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Attitude Control of Rocket via Thrust Vector Control Technique

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DEDICATIONS

I dedicate this work

To the dearest person of my life, my mother

To the one who made me the man I am today, my father

To my dear sisters Safia, Aisha, Zineb and Sihame

To my dear brothers Omar and Adam

To all my family for their support throughout my university career

To my fiancée

To all who are dear to me

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I dedicate this work

To my family

To my mother my father this is for you and I hope that you are proud of me

To my closest friends my sisters Sana

And my brother Tarek and to Noah my Allah make you a blessing to us

And to all my friend and the peoples whom I met in this journey

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List of Abbreviations

- **CAD:** Computer Aided Design
- **CAM:** Computer Aided Manufacturing
- **CG:** Center of Gravity
- **EEC:** Extendible Exit Cone
- **EP:** Electric Propulsion
- **GPS:** Global Positioning System
- **ICBM:** Intercontinental Ballistic Missiles
- **ISS:** International Space Station
- **LQR:** Linear Quadratic Regulator
- **NASA:** National Aeronautics and Space Administration
- **PID:** Proportional Integral Derivative
- **PWM:** Pulse Width Modulation
- **RF:** Radio Frequency
- **SP:** Sugar Propellant
- **SRAM:** Short-Range Attack Missile
- **SRB:** Solid Rocket Booster
- **TVC:** Thrust Vector Control
- **USA:** United States of America
- **USB:** Universal Serial Bus

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ملخص

كان التحكم في الصواريخ معقدًا بشكل أساسي ويهدف إلى هدف وهو الحفاظ على مسار الرحلة وهدفًا متقدمًا وهو مهمة طيران مرنة للمركبات بمدخلات مختلفة توفرها الاتصالات والتوجيه والملاحة وتغيير المدار. وبالتالي فإن إنشاء نموذج للتحكم في الصواريخ سيؤثر على القطاعات الصناعية بعدة طرق ، من تحديد موقع الأقمار الصناعية إلى مساعدة الباحثين للتحكم في او الاتصال بالإنترنت ولأهداف عسكرية; TVC:التحكم في ناقلات الدفع هو الاسلوب العام في التحكم في الصواريخ.

الفصل الاول مخصص لتاريخ الصواريخ والتحكم في ناقلات الدفع يتعلق الفصل الثاني بالنموذج الرياضي لديناميكا الصاروخ والتحكم فيه اما الفصل الثالث مخصص لتجربة التحكم في درجتين من الحرية.

ABSTRACT

Rocket control was primarily complex and aimed at one objective which is maintaining flight path directory and an advanced one which is an automotive flight mission flexible to different delivered inputs from communication guidance navigation and changing orbits. Thus, making a control model of rockets will impact industrial sectors in many ways from satellite emplacement to helping researchers internet connection and military purposes; thrust vector control TVC is the general technique of rocket control thus in this thesis we are willing to demonstrate the attitude control of small scaled rocket with linear control and this work will be in 3 chapters. Chapter 1 dedicated for rocket history and the TVC in general. Chapter 2 about the mathematical model for the rocket dynamics and will be on implementing a linear control method for our dynamical model. Chapter 3 will be about experimentation controlling two degree of freedom "pitch and yaw".

Résumé:

Le contrôle des fusées était principalement complexe et visait un objectif qui est le maintien du répertoire de la trajectoire de vol et un objectif avancé qui est une mission de vol automobile flexible à différentes entrées fournies par la communication, le guidage, la navigation et le changement d'orbite. Ainsi, la création d'un modèle de contrôle des fusées aura un impact sur les secteurs industriels de plusieurs façons, de l'emplacement des satellites à l'aide aux chercheurs pour la connexion à Internet et à des fins militaires ; le contrôle du vecteur de poussée TVC est la technique générale de contrôle des fusées. Le chapitre 1 est consacré à l'histoire des fusées et à la TVC en général. Le chapitre 2 concerne le modèle mathématique de la dynamique de la fusée et sera consacré à l'implémentation d'une méthode de contrôle linéaire pour notre modèle dynamique. Le chapitre 3 sera consacré à l'expérimentation du contrôle de deux degrés de liberté "tangage et lacet".

Introduction

Rocket science as a Cliché the sentence is as much it reflect a lot of reality ,to reach the capability of keeping a rocket into its desired path is trickier and difficult but a hard and efficient work done by different world space agency like NASA that sent a full rocket to the moon with only a 13 kb of redundancy for the navigation computer or SpaceX scaling down the industry budget with reusable rocket or crazy thought to make humanity multiplanetary, people can only trust and believe that our future is beyond earth and a blue sky .

To steer a rocket-propelled vehicle and retain its intended flight trajectory, torques "Moments" must be applied to turn the vehicle (in pitch, yaw, or roll) Fig1.1, as well as side forces to change the direction of the vehicle's flight velocity vector (u) as shown in Fig1.1. A spacecraft's steering control forces also counterbalance disruptive factors (such as wind, uneven Earth gravity, or moon pull) and enable the ability to correct or change flight direction. This thrust vector control can be accomplished in four different ways. The US and the Soviet Union appear to be the only countries to have deployed all four of these TVC designs in the past. The other nations have flown three or less

In chapter 1 a brief introduction to rocket and TVC implementation is discussed we will also deliberate the linear control theory in chapter 2 and our dynamics and kinematics with linear state representation of our model.

