine's cross-section,
b - temperature distribution in the combustion chamber at t = 6 s.

The authors coupled the blended solid fuel with EPDM (Ethylene-Propylene-Diene-Monomer) heat protection (Fig. 1) and 3D-printed rings in the pre-combustion and post-combustion sections to reduce the engine's cost. They achieved this by standardizing sizes, simplifying manufacturing, and implementing 3D printing. The engine's flexible connections, such as the oxidizer supply hose, gimbal connection, coupling adapters, and sensor cables, were designed according to the requirements of the engine's movement.

2.2.2 Gimbal

The current TVC system incorporates a two-degrees-of-freedom gimbal between the engine's combustion chamber and the oxidizer tank. To facilitate engine movement, flexible hoses are employed as feeding lines. Figure 2a illustrates the schematic of the gimbal system, featuring actuators that move in two perpendicular directions, enabling independent rotation of the engine in two axes. The distance between the gimbal's central point and the engine's injection plate allows housing movement. Similarly, the distance between the gimbal and the base plate is determined, considering the pipes' flexibility.

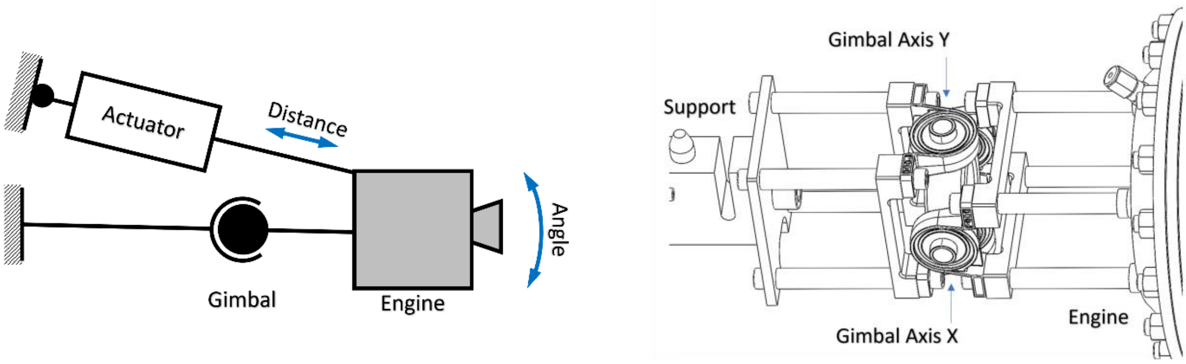

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Figure 2. Schematic of the gimbal system (a) and assembly (b).

Figure 2 depicts the main component of the gimbal system, a stainless-steel ring equipped with four pins for bearing connections. The gimbal is connected to the engine using rods. Through numerical analysis, it has been determined that the connection between the ring and the pins is the most critical part of the gimbal. These connections have undergone a thorough numerical investigation, and the results of this analysis are presented in Section 3.

Several important functions are provided by the gimbal in the thrust vector control system. Here are some reasons why the gimbal is essential to this system. In the gimbal, thrust can be directed in different directions based on the thrust generated by the engine. It is crucial for controlling the trajectory and stability of the spacecraft or rocket during flight. The spacecraft can adjust its position and orientation by directing thrust and performing necessary maneuvers and corrections. Furthermore, the ability to move independently on two perpendicular axes allows precise control of the spacecraft's attitude. It is possible to stabilize a spacecraft and correct any deviations or instabilities during flight by adjusting the angle and direction of thrust. Maneuverability is also a key factor to consider, where the gimbal system allows for complex maneuvers and maintains the maneuverability of the spacecraft. Controlling the thrust direction makes it possible to execute curves, rotations, and direction changes as needed to achieve mission objectives. Responsiveness and real-time control are important factors that make the gimbal important. This allows for quick and precise adjustments during flight, providing real-time control and allowing the spacecraft or rocket to adapt to changes in flight conditions or control commands.

