Research Paper
Journal of Smart Systems Research (JOINSSR) 3(1), 30-48, 2022
Recieved: 03-June-2022 Accepted: 28-June-2022

SAKARYA UNIVERSITY OF APPLIED SCIENCES

Design of A 3-DOF Thrust Control System for Rocket Engines

Haktan YAĞMUR[1*], Can BAYAR[1], Sinan ŞEN[1], Kasım SERBEST[1]

[1] Department of Mechatronics Engineering, Faculty of Technology, Sakarya University of Applied Sciences

ABSTRACT

Within the scope of this paper, a system that can direct the thrust of solid propellant rocket engines will be built. This method will provide high mobility for hybrid and liquid propellant rocket engines. The rocket will react to external effects (wind, etc.) that may occur while cruising. Sensors such as GYRO and IMU on the system are called TVC (Propulsion Vector Control), which provides the balance of the rocket by directing the thrust in the opposite direction of the rocket's trajectory. It also meets the requirements for angular speed control, route linearity and immediate response to emergencies. The design of the system has been created according to geometric properties, kinematics and forces, energy requirements, safety, cost, control methods requirements. Regarding the management of TVC, a literature review on TVC system design has been made first. Analyzes will be made taking into account the thrust and combustion time of the engine used. The system will be designed according to mechanical and avionic design principles. All of this is filtered out by focusing on the relevance, adaptability, economy and consistency of production. It is aimed to solve and support the software and algorithms to be created (differentiated design), thrust vector angular position and other motion problems through flow charts. With the possible design we mentioned in the report, we aim to solve similar examples of our project and to eliminate the question mark in our minds to some extent. Our project management will be carried out in accordance with work schedules, risk management and research facilities. We aim to work on projects such as literature research, system conceptual design, system visual design, preparation of the final design and the final report of the system.

Keywords: Thrust vector control, conceptual design, engineering design, product developming

1 Introduction

Propulsion Orientation consists of the modulation of the thrust vector in a variable direction other than the axial direction. The practical application of the thrust vector is achieved by mechanically turning the nozzle in different directions. By forcing and manipulating the flow in a nozzle with fixed geometry, the same effect can be achieved without operating mechanical equipment [1]. The second method, Fluid Drive Direction (FTV), uses auxiliary vents to actively manipulate and control the primary airflow to the breast. The injected fluid forms a variable "artificial" nozzle border, and the discomfort caused by secondary flow strain makes the breast wall pressure distribution asymmetrical. The resulting effect is a lateral force on the breast, which can be seen as the lateral component of the thrust vector.

In addition to providing a propellant to the rocket, it can provide moments to rotate the rocket. Therefore, it can control the attitude of the rocket and the path of flight. The direction of the propulsion

* Corresponding Author's email: haktanyagmur33@gmail.com

vector can be controlled by the mechanism, controlling the rolling and rolling motion of the rocket, and this control is effective only when the propulsion system is running and generating exhaust jets. During the flight, when the rocket propulsion system is not fired, and therefore the propulsion vector control does not work, the rocket must be provided with a separate mechanism to maintain control of its own state or flight path. In this context, the guidance of the system operating with the help of servo motors is determined as the main purpose of this article [2].

Within the scope of this article, a system capable of directing the thrust from solid-fuel rocket engines will be made. This approach will provide high maneuverability for hybrid and liquid-fueled rocket engines. The rocket will react to external influences (wind, etc.) that may occur while traveling. Sensors such as gyroscope and pressure on this system, called TVC (Thrust Vector Control), ensure to keep the rocket in balance by directing the thrust in the opposite direction of the rocket trend. It also meets requirements such as angular speed control, route linearity, and instant reaction to unexpected situations. There will be 2 servo motors on the thrust steering system. The servo motors are positioned to move on the X-axis and the Y-axis, and thanks to the gyroscope sensor on the system, the motors angle in the opposite direction of the rocket trend and the nozzle is moved by the shafts connected to the motor [3].

The design of the system is formed in accordance with the requirements of geometric properties, kinematics and force, energy requirements, safety, cost, control and operating methods. In order to manage TVC, a mixed mathematical model was first put forward by conducting a literature search for TVC system design. Analyses will be carried out by considering parameters such as the thrust force of the engine used, the burning time. The system will be designed based on avionics and mechanical design principles specific to aerospace disciplines. All these are filtered with care for suitability for production, easy integration, economy and consistency. With the software and algorithms to be created, the problems were intended to solve movements such as the angular position of the thrust vector and were supported by flow diagrams [4].

The mechanism made in this study works more effectively than systems such as Vacuum-Compatible 6-Axis Hexapod. It also includes the same avionics and software components as other Thrust Vector Systems. In this way, a design that can be integrated into all low altitude rockets has been revealed. The accuracy of all calculations and cost analyzes used in the production of the system has been examined. The design and software have been optimized for the stable operation of the system.

1.1 Movement of Rockets

Rockets are mainly aimed at getting out of the influence of the force of gravity. For this reason, a rocket must get rid of gravity in order to take off. If a force does not act on the rocket, the rocket naturally retains its status due to the law of immobility. In this part, the rocket engine comes into play. The task of the engine is to create the power to the rocket to move itself.

The rocket engine is powered by gases. For this, the gases suitable for rocket construction are heated with very high temperature. With this heat, the gas molecules begin to move rapidly, and the spraying effect caused by the movement of the gas exerts a force, which in turn moves the rocket.

It is not easy for the rocket to move from a state of immobility to a moving state. For example, your car moves comfortably on the highway thanks to its rotating wheels, or a train pushes the tracks backwards and moves forward. But there is no ground on which the rocket will receive power in this way. Rockets, therefore, ensure their movement in space with Newton's law of motion, known by Newton's statement that "there is a reaction to every effect" [5].

1.2 Rocket Fuel Preferences

There are two characteristics that are important in the selection of fuels used in spacecraft; The first is the change caused by a certain amount of fuel in the momentum of the spacecraft. The second is the magnitude of the thrust force generated by the fuel. The magnitude of the thrust is of great importance. A rocket needs to reach a speed of 28,000 km to orbit a satellite, and 40,000 km to escape the gravitational pull of the same rocket. At the same time in the selection of fuel; the stability of the fuel, its easy and safe storage and its cost are also considered. Rocket fuels are generally divided into two, liquid rocket fuels and solid rocket fuels. In rockets where liquid fuels are used, fuel and liquid oxygen are sent to the reservoir where combustion will take place. The thrust caused by the gas generated by the combustion as it exits the rocket accelerates the rocket [6].