Chapter 3 is dedicated for experimentation and realization of static attitude control on 2 axes using an Arduino script based on complementary filter

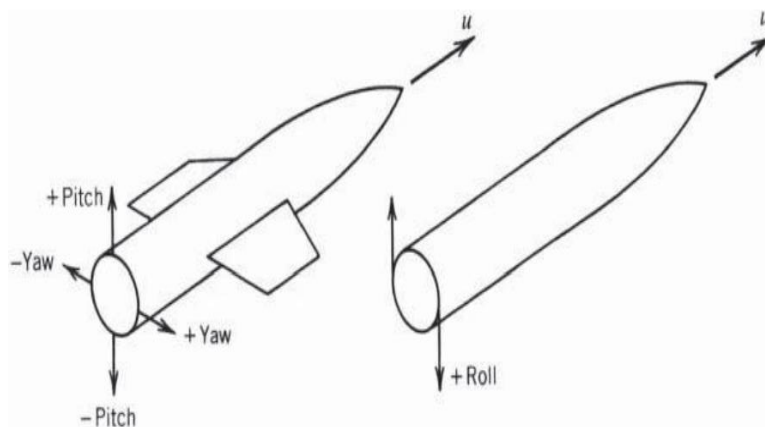


Figure 1. 1 Moments Applied to a Flying Vehicle [2]

CHAPTER 01: STATE OF ART OF ROCKETS

1.1 Introduction and history

History of rockets in general extends for more than 2000 years from invention experimentation, discovery and inspiration where the building blocks of modern rocketry were laid.

Archytas, a Greek philosopher, mathematician, and astronomer, was said to have constructed and flown a small bird-shaped device that was propelled by a jet of steam or compressed air and this was the first reported device to use rocket propulsion outdated in the period 428 to 347 B.C; and then the propellant made a new development extended to gunpowder where Chinese were reported to be the pioneers.

Another idea flow to the surface which consists of rocket being made from stages and that was a paper published by a polish Lithuanian “Kazimierz Siemienowicz”. In the 16th century’s and in those rapid technical improvements rocket science emerges from Galileo constructing the principle of property of which later been developed by newton as inertia that helped him in to condensing all rocket science by developing the three famous laws of motion.

America was unexpectedly the leading country to create the first liquid propellant rocket on March 16, 1926, even the experiment wasn’t quite impressive (the rocket reaches only 12.5 meters) this was led by college professor Robert Goddard this man was the first to include gyroscopes system to control his rockets flight a parachute recovery system and also an instrumentation payload compartment for the purpose to isolate fuel and oxygen tanks from the chamber of combustion. He is often referred to as the father of modern rocketry.

After World War 2 the space era begins Dr Wernher von Braun a figure in Germany rocket program that resulted the V2 “most powerful rocket in that time. He became a leading proponent of the American space program. He entered the United States after the war and became a naturalized citizen. His work focused on making ICBM “intercontinental ballistic missiles” and not to mention creating America’s first satellite “Exploerer-1”, as an engineering architect chief, he supervises the making of Saturn V moon fig 1.1 which eventually landed on the moon under Apollo 12 mission, in his time an era of astronauts emerged under America media influence.

Russia was and steels partially the leading space company specially on making cryogenic rocket engine Fig 1.2 a type which built only later by just 7 major countries but Russia engines still led in

Efficiency by using a secret which recently been debunked consisted of fuel cycles and ratio of pumped fuel to oxygen “the combustion chamber was reach in oxygen more than fuel”.

Privet sector is taken apart of space industry and lifting it to a commercial level SpaceX is one of the innovative companies that reduced engines production cost by including the reusability factor to it and creating high powerful rocket “The Merlyn” that compete with Russian engines.

Recent rockets engines are more complex and diverse from liquid engines to hybrid and solid not forgetting ion and plasma propellers, the choice of engine depends mainly on your objectives your resource and strategy of space missions in chapter 3 dedicated for experimentation we will discuss our type of rocket engine and why we chosen our own type and the complete process of its realization.

Control methods of rockets also encounter many enhancements ranging from the optimal roll control of missiles to multi-variable control, adaptive guidance of gravity-turn rockets, and two-point boundary value and using simple methods from tuning to disturbance observers[1].



Figure 1. 3 Saturn V launches Cape Canaveral

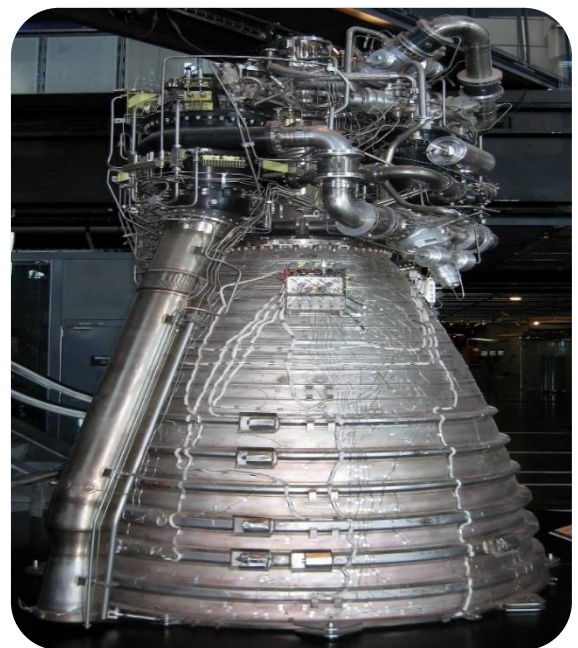


Figure 1. 2 cryogenic rocket engine: most powerful rocket engines in space industry