To obtain the best performance from a gimbal system, it is important to consider the following key requirements when purchasing components:

1. Strength and durability: gimbal components should be constructed of high strength and durable materials capable of withstanding the forces and stresses encountered in thrust vectoring. This includes rings, connecting pins, rods, and all other system parts. Rugged components ensure the structural integrity and longevity of the system. Due to these requirements, the material used in the system was aluminum.

2. Accuracy and Stability: gimbal components must be designed to provide high precision and stability during motor movement and rotation. The connection between the ring and pin should be designed to minimize any play and ensure proper coupling to avoid unwanted movement or vibration during system operation. To determine the components' dimensions, analytical calculations were performed to analyze certain dimensions of parts already used in the market. These calculations aimed to ensure that the components would resist unwanted and unexpected movements and that their dimensions would be compatible with other parts for system integration.

By conducting analytical calculations, various factors such as load-bearing capacity, structural integrity, stability, and compatibility with other components could be considered. These calculations would help ensure that the dimensions of the parts selected would meet the requirements for the proper functioning and fit of the system.

Analytical calculations are an important step in the design and selection process, as they allow for a comprehensive evaluation of the dimensions and characteristics of the components to ensure their suitability for the intended application.

3. Durability: gimbal components should be able to withstand the stress and thrust of the motor. Consideration should be given to the weight of the motor and the acceleration forces acting on the system. Components must have sufficient load-carrying capacity to prevent structural failure or deformation during use. Due to these factors, the load cells have maximum capacities of 50 kg and 200 kg, ensuring the system operates without risks of structural failures or deformations.

4. Tolerance and Adjustment: To ensure smooth and precise operation of the gimbal system, the components must have the correct tolerance and adjustment. This allows for proper assembly and precise alignment of rings, pins, and other system components, ensuring smooth motion and efficient operation.

5. Analysis and Testing: When purchasing gimbal components, it is important to consider the availability of numerical analysis and testing availability. These analyses and tests provide data and information on the structural strength, integrity, and performance of the components and aid in selecting the best product for the gimbal system.

2.2.3 Actuators

Actuators play a vital role in TVC systems by converting the rotary motion of a motor into controlled linear motion. It enables precise control of thrust vectoring, meeting performance requirements, and ensuring proper integration with other system components. This is critical for the stability, maneuverability, and control of a spacecraft or rocket during flight.

To facilitate the operation of the TVC system, two linear actuators are installed. A stepper motor is connected to a linear shaft through a gear mechanism, enabling the rotational motion of the motor to be transmitted as a linear movement. This linear displacement is then converted into the rotation of the combustion chamber, thereby controlling the thrust vector.

The selection of suitable actuators is based on several key requirements, including the availability of electric power onboard, the required stroke length, and the desired linear movement speed. The electric power supply is contingent upon factors such as the duration of operation and the battery capacity installed on the rocket. Given the relatively short active operation time of the hybrid engine, typically 10 to 20 seconds, the power source can be relatively compact.

The actuators' stroke length and linear movement speed are crucial parameters that influence the kinematic configuration of the TVC system. These parameters are determined to meet the angular engine speed requirements and maximum deflection angle. The relationship between the engine's moment of inertia, angular acceleration, and momentum force can be expressed using Equation (1)

$$I\,\ddot{\varphi}(t) = M_{sum} \tag{1}$$

In Equation (1), we represent the engine's rotational inertia I around the gimbal axis, $\ddot{\varphi}(t)$ denotes the engine's angular acceleration, and M_{sum} corresponds to the sum of momentum forces acting on the engine. M_{sum} considers the forces generated by the actuators, friction and the resistance to bending in the housing.

In addition to the information provided, it is essential to provide details of the specific components used in the actuator system. This example has a servo actuator, servo motor, and 200 kg capacity linear actuator.