The history of solid fuels goes back to earlier than liquid fuels. But they are not very preferable. This is because the speed of the rocket cannot be controlled as desired when they are burned. At the same time, it is not possible to stop solid fuels after reacting. For this reason, solid fuels are mostly used in support rockets that are separated from the original rocket after providing the initial speed that the rocket needs.

1.3 Solid Fuel Rocket Engines

The best part of solid-fuel rockets is that they are simple. The rocket simply consists of three parts. The first part is the load (satellite or explosive), the second part is a single fuel tank with a combination of flammable and caustic material, and the third part is exhaust. They are usually used to carry loads in or to the upper parts of the atmosphere. There is no engine assembly that allows and controls the combustion of fuel. They are the most widely used types of rockets in the military field. They can be very small in volume and size compared to liquid-fueled rockets. In the military, rockets used against tanks and planes over the shoulder use this type of fuel. They have larger wings so that they do not deviate from their course due to the resistance of air in the atmosphere [7].

In solid-propellant rockets, flammable and caustic substances are mixed homogeneously as much as possible. Therefore, if the mixture is not homogeneous, it causes regional explosions in the rocket's combustion chamber and exhaust output, so the rocket's speed is not regular. Their biggest advantage is the high thrust power. They provide thrust twice as great as liquid-fueled ones. Since the exhaust temperatures are very high, the fuel tank and the exhaust must be very robust. Some rockets have some additional devices that cool the exhaust. There is no mechanism that controls the speed and burning rate of the rocket. The absence of additional devices can be considered an advantage in one place, as it reduces the load of the rocket.

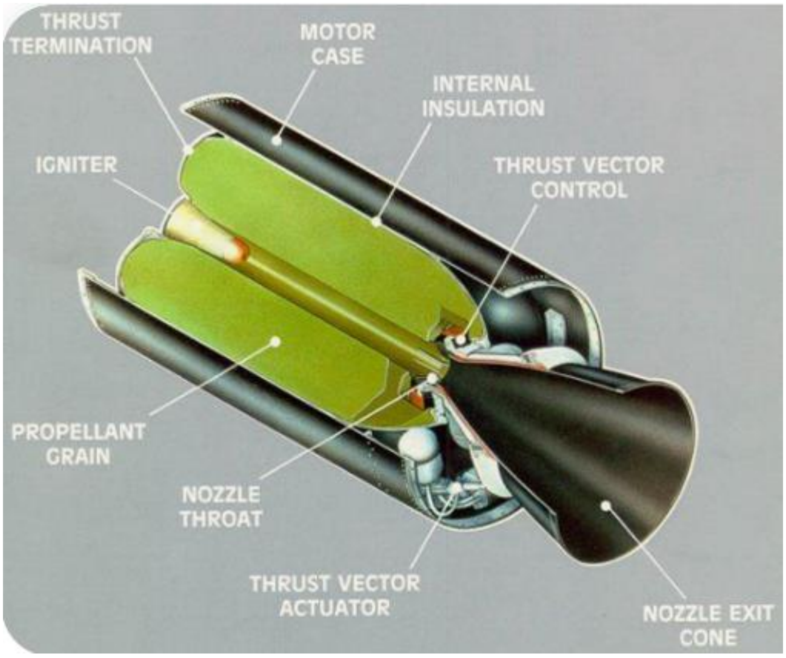

Figure 1: Cut image of solid fuel rocket engine [7]

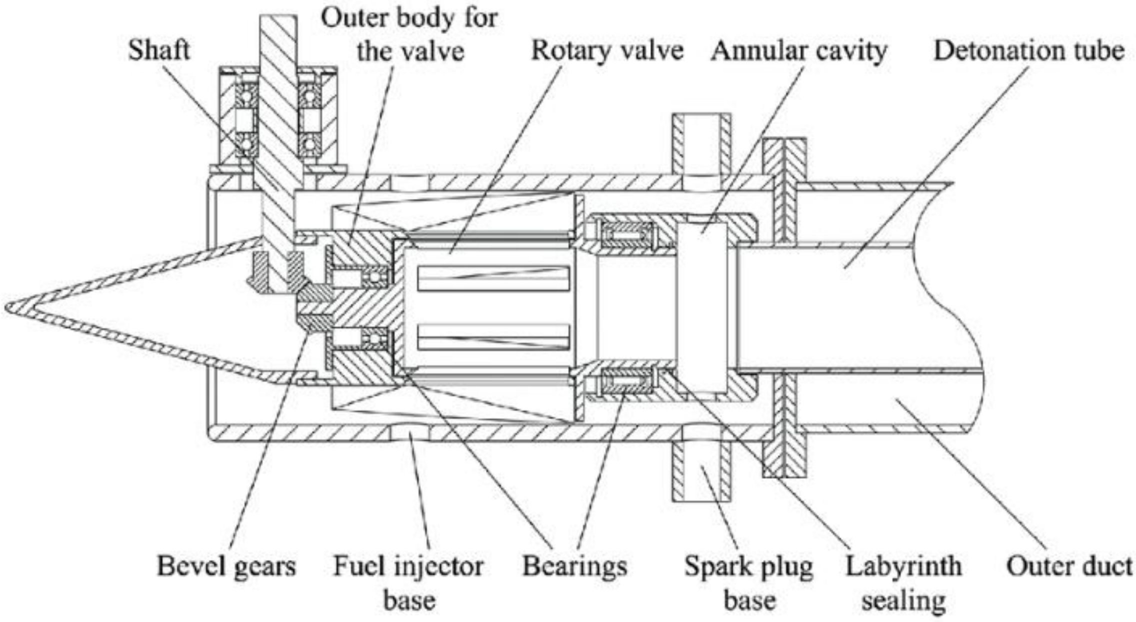

Figure 2: Detonated views of the solid-fuel rocket engine [7]

1.4 Flexible Nozzle Joint

Flexible articulated TVC systems are used today in large strategic and satellite launch systems, as well as tactical systems that require a vector angle of $5°-15°$. Flexible nozzle joints have a layered structure, which is formed by gluing and reinforcing the elastomer. Its layers are connected to each other together with the front and back rings. Orientation is achieved through shear deformation of elastomeric layers. Reinforcing layers are made of metal (steel) or composites. Elastomers used so far, silicone, natural rubber and synthetic polyisoprenes. These elastomers are used at a wide range of temperatures, making them suitable for submerged nozzles. With increasing vector angle, pressure, flexible joint torque values increase and create deformation in a shorter time. The general application in this type of nozzle joints is spherical, but there are applications of tapered design. When deflected at an angle in any direction, the layers of elastomer are subjected to cutting. The deformation and hardness of the rotated layers with a certain ratio of the total vector may vary depending on the angle. Flexible nozzle connection design involves the choice of connection configuration, the number of reinforcing elements and the choice of material can vary according to multiple factors such as elastomers [8].