1.2 TVC (Thrust Vector Control)

Thrust vector control is a technique used to steer a rocket an aircraft or an airplane into the desired trajectory using an applied torque on one of three axes (pitch yaw or roll) with maximum angle shifting of 5 deg, the thrust generated from the engine or the motor is modulated as vector to be controlled.

1.3 TVC Mechanism

TVC keeps up the vehicle's rectify demeanor for the pushed length by pivoting (gimballing) the pushed chamber or by diverting the exhaust-gas stream so the pushed produces a vehicle torque. Common strategies for coordinating the debilitate gases are moveable vanes or infusion of another liquid into the stream. TVC is regularly utilized to control pitch and yaw demeanor on boosters and upper stages (high-thrust frameworks). Shuttle utilizes devoted attitude-control thrusters rather than TVC. Some implies of coordinating the pushed vector may be given to guarantee that the pushed vector focuses through the spacecraft's center of mass. This framework must account for center-of-mass shifts as fuel burns, permitting for essential fabricating resilience. In the event that the unsettling influence torques coming about from a misaligned pushed vector is little, the spacecraft's reaction control framework (that's, beating thrusters) can overcome them. In other cases, the complete vehicle may be intentioned spun amid firings of the most engines.

1.3.1 TVC Mechanisms Types with a Single Nozzle

Many different mechanisms have been successfully used. They can be classified into four categories [3]:

1. Mechanical deflection of the main nozzle or thrust chamber.
2. Insertion of heat-resistant movable bodies into the exhaust jet, these experience aerodynamic forces and cause deflection of part of the exhaust gas flow.
3. Injection of fluid into a side portion of the diverging nozzle section, causing an asymmetrical distortion of the supersonic exhaust flow.
4. Separate thrust-producing unit that is not part of the main propulsion system.

1.3.2 Liquid injection

Liquid injection encompasses any addition of a fluid that changes the characteristics of the combustion. By changing the combustion on one side of the nozzle the thrust vector can be changed. The method of injection, as well as the fluid that is injected, are both topics of much debate and research. One of the biggest decisions when considering this method of thrust vectoring is the liquid that will be used. The two main divisions are whether the liquid will inhibit the combustion or contribute to combustion. Combustion inhibitors will tend to cool one side of the nozzle while combustion contributors will add fuel or other additives to increase thrust on one side of the nozzle. Advantages of this method of thrust vectoring are that it has fast response capability and adds to thrust by adding mass to the fluid stream. The disadvantages of this system are that they are heavy and the amount the valve opens is not linearly related to the rate of change of the thrust vector.

1.3.3 Gas injection

Gas injection is very similar to liquid injection the difference being that instead of new gas being added to the fluid stream combustion gases are rerouted from behind the nozzle into the diverging section changing the flow through the nozzle itself. The advantages of this method are that additional fluids do not need to be stored on board and so the system overall is lighter in weight. The downside to this method however, is that the hot combustion gasses have to be routed through valves. In stationary tests the valves could never be made reliable enough to consider further testing.

1.3.4 Jet vane

The jet vane deflector is characterized by any fin or plate that is directly placed in the existing flow of the nozzle. As the plate or fin moves it will cause the flow exiting the nozzle to deflect from the centerline of the rocket. Advantages of these systems are that the forces on actuators are low and thus they can be capable of quick response times. Since the blades are directly in the exhaust this causes the designer to make one of three choices, the propellant can burn relatively cool, the propellant can burn for a relatively short period of time, or the vanes can be made of exotic heat resistant material. The other problem with this method is that a large deflection of the vane must be made in order to cause a change in the thrust vector. The large deflection and the inherent drag of fluid on the vanes reduce thrust.

1.3.5 Jetavator

The jetavator is a similar concept to the jet vane the difference being that instead of the vanes being in the flow the nozzle they are positioned around the perimeter of the nozzle and are parallel to the flow. This system has similar heat restrictions to the jet vane. Advantages include that the deflection of the jetavator is linearly related to the deflection of the thrust vector. The downsides of this design, besides the heat considerations mentioned in the jetvane section, are that the system can be heavy and that the jetavator restricts the exit diameter.

1.3.6 Jet tab

The jet tab system involves a plate at the end of the nozzle that can be rotated into and out of the nozzle disrupting the flow. Initial advantages that the thrust deflection is proportional to the area of the tab that is exposed to the flow this makes controlling the system relatively easy. The downside of this system is that when the fluid streams the flow stalls on the tab. The stalled flow causes lots of erosion on the inside of the nozzle.

Testing was stopped on this method because of the material erosion problems.