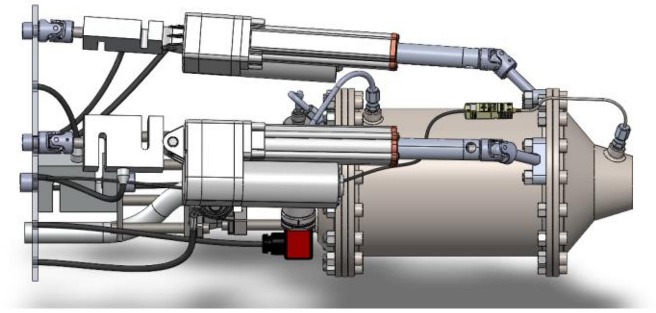
The servo driver plays a vital role in controlling the servo motor. Servo motors and their corresponding power convert electrical signals into mechanical motion. It provides the power required to drive the linear actuator and control its linear displacement. With its 200 kg capacity, the linear actuator is designed to handle substantial loads and ensure system stability and safety. The linear actuator model has specific features, such as a 100 mm stroke, which meets the linear motion requirements of the TVC system.

Integrating these components (servo drives, motors, and linear actuators) into a TVC system is critical for precise and reliable thrust vectoring control. The servo drive provides the power needed to drive the motor, which moves the linear drive to achieve the desired thrust vectoring direction. These components are selected based on the system's requirements, such as performance, resilience, and linear travel. Proper selection of these components ensures efficient, accurate, and safe operation of the thrust vectoring system.

2.2.4 Assembly

The designed assembly of the thrust vector control system is meticulously crafted to ensure reliable operation while minimizing potential failures and energy losses, thereby maintaining the desired performance of the rocket engine. Additionally, the design emphasizes reducing the size and mass of the components employed in TVC operation. This entails minimizing the number of actuators, connections, and gimbal size.

To meet the lateral and axial force requirements and the displacement of engine parts, the current design adopts two primary reference sizes: 6 mm and 10 mm threads, pins, and shafts for connecting various parts. Figure 3 shows the engine with assembled TVC and sensors on an assembling table.



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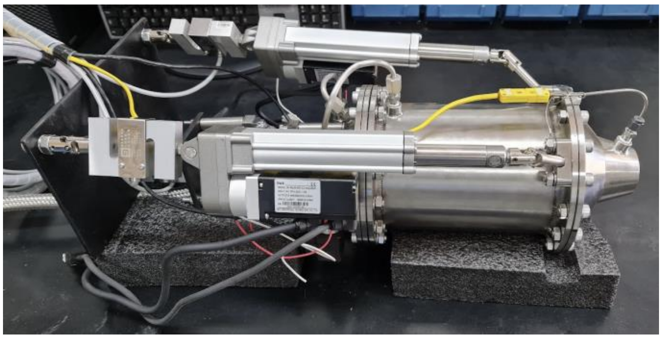

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Figure 3. Hybrid rocket engine assembled with TVC: a - 3D model, b - test model.

The design balances structural integrity and weight considerations by adhering to these reference sizes. Using standardized thread sizes, pins, and shafts facilitates ease of assembly and allows for the interchangeability and compatibility of components, enhancing the overall efficiency and versatility of the TVC system.

2.2.5 Instrumentation

The thrust vector control system in our conceptual design incorporates various sensors for precise instrumentation. The following sensors are employed:

Load Cells: Three load cells are utilized to measure forces in three directions, enabling estimation of axial and lateral TVC force components. The nominal range of these load cells is determined based on analytical and numerical analyses of the propulsion system, as discussed in Section 3.

Pressure Sensors: Two pressure sensors are incorporated into the system. One sensor is positioned before the injection plate, while the other is located within the combustion chamber. These sensors are designed to monitor low-frequency pressure behavior. In future research, they will be complemented by a high-frequency sensor to analyze instability within the combustion chamber.

Thermocouple: A thermocouple is strategically placed in the nozzle throat, recognized as the engine's most critical point. This sensor facilitates accurate temperature measurement, providing crucial data for engine performance analysis.

The data acquisition (DAQ) system employed in this project is based on the NI CompactDAQ modular system, which includes dedicated modules for acquisition and control purposes.

Additionally, the test bench instrumentation incorporates several other sensors. These include pressure and temperature sensors, a flow meter, and a load cell. The comprehensive instrumentation allows for detailed characterization and control of propellant flow before entering the hybrid engine.