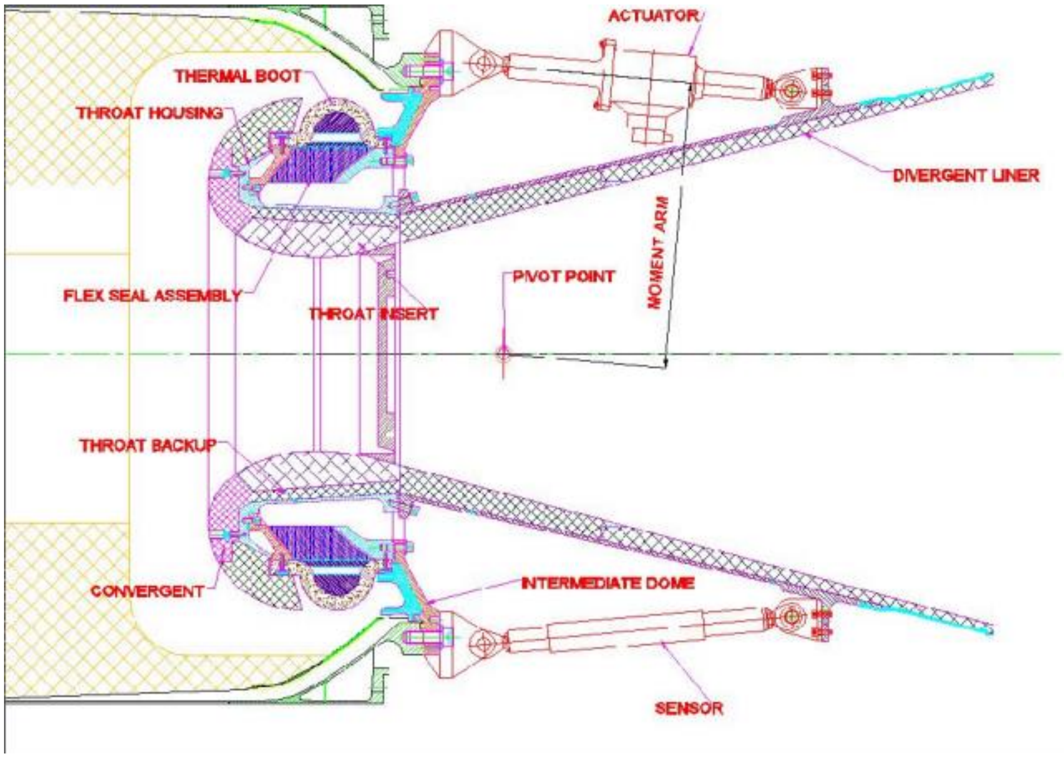

Figure 3: Flexible nozzle joint design [8]

1.5 Jet Deflector / Jet Tab / Jetavator TVC Systems

In these systems, mechanical deflectors are placed around the exit zone of the nozzle and the propulsion vector control is provided by this deflector located at the outlet. They do not create a rolling moment on these systems. Jet deflectors and jet tabs have blunt structures created to prevent flow at the nozzle outlet. Therefore, the use of jet deflectors and jet blades causes excessive loss of power. The JD at the end of the insertion nozzle causes the shock wave to occur before the deflector, and the pressure on the deflector increases. The resulting pressure increase also creates a side force.

This side force is directly proportional to the values of the JD field. The side force is adjusted by moving the JD at the nozzle output to enlarge and decrease the nozzle output area differs for side force.

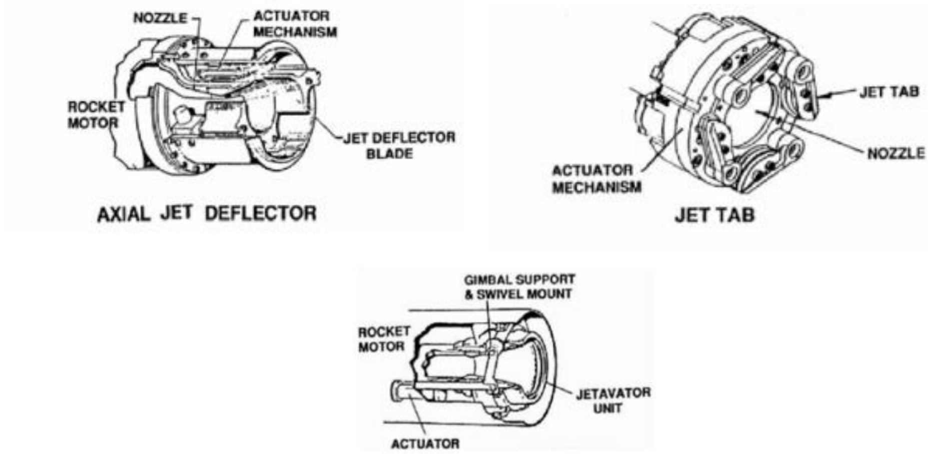

Figure 4: Jet wings and jet deflectors-tabs [8]

1.6 TVC System With Jet Valve

Jet Vane TVC systems are one of the effective TVC systems used in missiles. In TVC systems with jet wings, a blade is placed at the nozzle outlet and at the base of the blade. It follows the contour of the nozzle. In addition to the rolling moment relative to the center line, the jet creates moments of wobble and wobble. Jet wing control work was first used on the German V-2 missile. The sash is characterized by any small fins or plates that are located directly at the outlet. The principle of creating control forces using the flow of the nozzle, the wings, to control the thrust vector is like generating supersonic wing buoyancy. In the upward movement, the pressure difference and the lower sides of the jet wing provide a normal force to the beam of the jet. Normal force has a component in the direction of lifting, it is also called the side force. It is useful to control the force and missile with a security system. The main purpose of the design of a jet wing is to create a side wing. What is really created here is that there is no loss of force with minimal drag [9].