1.3.7 Movable nozzle

Movable nozzles control the direction of the existing flow by having the nozzle itself move. These are more recently developed technologies. The reason that they were developed more recently, and are now becoming more popular, is that it was difficult to support the thrust on the nozzle while sealing the gasses and remaining flexible. Moveable nozzle systems are broadly categorized into the type of flow inside the nozzle.

The following **Table 1. 1** resumes a comparative analysis between rocket control techniques [4]

Types	L/S	Avantages	Désavantages
Gimbal or hinge	L	Simple, proven technology; low torques, low power, up to $\pm 12^\circ$, duration limited only by propellant supply, very small thrust loss.	Requires flexible piping; high inertia; large actuators and a power supply for high slew rate
Movable nozzle (flexible bearing)	S	Proven technology; no sliding, moving seals; predictable actuation power; up to $\pm 12^\circ$	High actuation forces; high torque at low temperatures; variable actuation force
Movable nozzle (Rotary ball with gas seal)	S	Proven technology; no thrust loss if entire nozzle is moved; $\pm 20^\circ$ possible	Sliding, moving hot gas spherical seal; highly variable actuation power; limited duration; need continuous load to maintain seal
Jet vanes	L/S	Proven technology; low actuation power; high slew rate; roll control with single nozzle; $\pm 9^\circ$.	Thrust loss of 0.5-3%; erosion of jet vanes; limited duration; extend missile length.
Jet Tabs	S	Proven technology; high slew rate; low actuation power; compact package.	Erosion of tabs; thrust loss, but only when tabs are in the jets; limited duration.
Jetavator	S	Proven on Polaris missile, low actuation power, can be light weight.	Erosion and thrust loss induce vehicle base hot gas recirculation, limited duration.
Liquide side injection	S/L	Proven technology, high slew rate Easy to adapt to various motors; can check out before flight components are reusable, duration limited by liquid supply; $\pm 6^\circ$	Toxic liquids are needed for high performance often difficult packaging for tank and feed systems, sometimes require excessive maintenance; potential spills and toxic fumes, hot piping expansion; limited duration requires special gas valves.

<p>Hinged auxiliary thrust chambers for high thrust engine</p>	<p>L</p>	<p>Proven technology, feed from main turbopump; low performance loss, compact, low actuation power, no hot moving surfaces, unlimited duration</p>	<p>Additional components and complexity, moment applied to vehicle are small, not used for 20 years in USA</p>
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“Actuators and structural details are not shown. The letter L means it is used with liquid propellant rocket engines and S means used with solid propellant motors “[5].


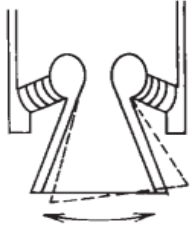
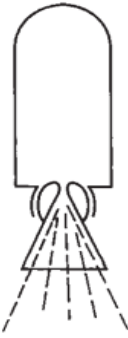
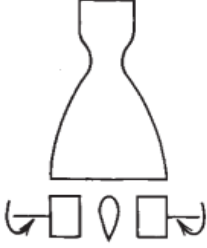
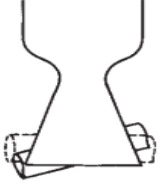
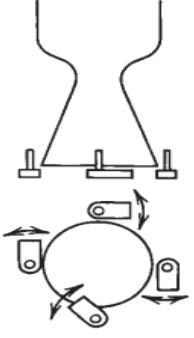
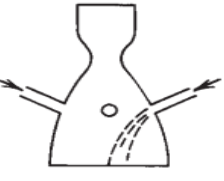
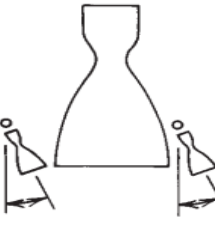
<p>Gimbal or hinge</p>  <p>Universal joint suspension for thrust chamber</p> <p>L</p>	<p>Flexible laminated bearing</p>  <p>Nozzle is held by ring of alternate layers of molded elastomer and spherically formed sheet metal or plastic composite (fiberglass epoxy)</p> <p>S</p>	<p>Flexible nozzle joint</p>  <p>Sealed rotary joint</p> <p>S</p>	<p>Jet vanes</p>  <p>Four rotating heat resistant aerodynamic vanes in jet</p> <p>L/S</p>
<p>Jetavator</p>  <p>Rotating airfoil shaped collar, gimballed near nozzle exit</p> <p>S</p>	<p>Jet tabs</p>  <p>Four paddles that rotate in and out of the hot gas flow</p> <p>S</p>	<p>Side injection</p>  <p>Secondary fluid injection on one side at a time</p> <p>S/L</p>	<p>Small control thrust chambers</p>  <p>Two or more gimballed auxiliary thrust chambers</p> <p>L</p>

Figure 1. 4 Schematic diagrams for eight different TVC mechanisms

1.4 Applications of Rocket Propulsion

Because rocket propulsion may achieve performance levels unmatched by other prime movers, it has its own set of applications and seldom competes with other propulsion technologies. The process of determining the optimal rocket propulsion system type and design for a specific application is complicated, involving numerous aspects such as system performance, dependability, cost, propulsion system size, and compatibility [6]:

1.4.1 Space Launch Vehicles:

Since 1957 there have been numerous space launch attempts with a better than 95% success record. Space launch vehicles or space boosters can be broadly classified as expendable or recoverable/reusable, by the type of propellant (storable or cryogenic liquid or solid propellants), number of stages (single-stage, two-stage, etc.), size/mass of payloads or vehicles, and as manned or unmanned. There are many different missions categories and payloads for space launch vehicles: commercial missions (e.g., communications), military missions (e.g., reconnaissance), nonmilitary missions (e.g., weather observation), and space exploration missions (e.g., flights to the planets).