2.2.6 Test bench

The environment in which the motor is tested is key to gathering data and having reliable results. In this scenario, a new vertical test bench had to be developed since a vertically mounted gimbal system alleviates the excess stresses caused on the actuators due to lateral forces from being horizontally mounted. As a basis, the new test bench is constructed on the previously developed stand (Gontijo et al, 2021). The test facility must be reliable and accommodate all needed structures, such as flame deflectors and auxiliary pipelines. With that in mind, a detailed CAD model was created using a simple lattice structure. Later, the structure was statically simulated using "*Ansys static structural*" software, with a target safety factor 1.5. The results were validated and led to constructing of the vertical test bench 1, which will be published in the future.

Additional static testing was done in the physical structure to validate and ensure safety. A hydraulic jack was used to create loads that would reflect those of a static burning test, using the targeted 1.5 safety factor.

2.3 Analytical modeling

To model the geometry of TVC movement, it was necessary to first simplify to just one actuator. Doing so makes it possible to visualize the engine just by a plane passing through its and the actuator's axes. On that plane, a coordinate system is defined with the origin on the gimbal and x-axis on the engine axis. In Figure 4, the engine's profile schematic is shown, and the nomenclature of some measurements may be explained visually. The actuator labeled part of the figure holds for the actuator itself (with a height of H_{act} and stroke length Δy_{stroke}), the load cell, and the couplings (with a combined height of h_{load_cell}).

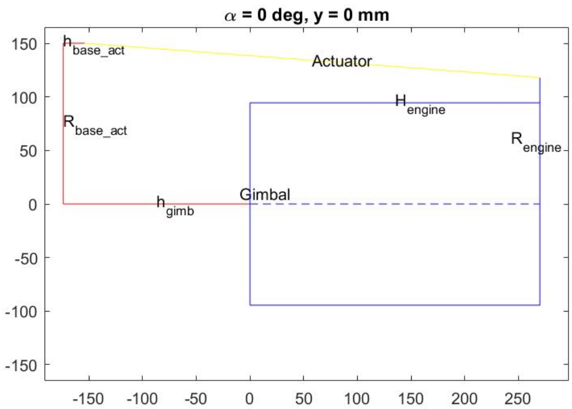

Figure 4. Schematic of the engine profile.

After that, two vectors need to be defined in Cartesian and polar coordinates: the basis vector v_b is limited by θ_b

$$v_b = (h_{base\_act} - h_{gimb}, R_{base\_act}) = v_b \angle\, \theta_b, \tag{2}$$

and the engine vector v_{eng} is limited by $\theta_{eng,0}$,

$$v_{eng}(y = 0) = (H_{engine}, R_{engine}) = v_{eng} \angle\, \theta_{eng}(y = 0) = v_{eng} \angle\, \theta_{eng,0}, \tag{3}$$

where y is the actuator displacement. It is positive in the stretching direction of the actuator and starts from the length that holds the engine in a vertical position (that means, in this section, the direction in which the engine's axis is aligned with the gimbal's axis, perpendicular to the base). Both are shown in Figure 5. And from its analysis, it is possible to see that

$$\theta_{eng}(y) = \theta_{eng,0} - \alpha(y), \quad (4)$$

where $\alpha(y)$ is the engine tilt angle, which is positive clockwise to match signs with the actuator displacement, with $y = 0 \iff \alpha = 0$ (vertical position).

The last definition is the actuator vector, that is

$$v_{act}(y) = v_{eng}(y) - v_b, \quad (5)$$

which has an important norm that can be calculated both by a Cosine Law, with an angle between the two vectors

$$\delta(y) = \delta_0 + \alpha(y), \quad (6)$$

where $\delta_0 = \theta_b - \theta_{eng,0}$ and by the actuator displacement

$$|v_{act}(y)| = H_{act} + h_{load\_cell} + (y - y_{min}) = h_0 + y, \quad (7)$$

where $h_0 = |v_{act}(y = 0)|$, which can be found by the definition of $v_{act}(y)$ since $v_{eng}(y = 0)$ is known, and $y_{min} < 0$ is the value of y so that the actuator is closed (in other words, when the actuator has a displacement of $|y_{min}|$, the engine is vertical, $y = 0$).