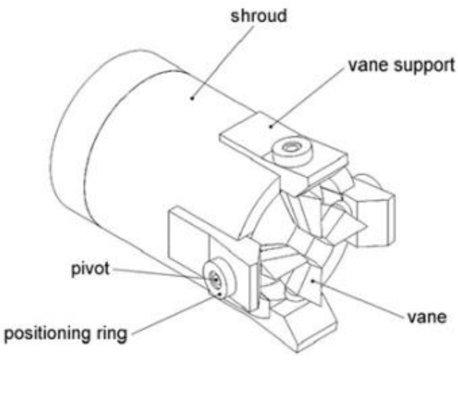

Figure 5: Jet propeller system [9]

2 Methodolgy

2.1.1 Propulsion Guidance System Design Specification

The design specification of the Propulsion Guidance System to be made here is aimed to be tabular and a more stable design is revealed.

Demands (D) are the characteristics that the nature-inspired system must meet. Wihes (W) refers to the secondary characteristics that can be found in the device.

Table 1: Design Specification

DESIGN SPECIFICATION			
	D/W		**D/W**
Geometric Features:	**D**	**Security:**	**D**
• Parts can be produced easily.		• Enviromental Security	
• Easy to integrate into the rocket		• Material Safety	
• Designing the parts so that they are intertwined		**Cost:**	
• System consistency		• Be Comptetive	**W**
		Control And Operation	
Kinematics and Force:	**W**	• Ease of assembly	**W**
• Have a high degree of freedom		• Propulsion Vector Control	**D**
• The inertia unit provides relationships between command angles, servo motors connected to the spindle and system position		• Digital control	**W**
		Material:	
• Defining an internal fixed reference		• Rigidity	**D**
		• High temperature resistance	**W**
Energy Requirement:	**D**	• Durability	**W**
• There is an energy need to drive avionics systems and servo drives along the route.		• Lightness	**W**
• Low voltage			

2.1.2 Overall Function

Overall function of the system; The energy input of the system is referred to as the electrical energy of the servo motors, the energy output of the system is also referred to as the mechanical energy generated. The thrust guidance system, which is designed as material input, is discussed. The material output is the delivery of the product to the customer. The signal input is the operation of the system through the control unit, the signal output is the system movement with the servo motor movement in 2 axes with the energy we provide from the battery [10].

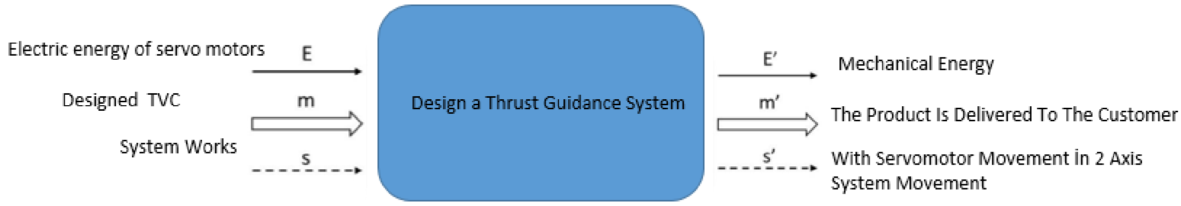

Figure 6: Overall function

2.1.3 Subfunctions

The subfunctions of the generated thrust guidance system are determined. According to the determined aerodynamic limitations, the rocket body is formed, and the product is obtained. According to the area of use, it is used in tasks such as vertical landing rocket steering, space space activities and directing warplanes.

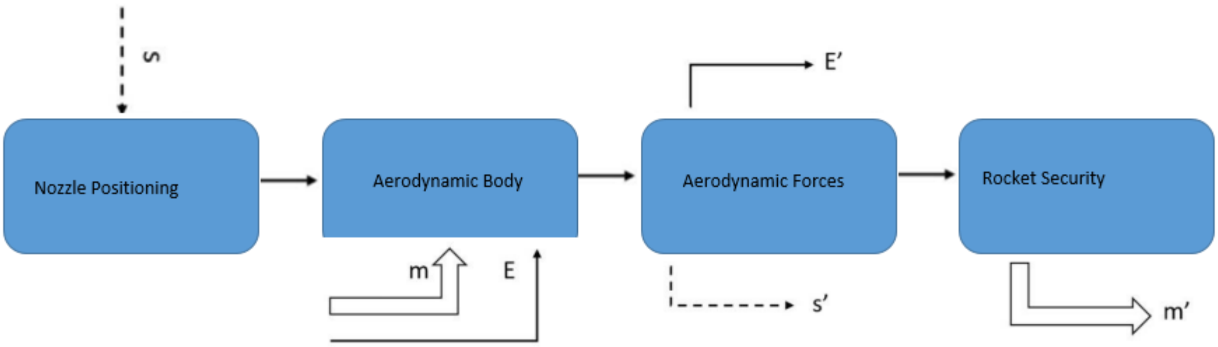

Figure 7: Subfunctions

2.1.4 Possible Designs

Movable Nozzle Thrust Vector Control Systems

The combustion gas is vectorized and moved by the deflection of the nozzle to achieve the desired thrust vector control. Moving nozzle systems are one of the most efficient. Since the system produces a thrust vector, the loss is much less than other systems.

TVC systems with moving nozzles do not have mechanical deflectors or other deflectors that can alter the nozzle angle and cause a loss of axial thrust in the flow [11].

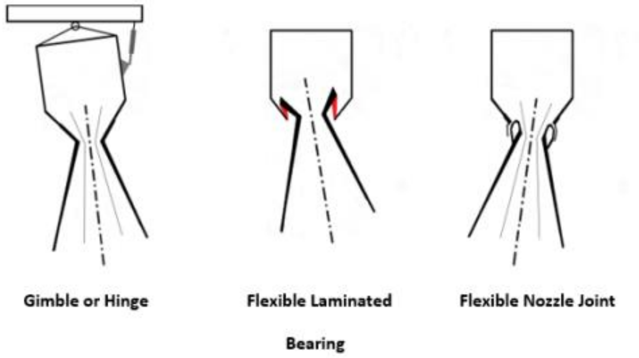

Figure 8: Movable nozzle control systems [11]

Gimbal Type Nozzle

TVC systems with movable nozzles are classified according to minor differences. In moving nozzle systems, the divergent part of the nozzle can be rotated independently. In the moving TVC system, the external geometry is divided into two parts: the throat and the fixed part. The expansion part is the moving part, and the moving part is the fixed part. The outer geometry of the most moving part is rounded and integrated like a hinge so that the fixed part can rotate around (Figure 4).