Each space launch has a specific space flight objective, such as an Earth orbit or a moon landing. It uses between two and five stages, each with its own propulsion systems and each usually fired sequentially after the lower stage is expended. Selection for the number of stages is based on the specific space trajectory, the number and types of maneuvers, the energy content of a unit mass of the propellant, the payload size, as well as other factors. The initial stage, usually called the booster stage, is the largest; this stage is then separated from the ascending vehicle before the second-stage propulsion system is ignited and operated. Adding extra stages may permit significant increases in the payload (such as more scientific instruments or more communications gear). Each stage of a multistage launch vehicle is essentially a complete vehicle in itself and carries its own propellant, its own rocket propulsion system or systems, and its own control system. Once the propellant of a given stage is expended, its remaining mass (including empty tanks, cases, structure, instruments, etc.) is no longer useful to succeeding stages. By dropping off this mass, it is possible to accelerate the final stage with its payload to a higher terminal velocity than would be attained if multiple staging were not used. Both solid propellant and liquid propellant rocket propulsion systems have been utilized in low Earth orbit missions.

1.4.2 Spacecraft

Based on their mission, shuttle can be categorized into earthly, lunar, interplanetary and trans-solar satellites, and/or kept an eye on and unmanned shuttle. Satellites can be classified as communication, meteorological, route, logical investigation, profound space tests, perception (counting radar observation), surveillance and other applications. Rocket drive is required both for essential drive (i.e., increasing speed along the flight way, such as for rising, circle addition or circle alters maneuvers) and for the auxiliary drive capacities of these vehicles. Auxiliary drive capacities incorporate demeanor control, turn control, flywheel and whirligig emptying, space meet, organize partition and tank fluid tapping. Shuttle require diverse rocket drive frameworks and a few thrusters can be exceptionally little. For demeanor control of a shuttle approximately three opposite tomahawks, each in two bearings of turn, the framework must permit the application of unadulterated torque for six modes of precise flexibility, which needs a least of 12 thrusters. A few missions require only 4-6 thrusters, whereas the foremost complex kept an eye on shuttle has 20-50 thrusters in all their stages. Frequently, little demeanor control rockets must give beats or brief bursts, requiring thousands of restarts. A few shuttle work effectively with electric drive for state of mind control. As of late, electric drive (EP) frameworks have too been utilized for a few essential and auxiliary shuttle impetus missions on long-duration space flights. Due to their moo pushed, space operations/maneuvers with EP require moderately longer times to realize the required speed increments. For case, the transfer from moo Soil circle to a geosynchronous circle can take up to two or three months, compared to many hours with chemical drive frameworks. Micro-propulsion may be an unused assignment for pushed levels pertinent to little shuttle beneath 100 kg.

1.4.3 Military and Other Applications

U.S. missiles are presently based almost exclusively on solid propellant rocket motors. These can be strategic missiles, such as long-range ballistic missiles (800 to 9000 km range), which are aimed at military targets within an enemy country, or tactical missiles, which are intended to support or defend military ground forces, aircraft, or navy ships.

The term surface launch can mean launching from the ground, the ocean surface (from a ship), or from underneath the sea (submarine launch). Some tactical missiles, such as the air-to-surface short-range attack missile (SRAM), have a two-pulse solid propellant motor, where two separate insulated grains of different solid properties are in the same motor case; the time interval before starting the second pulse can be timed to control the flight path or speed profile. Many countries now have tactical missiles in their military inventories, and many of these countries have the capability to produce their own vehicles and their rocket propulsion systems. Applications that were popular 40 to 70 years ago but are no longer active include liquid propellant rocket engines for propelling military fighter aircraft to altitude, assisted takeoff rocket engines and rocket motors, and super performance rocket engines for augmenting the thrust of an aircraft jet engine

Other applications of rocket propulsion systems to space operations include communication satellites—these have been successfully deployed for many years providing relays of telephone and television signals between Earth stations; this application is managed and operated by commercial organizations. Other countries also have their own satellite-based communications. The U.S. government sponsored programs that include weather satellites and the now ubiquitous Global Positioning System (GPS). Examples of space exploration include missions to the planets and/or into deep space, such as the Voyager mission and the MESSENGER program. A good number of these missions and probes were developed by NASA's Jet Propulsion Laboratory; they use the multiple thrusters from a monopropellant hydrazine reaction control system. Another application is for suborbital winged space vehicles for space tourism



Figure 1. 5 The Soyuz is a Russian spacecraft.



Figure 1. 6 Space shuttle docking with the ISS



Figure 1. 7 Iskandar missile deployed from Algeria

1.5 Motives for TVC may be stated as [2]:

1. Willful changes to a flight path or trajectory (e.g., changing flight-path direction of a target-seeking missile).
2. Vehicle rotation or changes in attitude during powered flight.
3. deviation corrections from intended trajectory or attitude during powered flight;
4. Thrust corrections for misalignments of fixed nozzles in main propulsion system during its operation (when the main thrust vector misses the vehicle's center of mass).