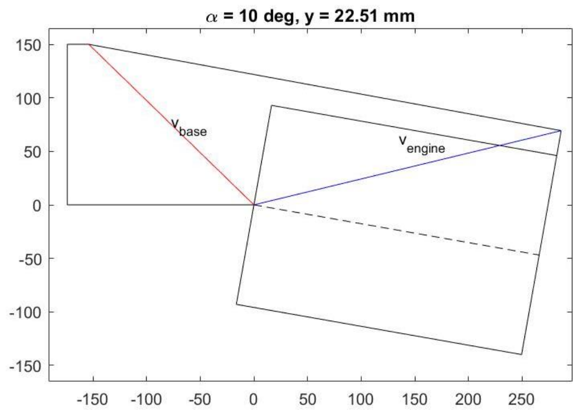

Figure 5. Schematic of the engine's vectors with $\alpha = 10\,°$.

By equaling the Cosine Law and the actuator displacement values of $|v_{act}(y)|$, considering the domain of the inverse cosine function to be $[0, \pi]$, one can demonstrate that

$$\alpha(y) = arccos\left(\frac{v_{eng}{}^2 + v_b{}^2 - (h_0 + y)^2}{2\, v_{eng} v_b}\right) - \delta_0. \quad (8)$$

And, since all constants can be determined by measurements and the definitions above, this is a direct function $\alpha = f(y)$. It is possible to demonstrate, considering the domain and codomain of the functions involved, that the inverse function is

$$y = f^{-1}(\alpha) = \sqrt{v_{eng}{}^2 + v_b{}^2 - 2\, v_{eng} v_b \cos\,(\delta_0 + \alpha)} - h_0. \quad (9)$$

The functions $\alpha = f(y)$ and $y = f^{-1}(\alpha)$ will be both central to the control algorithm later. They can also make predictions about the actuator length and arrangement so the engine's assembling can be optimized.

2.4 Numerical modeling

The numerical simulation of the engine assembly plays a crucial role in providing essential information about the loads experienced by the most critical components, such as the central gimbal and the extremities of the actuators. These load data are instrumental in validating the system design and selecting suitable models and materials for the construction of the system.

Given the complexity of the actual engine model with thrust vector control, which consists of over 100 parts, conducting a detailed simulation of the entire model would be practically infeasible without significant simplification. A simplified 3D model, as depicted in Figure 6, was developed to address this challenge. This simplified model accurately represents a body of the same size and mass as the real system, incorporating gravitational, thrust, and reaction forces.

Finite element method (FEM) analysis will be performed for four different system states: vertical and horizontal positions, with and without thrust, and at nine angle combinations of the engine in the *x* and *y* directions. This results in a total of 36 combinations of simulation cases. It is important to note that the maximum total mass of the system was assumed to be 20 kg in this study.

By conducting these simulations and analyzing the resulting data, the study aims to gain valuable insights into the structural behavior of the engine assembly under different operating conditions. These findings will inform the system design, aid in material selection, and support the construction of a robust and reliable TVC system.