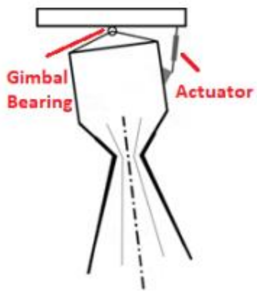

Figure 9: Gimbal type nozzle [11]

Fixed Nozzle Propulsion Vector Control Systems

In these systems, thrust vector control is provided by deflecting the exhaust gases of the rocket engine using mechanical obstacles. Such systems use a jet flap or a jet deflector. Jet wings, which mechanically change the direction of flow in the nozzle outlet area, change the direction of flow with small wings placed on the inner surface of the aircraft and provide rotational torque over jet deflector systems.

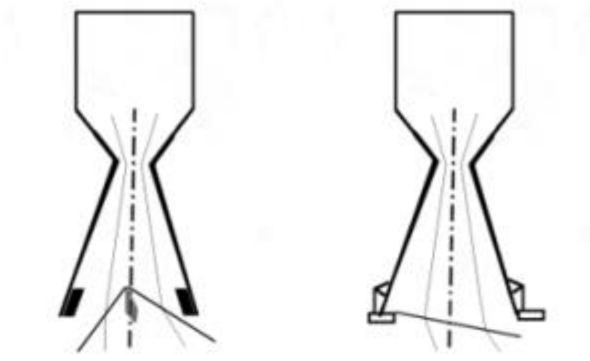

Figure 10: Fixed nozzle control system [11]

Secondary Injection Propulsion Vector Control Systems

TVC systems with secondary injection work on the principle that the flow of propellants in a fixed nozzle is driven by another secondary hot or cold gas injected (Figure 4). The secondary injection directs the flow of gas in the nozzle by disrupting the supersonic flow to create an oblique shock wave. An impulse vector is provided by the torque produced [12].

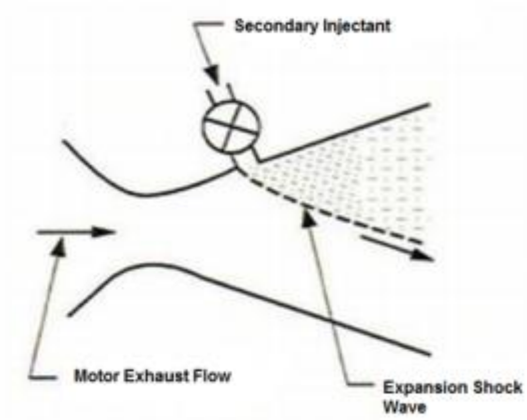

Figure 11: Secondary injection control systems [12]

Evaluation of Proposed Solutions

Determined criteria; easy maneuverability, reliability aviation compliance, aerodynamic structure, light weight are the features expected in the vehicle

• Easy maneuverability: The length, position and dimensions of the designed system should be done carefully for the system to maneuver easily in the air and to ensure smooth air climbing and advancing.

• Reliability: flight safety, electrical and systemic security of the system must be ensured.

• Aaerodynamic structure: Since the vehicle will be exposed to high altitude and aerodynamic forces in the air, the external structure must be designed appropriately according to aerodynamic forces and resistances.

• Lightness: The total rocket weight is required to be at the lightest values with payload so that the system can travel longer distances while moving through the air [13].

Objective Tree

There are 5 criteria determined in the vehicle such as easy maneuverability, reliability, aerodynamic structure suitable for public transport and individual use, lightness. It has a weighted value of 20% of all these determined criteria [14].

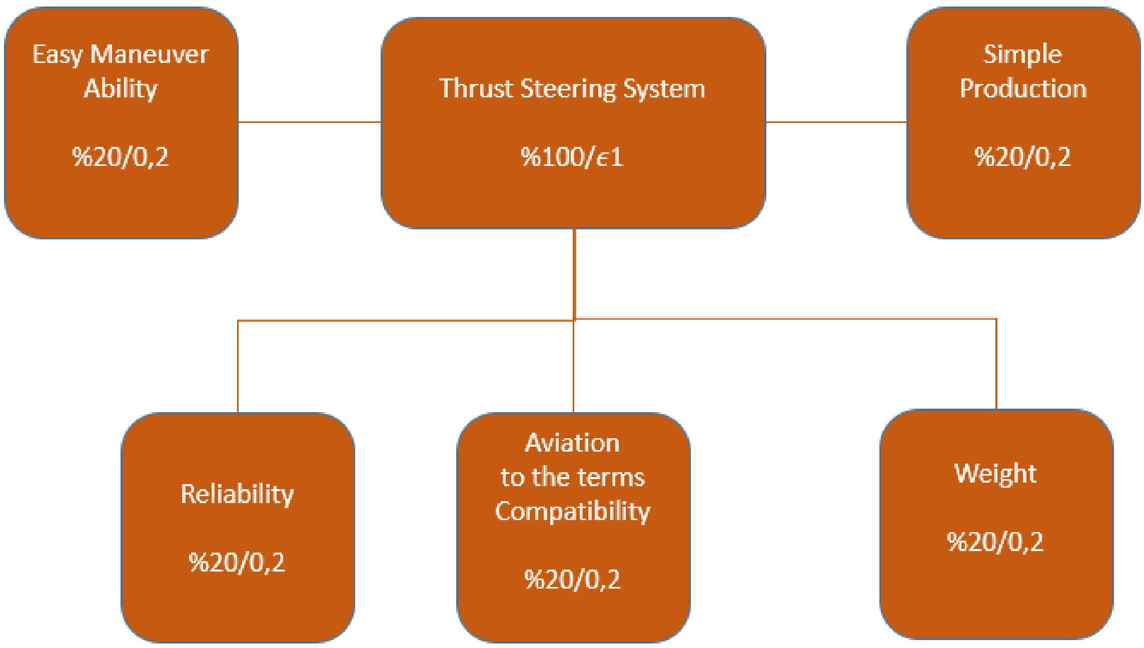

Figure 12: Objective Tree

Table 2: Evaluation of solutions

Value Analysis		**Movable Nozzle Thrust Vector Control Systems**		**Gimbal Type Nozzle**		**Fixed Nozzle Propulsion Vector Control Systems**		**Secondary Injection Propulsion Vector Control Systems**	
Criteria	Ratio	Value	w	Value	w	Value	w	Value	w
1) Maneuverability	0,2	1	0,2	2	0,6	3	0,5	3	0,5
2) Cost-Effectivenes	0,2	2	0,8	2	0,2	2	0,6	2	0,6
3) Reliability	0,2	3	0,5	2	0,5	2	0,8	2	0,8
4) Aviation Compliance	0,2	2	0,2	2	0,5	2	0,65	2	0,65
5) Simple Production	0,2	2	0,9	1	0,2	1	0,8	1	0,8
6) Weight	0,2	1	0,8	2	0,2	3	0,7	3	0,7
TotalΣ	**Σ = 1**	**Σw = 4.5**		**Σw = 3,85**		**Σw = 4,05**		**Σw = 3.7**	