In all prior analyses, we have implicitly assumed that the thrust vector passes through the center of mass and is perfectly aligned with the direction of flight. For TVC, moments are purposely generated about the center of mass to control flight trajectories. The location of the side force (or its perpendicular component) along the vehicle's axis determines its moment arm and thus the magnitude of the force needed for any given application; this implies that locations as far away as possible from the center of mass (i.e., the longest moment arms) are most desirable to minimize the needed forces and thus the propellant usage. Pitch moments are those that raise or lower the nose of a vehicle; yaw moments turn the nose sideways; and roll moments are applied about the main axis of the flying vehicle. Most often, the thrust vector of the main rocket nozzle is in the direction of the vehicle axis and goes through its center of mass. Thus, it is possible to obtain pitch and yaw control moments by simple deflections of the main rocket thrust vector. Roll control, however, requires the use of two or more rotary vanes or two or more separately hinged propulsion system nozzles.

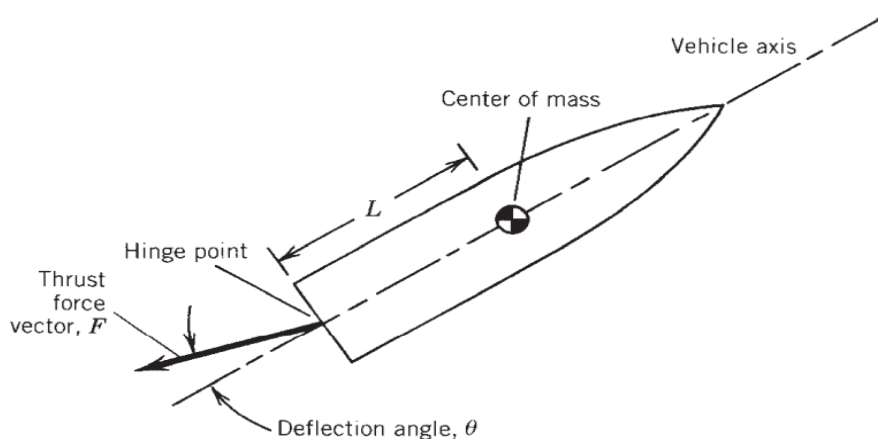


Figure 1. 8 shows how a pitch moment is obtained from a hinged thrust chamber or nozzle.[2]

1.6 Missile control techniques include [7]

The goal of a missile command system, also known as an auto-piloted missile, is to ensure missile stability and high performance while also allowing the missile to fly in accordance with guiding law requirements.

The command variables are typically chosen to be the missile's lateral acceleration components in the majority of missile command systems. Depending on the sort of guiding command, the commendable variables may include body velocities (velocities of yaw, pitch, and roll), body angles (angles of yaw, pitch, and roll), angles of the wind reference system (angles of attack and skidding), or their velocities.

1.6.1 Conventional command methods

If the missile's roll motion is stabilized, the motion of its yaw planes and pitch will be separated. Autopilots can be developed easily using traditional control techniques in such a system, where the equations of motion are essentially linear for wind angles and control surface deflections are not too significant. In this regard, yaw and pitch autopilots are typically designed using PI (proportional plus integral) or PID (proportional plus integral plus derivative) control with synthetic pitch and yaw damping. The desired poles are usually set according to the pole positioning approach in the control system that results. The gain method scheduling is commonly used to keep these poles at the desired locations under changing operating conditions. The controller gains are continuously changed in this technique in relation to current flight conditions in order to maintain desired pole placements in a closed loop control system.

1.6.2 Modern command techniques

The vast majority of modern command strategies fall into one of two categories, they are state feedback strategies or exit feedback strategies. The majority of linear and nonlinear design methods assume that complete state information is available. However, putting in place a command law based on a return of state is not always viable because all states may not be available for the measurement. In such a case, a return to origin is a possible option, usually combined with a Kalman filter to estimate the overall state. On the other hand, the use of state feedback and sortie strategies is restricted in missile command. For example, in a problem where the missile is launched from the ground in a vertical position, the state command by retroaction can be used to maintain the missile's vertical position during its flight.

Chapter 02: Attitude and Control of Rockets

2.1 Introduction

It is vital for an aerodynamic vehicle to be always line up with the velocity vector due to aerodynamic considerations. And this why, all launch vehicles are equipped with an attitude control system to help the vehicle's orientation follow the flight-path such that angle of attack and sideslip angle remain zero. But to maintain longitudinal (pitch–yaw) stability at lower altitudes, aerodynamic vehicle is generally fitted with fins near the base. If made movable, the fins can also apply limited control torques in the denser region of the atmosphere (as in the case of the German V-2 rocket of the Second World War). However, because launch vehicle operates at a wide range of speeds and altitudes, we cannot rely only upon aerodynamic moments generated by movable fins. Instead, the attitude control torque is generated by a combination of thrust-vectoring (i.e., changing the direction of the thrust vector), cold gas reaction jets, or making a moveable nozzle or engine to deliver the necessary torque [9].