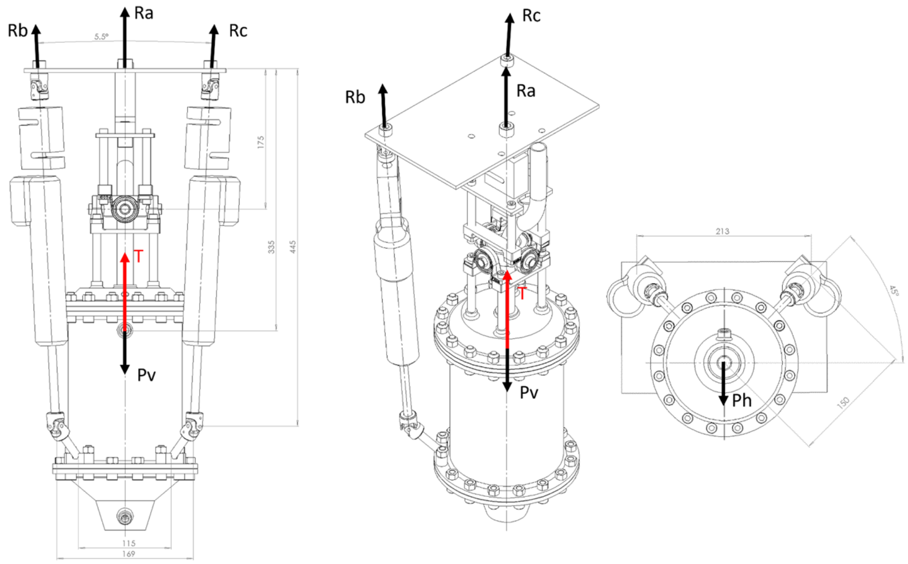

Figure 6. System schematic for numerical analysis with applied forces.

The simulation results, as depicted in Figure 7, highlight key findings regarding the forces acting on the central axis. In the horizontal motor position, the maximum reaction on the central axis is Ra = 1420 N. Additionally, when the motor is horizontal, and the thrust is zero, the maximum force applied to the actuator is recorded as Rb = Rc = -297 N.

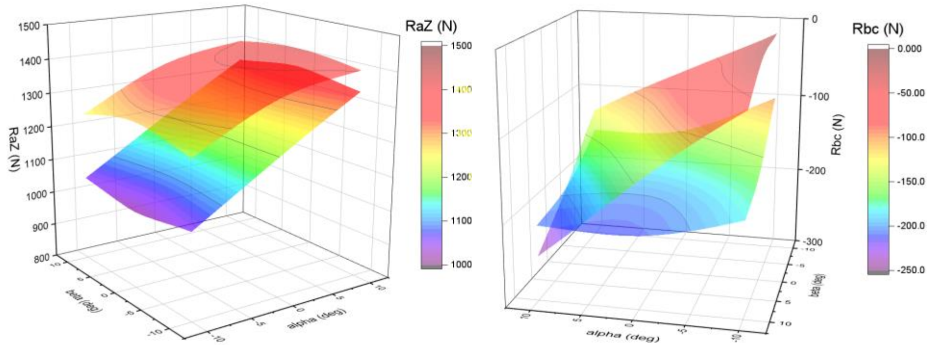

Figure 7. Results of FEM analysis for the engine with TVC.

Based on these simulation outcomes, it can be inferred that the system's minimum safety factor, as determined through numerical analysis, exceeds 2.0. This conclusion suggests that the system is designed with a sufficient margin of safety to withstand the loads experienced during operation.

However, it is important to note that future experimental tests are planned to validate the numerical simulations. These experimental tests will serve as a critical verification step, providing practical evidence to confirm the accuracy and reliability of the simulation results.

3 CONCLUSIONS

The study discussed the design and implementation of thrust control systems for a 1 kN hybrid rocket engine. Various TVC methods were analyzed, considering factors like technology readiness, materials, manufacturing, and cost optimization. The options evaluated included secondary injection, jet vanes/interceptors, gimbal (nozzle), and chamber gimballing. Considering the limitations of university research projects, the authors concluded that chamber gimballing is the most feasible TVC method for a compact hybrid rocket engine. They successfully addressed design modifications such as mass and cost reduction, flexible connections, and test bench adjustments.

The mechanical design of the TVC system, including the engine, gimbal, actuators, and assembly, was discussed, emphasizing the importance of suitable materials and components for strength, durability, accuracy, stability, and adjustability. The authors also covered the instrumentation and test bench requirements for data acquisition and reliable testing. Analytical and numerical modeling techniques were used to analyze the TVC system's behavior, including actuator displacement, engine tilt angle, and vectors involved. Finite element method analysis evaluated the system's loads and forces under different conditions, confirming its structural integrity and safety margins.

Overall, the research offered valuable insights into thrust control system design and implementation for hybrid rocket engines, with plans for future experimental confirmation on the test bench.

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