Evaluation of Proposed Solutions with Table

Each of the proposed design solutions has been evaluated. Each design criterion is compared and scored 0-4.

Clearly, the possible design of the Moving Nozzle Thrust Vector Control Systems scored more points than any other possible design. It was decided to do the Movable Nozzle Thrust Vector Control System.

2.2. Mathematical Model the System

2.2.1. System Dynamics

The rotational dynamics of a general rigid body of this system is described by Euler's equations. But the system described is not a completely rigid body.

The body is constant, as we have the relative movement of the motor relative to the whole system.

and the dynamics of the engine itself. In the most general case, Euler's equations (Eq.1) were used for the s claim analyzed.

$$I\dot{\omega} = -\dot{I}\omega + M_{atm} + M_{wind} + M_{dis} + M_{TVC} + M_{RCS} - \omega \times I\omega \quad (1)$$

Here M_{atm} ve M_{wind}, represents the external moments acting on our rocket.

M_{TVC} ve M_{RCS} forces, respectively, the draging force and the moments due to the presence of the wind, M_{dis} represents the control torques applied against defects such as fuel bloating.

$$\dot{\omega} = I^{-1} + (M_{atm} + M_{wind} + M_{dis} + M_{TVC} + M_{RCS} - \omega \text{ x } \mathrm{I}\omega \tag{2}$$

It is designed to analyze the feasibility liteness and effectiveness of the TVC system, which is designed to understand what kind of improvements it can lead to with this study. To do this, the actual state of the prototype in the air is simulated, and the TVC is handled in the attitude holding function. Therefore, assuming the prototype is suspended in the air, the drag on the impact is assumed to be small and is considered negligible.

$$\dot{\omega}_x = \mathrm{I}_x^{-1} + (M_{wind,x} + M_{dis,x} + M_{TVC,x} + (\mathrm{I}_y - \mathrm{I}_z)\omega_y \text{ x } \omega_z \tag{3}$$

$$\dot{\omega}_y = \mathrm{I}_y^{-1} + (M_{wind,y} + M_{dis,y} + M_{TVC,y} + (\mathrm{I}_z - \mathrm{I}_x)\omega_z \text{ x } \omega_x \tag{4}$$

$$\dot{\omega}_z = \mathrm{I}_z^{-1} + (M_{wind,z} + M_{dis,z} + M_{TVC,z} + (\mathrm{I}_x - \mathrm{I}_y)\omega_x \text{ x } \omega_y \tag{5}$$

Since different terms describing the control torques applied by the two control systems are known, they can be written in analytical terms. As it relates to what the RCS system is concerned with, due to the specific placement of the thrusters shown, the given control torques must be reflected on the pitching and deflection axes, since they are aligned with the main axis of inertia. However, theloop-free channel of this s is the only channel where RCS is considered. About the TVC, obviously, the two control torques applied to the pitching and deflection motion are interconnected as they are provided by the same actuator (motor).

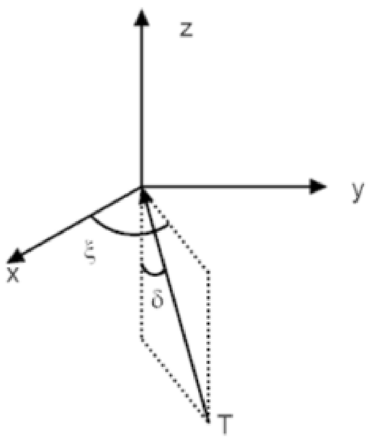

Figure 13: Thrust Vector Spherical Decomposition

where T represents the thrust vector, δ is the gimbal offset angle, and ξ is defined.

gimbal rotation angle. The demonstration usedis given below (Eq. 6, 7).

$$-90\circ < \xi < 90\circ \tag{6}$$

$$--5\circ < \delta < 5\circ \tag{7}$$

ξ is a positive rotation around z.

- ξ = 0 and δ > 0 give a positive pitching moment (moment around it)$y^{\cdot}$

According to Figure 13, the components of the thrust along the three body axesare as follows (Eq. 8, 9).

$$\vec{T} = T \begin{matrix} -sin\delta cos\xi \\ -sin\delta sin\xi \\ cos\delta \end{matrix} \tag{8}$$

S on, the moments acting on the body are as follows:

$$\overrightarrow{M_{TVC}} = Tl \begin{matrix} -sin\delta sin\xi \\ -sin\delta cos\xi \\ 0 \end{matrix} \tag{9}$$

Here l is the distance between the center of mass and the thrust centerof gravity. This coincides with the thrust center gimbal turning point.

2.2.2 Cost function and Riccati equation

With differential equations, the system can be written in the form of aset of linear equations in the form of a space state (Eq. 10).

$$x^{\cdot} = A_x + B_u \tag{10}$$

where x and u represent the state vector and the input vector, respectively. These two matrices A and B are referred to as state matrix and input matrix. This set of equations is usually complemented by the output equations (Eq. 11, 12).

$$y = C_x + D_u \tag{11}$$

$$J = \frac{1}{2}\int_0^x (x^t Qx + u^T + Ru)dt \tag{12}$$

Q and Rare square diagonal matrices in sizes (n×n) and (m×m), respectively. where n is the length of the state vector and m is the length of the input vector (Eq. 13-18).

$$H = x^T Qx + U^T Ru + \lambda^T (Ax + Bu) \tag{13}$$

$$u = -R^{-1}B^T\lambda \tag{14}$$

$$\lambda^{\cdot} = S^{\cdot}x + S(A - BR^{-1}B^T S)x \tag{15}$$

$$-\dot{S} = SA + A^T - BR^{-1}B^TS + Q \tag{16}$$

$$u(t) = R^{-1}B^TS(t)x \tag{17}$$

$$K_{opt} = R^{-1}B^TS \tag{18}$$

We see that the solution of the Riccati equation provides the optimal control law, which must be formulated in such a way as to minimize the cost function. Not always, the solution of the Riccati equation is not always possible, but onlyexists under certain conditions. The conditions mentioned in the literature are as follows.