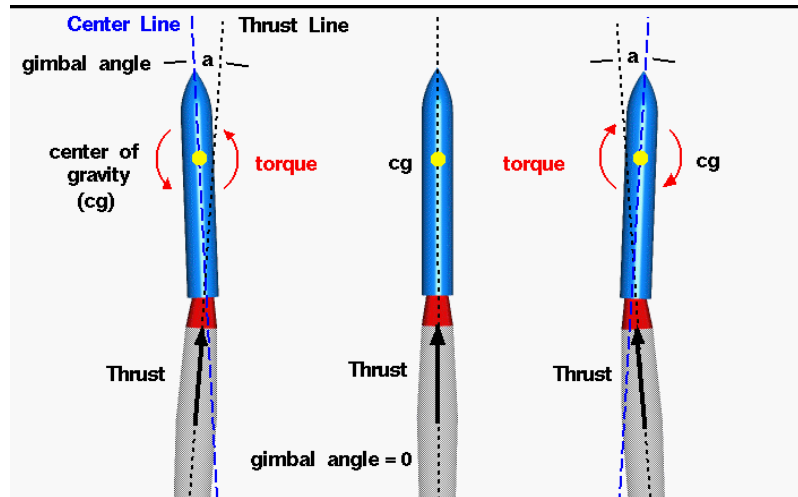


Figure 2. 1 Gimbaled Thrust with moveable nozzle

2.2 Rigid-Body Control Analysis

In this chapter we are willing to simulate one angle control (pitch angle) for the Space Shuttle, Ares I vehicle via an LQR feedback control and an auto tuned PID control

The linear quadratic regulator (LQR) is a well-known method that provides optimally controlled feedback gains to enable the closed-loop stable and high-performance design of systems. The LQR algorithm is essentially an appropriate state-feedback controller. The LQR algorithm reduces the amount of work done by the control systems engineer to optimize the controller. However, the engineer still needs to specify the cost function parameters, and compare the result with the specified design goals. Often this means that controller construction will be an iterative process in which the engineer judges the “optimal” controllers produced through simulation and then adjusts the parameters to produce a controller more consistent with design goals.

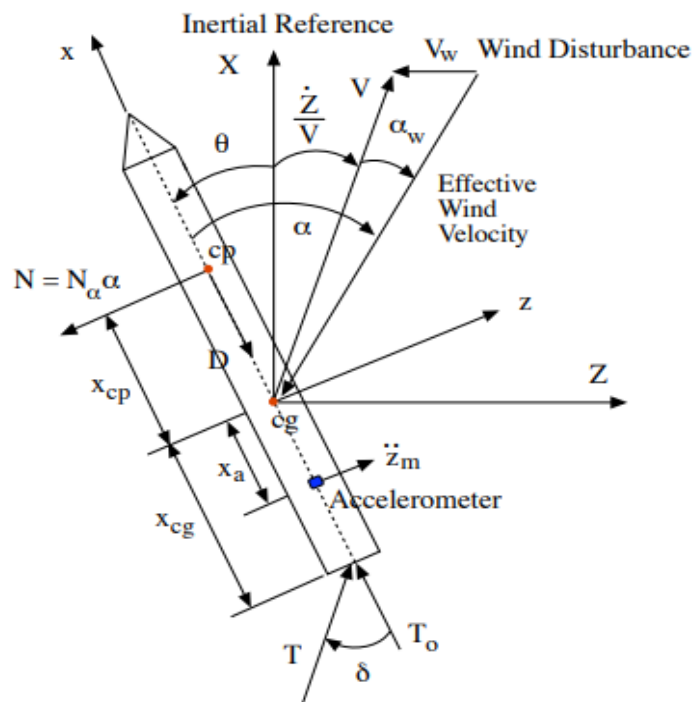


Figure 2. 2 Simplified pitch-axis model of a launch vehicle.

- The related parameters acting on the missile are defined in the table below:

Table 2. 1 Rocket Parameters

Parameters	Sinification
Θ	The Pitch angle
α	Angle of attack
Z	The Drift of COM
\dot{Z}	The inertial drift velocity
M	The vehicle mass
T_0	The ungimbaled sustainer thrust
T	The gimbaled thrust
$N = N_\alpha \alpha$	the aerodynamic normal (lift)
D	the aerodynamic axial (drag)
F	the total x-axis force
δ	the gimbal deflection angle
V_w	the wind disturbance velocity
M_α	Moment of inertia of the vehicle
M_δ	Moment of inertia of the TVC
I_y	Moment of Inertia along y axes (pitch moment of inertia)
m	Vehicle mass

Consider a simplified linear dynamical model of a launch vehicle [15], as illustrated in 2.2, as follows:

Fig.