1) Q ≥ 0 ve R > 0

2) The pair (A, C) is observable

3) The pair (A, B) can be checked

These conditions need to be mentioned because they indicate a weakness.

Although the quaternion notation parameter has several advantages, a linear model based on the exact probability of the four components cannot be precisely controlled, which makes it impossible to implement a classical LQR control. However, it has been shown that a reduced pattern of quaternioncan also be handled. K is a system that is controlled by considering only three vectorsl components of the uternion. We will examine this reduced quaternion model in the form of a subheading.

2.2.3 Reduced quaternion model

Let's use theequations of non-computational attitude kinematics by accepting Quaternion as the scalar component of the quaternion q_4 and simply construct the vectorial part of the q quaternion (Eq. 19, 20).

$$\dot{q} = \frac{1}{2}\dot{\Omega} q + \frac{1}{2}q_4 \omega b \tag{19}$$

$$\dot{q}_{A}. = -\frac{1}{2}\omega_b^T\vec{q} \tag{20}$$

In this formulation it has been shown that there is a one-to-one mapping between ω and $\dot{q}$, for which

It can be replaced by a set of nonlinear attitude kinematics equations that can lead to a linear dynamical system based on quaternion (Eq. 21-23).

$$\omega = 2\Theta^{-1}\dot{q} \tag{21}$$

$$\Theta = \begin{bmatrix} f(q) & -q_3 & q_2 \\ q_3 & f(q) & -q_1 \\ -q_2 & q_1 & f(q) \end{bmatrix} \tag{22}$$

$$f(q) = \sqrt{1 - -q_1{}^2 - q_2{}^2 - q_3{}^2} \tag{23}$$

Basically, what is done is to formulate in terms of the 4th kuternion component statement and the other three components. However, the mapping between ω and $q^{\cdot}$ occurs only when Φ= π/2 is not case (Eq. 24, 25).

$$\begin{bmatrix} q^{\cdot}{}_1 \\ q^{\cdot}{}_2 \\ q^{\cdot}{}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} f(q) & -q_3 & q_2 \\ q_3 & f(q & -q_1 \\ -q_2 & q_1 & f(q \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ q\omega_3 \end{bmatrix} \tag{24}$$

$$\mathrm{I}\,\vec{\omega} = \mathrm{u} - \vec{\omega} \times \mathrm{I}\,\vec{\omega} \tag{25}$$

where u = $[u1, u2, u3]^T$ represents the vector of control torques on the body axis, applying Taylor expansion to this given formulation we derive the final linear reduction work quaternion model, and by going through h stubs, we can obtain the final expression of the linear equation as follows (Eq. 26)

$$\begin{bmatrix} \omega^{\cdot} \\ q^{\cdot} \end{bmatrix} = \begin{bmatrix} 0_3 & 0_3 \\ I \;\; 3 & 0_3 \end{bmatrix} \begin{bmatrix} \omega \\ q \end{bmatrix} + \begin{bmatrix} I^{-1} \\ q0_3 \end{bmatrix} u = Ax + Bu \tag{26}$$

With this inference, it is fully controllable and solves the typical problem of full quaternion dynamics.

The derived model can show us much more useful results when a linear analysis is performed in terms of quaternion. However, as explained earlier, the evaluation of the behavior of the TVC system in this study is that the prototypeperforms a contro led landing while performing a landing.

2.3. Mechanical Design of the System

During the mechanical design phase, many issues such as manufacturability, cost, mechanism stability, precaution against problems that may occur during the thrust guidance phase are examined. In the process up to the final design stage, it is aimed to make the most perfect design with all revisions. 2 Power HD Mini Copper Gear Analog servo motors integrated into the system make angular movements according to the data coming from the gyro sensor. The 2 shafts connected with the help of the 25T servo arm move the part at the output of the rocket motor thrust vectorally. In this way, the thrust coming out of the nozzle is directed in a vectorial way. Also, while producing prototypes, compliance with engineering standards was also checked.

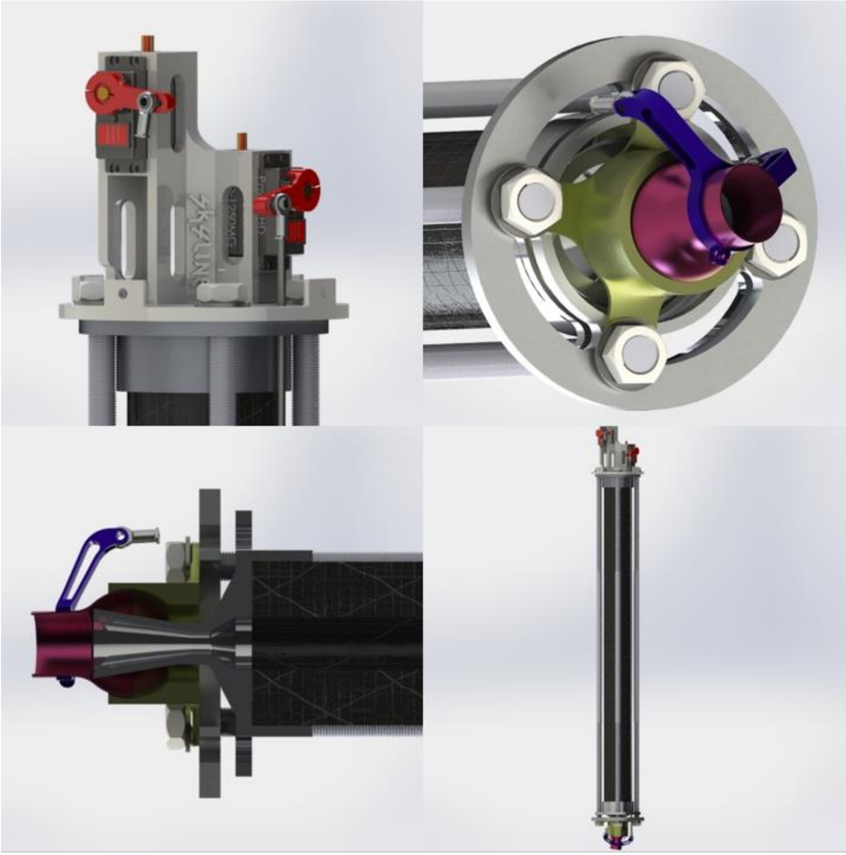

Figure 14: TVC CAD Modeling

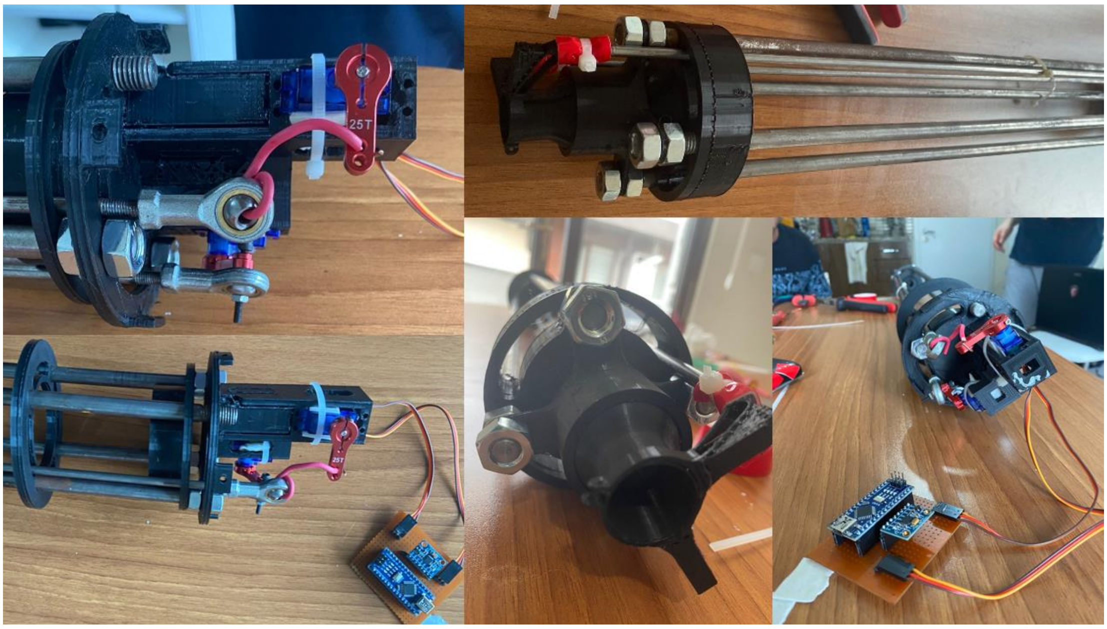

Figure 15: Prototype of the system

3 Results and Conclusions

In this study, a propulsion guidance system (TVC) was developed to be used in innovative low-altitude rockets that would use solid-fuel engines. This study, which is at the conceptual level, was produced and mechanical experiments were made. The next step in this work is to conduct experiments with a real solid-fuel rocket engine and analyze more consistent data. Today's rockets use conventional guidance systems. However, in the coming years, it is foreseen that this system will develop in order to grow space and aviation, to spread space tourism, and to obtain more stable rockets in the defense industry. Therefore, as one of the next studies, it is aimed to make a hybrid rocket-powered cargo or a rocket capable of carrying people to be used entirely in space tourism.

4 Declarations

4.1 Study Limitations

None.

4.2 Acknowledgements

Authors: they would like to thank Sakarya University of Applied Sciences, the SKYLINE Team and TÜBİTAK for their support in their studies.

4.3 Funding source

TÜBİTAK 2209-A, Project number: 1919B012102469

4.4 Competing Interests

There is no conflict of interest in this study.

4.5 Authors' Contributions

Corresponding Author Haktan Yağmur: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review, taking responsibility for the creation of the entire manuscript.

Can Bayar: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review, taking responsibility for the creation of the entire manuscript.

Sinan Şen: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review, taking responsibility for the creation of the entire manuscript.

Kasım Serbest: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the creation of the entire manuscript.

References

[1] Buschek, H. (2003). Design and flight test of a robust autopilot for the IRIS-T air-to-air missile. Control Engineering Practice, 11(5), 551–558.

[2] https://arc.aiaa.org/doi/abs/10.2514/3.1597?journalCode=aiaaj , Accesed: 10.07.2021.

[3] https://en.wikipedia.org/wiki/Thrust_vectoring , Accesed: 15. 07.2021.

[4] https://dergipark.org.tr/tr/download/article-file/438514 , Accesed: 15. 07.2021.

[5] https://core.ac.uk/download/pdf/19143575.pdf , Accesed: 20. 07.2021.

[6] https://www.researchgate.net/publication/323685633_Design_and_Implementation_of_a_Thrust_Vector_Control_TVC_Test_System , Erişim Tarihi: 20. 07.2021

[7] Lazic´, D. V., & Ristanovic´, M. R. (2004). Thrust vector control of twin nozzle engine. Proceedings of the VIII triennial international SAUM conference (pp. 94–97). Belgrade, Serbia, November 2004.

[8] Schinstock, D. E., & Haskew, T. A. (2001). Transient force reduction in electromechanical actuators for thrust-vector control. Journal of Propulsion and Power, 17(1), 65–72.

[9] Skogestad, S., & Postlethwaite, I. (1996). Multivariabile feedback control. England: Wiley.

[10] Ünal A., Yaman K., Okur E. ve Adlı M.A., "Design and implementation of a Thrust Vector Control (TVC) test system", Politeknik Dergisi, 21(2): 497-505, (2018).

[11] Song, C., Kim, S. J., & Kim, S. H. (2006). Robust control of the missile attitude based on quaternion feedback. Control Engineering Practice, 14(7), 811–818.

[12] Zipfel, P. H. (2000). Modeling and simulation of aerospace vehicle dynamics. Reston, VA: American Institute of Aeronautics and Astronautics, Inc.

[13]https://www.esa.int/ESA_Multimedia/Images/2008/11/The_thrust_vector_control_system_of_the_Zefiro_23_engine_part_of_the_Vega_launcher_was_developed_under_GSTP

[14] Wie, Bong. "Thrust vector control analysis and design for solar-sail spacecraft." Journal of Spacecraft and Rockets 44.3 (2007): 545-557.