$$\ddot{\Theta} = M_\alpha \alpha + M_\delta \quad (1)$$

$$\ddot{Z} = -\frac{F}{m} \Theta - \frac{N_\alpha}{m} \alpha + \frac{T}{m} \delta \quad (2)$$

$$\alpha = \Theta + \frac{\dot{Z}}{V} + \alpha_w \quad (3)$$

$$F = T_0 + T - D \quad (4)$$

Where

$$M\alpha = x_{cp}N_\alpha / I_y \quad (5)$$

$$M_\delta = x_{cg}T / I_y \quad (6)$$

$$N\alpha = \frac{1}{2} \rho V^2 SC N_\alpha \quad (7)$$

For an effective thrust vector control of a launch vehicle, we need

$$M_\delta \delta_{\max} > M_\alpha \alpha_{\max} \quad (8)$$

Where δ_{\max} is the gimbal angle constraint and α_{\max} is the maximum wind-induced angle of attack. The open-loop transfer functions from the control input $\delta(s)$ can then be obtained as

$$\frac{\theta(s)}{\delta(s)} = \frac{s}{\Delta(s)} \left[M_\delta \left(s + \frac{M_\alpha}{mv} \right) + \frac{M_\alpha}{mv} \right] \quad (9)$$

$$\frac{Z(s)}{\delta(s)} = \frac{1}{\Delta(s)} \left[\frac{T}{m} (s^2 - M_\alpha) + \frac{M_\alpha(F + N_\alpha)}{m} \right] \quad (10)$$

$$\frac{\alpha(s)}{\delta(s)} = \frac{s}{\Delta(s)} \left[\frac{T}{mv} s^2 - M_\delta s + \frac{M_\delta F}{mv} \right] \quad (11)$$

$$\Delta(s) = s \left[s^3 + \frac{N_\alpha}{mv} s^2 - M_\alpha s + \frac{M_\alpha F}{mv} \right] \quad (12)$$

in general state representation for any linear dynamical model is given as:

$$\begin{cases} \dot{X} = Ax + Bu \\ Y = Cx \end{cases}$$

Consequently, the 2-order and the first order systems described by Eq. (1) - (3) are completely controllable by δ « angle of control of the TVC system »; however, the system is not observable by α because angle of attack is the angle between the path trajectory and the wind disturbance velocity and there is a problem to modulate the wind disturbance velocity into one vector therefore having a clear-cut data about α is impossible.

In 1959, Hoelkner introduced the “drift-minimum” and “load-minimum” control concepts as applied to the launch vehicle flight control system. Basically, Hoelkner’s controller utilizes a full-state feedback control of the form

$$\delta = -K_1 \theta - K_2 \dot{\theta} - K_3 \alpha = u \quad (13)$$

From the equation we get the state space matrix

$$A = \begin{bmatrix} 0 & 1 & 0 \\ M_\alpha & 0 & \frac{M_\alpha}{v} \\ -\frac{(F-D+N_\alpha)}{m} & 0 & -\frac{N_\alpha}{mv} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M_\delta \\ \frac{Tc}{m} \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

For a 3rd-order dynamical model of the form:

$$\frac{d}{dt} \begin{bmatrix} \theta \\ \dot{\theta} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ M_\alpha & 0 & M_\alpha/V \\ -\frac{(F-D+N_\alpha)}{m} & 0 & -N_\alpha/(mv) \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ \dot{Z} \end{bmatrix} + \begin{bmatrix} 0 \\ M_\delta \\ Tc/m \end{bmatrix} \delta + \begin{bmatrix} 0 \\ M_\alpha \\ -N_\alpha/m \end{bmatrix} \alpha_w \quad (14)$$

This 3rd-order system is observable by θ , $\dot{\theta}$, and \dot{Z} . The feedback gains are to be properly selected to minimize the lateral drift velocity $\dot{z} = V(\alpha - \theta - \alpha_w)$ or the bending moment caused by the angle of attack. Note that:

$$\frac{\dot{z}}{V} \equiv \gamma = \alpha - \theta - \alpha_w \quad (15)$$

Where γ is often called the flight-path angle.

Instead of measuring the angle-of-attack, we may employ a body-mounted accelerometer (MPU6050), as illustrated in Fig. 2.2, as follows:

$$\begin{aligned} \delta &= -K_1 \theta - K_2 \dot{\theta} - K_a \ddot{z}_m \\ &= -K_1 \theta - K_2 \dot{\theta} - K_a \left(-\frac{N_\alpha}{m} \alpha + \frac{T}{m} \delta + \frac{x_a}{m} \ddot{\theta} \right) \\ &= -K_1 \theta - K_2 \dot{\theta} - K_a \frac{x_a}{m} \ddot{\theta} - K_a \frac{N_\alpha}{m} \alpha + K_a \frac{T}{m} \delta \end{aligned}$$

Because the resulting effect of \ddot{Z}_m feedback is basically the same as the α feedback, we consider here only the control logic described by Eq. (13).

the closed-loop transfer function from the wind disturbance $\alpha_w(s)$ to the drift velocity $\dot{Z}(s)$ as

$$\frac{\dot{Z}}{\alpha_w V} = - \frac{A_2 s^2 + A_1 s + A_0}{s^3 + B_2 s^2 + B_1 s + B_0} \quad (16)$$

Where

$$B_2 = M_\delta K_2 + \frac{T}{mV} \left(K_3 + \frac{N_\alpha}{T} \right)$$

$$B_1 = M_\delta (K_1 + K_3) - M_\alpha \frac{K_2 T}{mV} \left(M_\alpha + \frac{M_\delta N_\alpha}{T} \right)$$

$$B_0 = \frac{K_1 T}{mV} \left(M_\alpha + \frac{M_\delta N_\alpha}{T} \right) - \frac{F}{mV} \left(M_\delta K_3 - M_\alpha \right)$$

$$A_2 = \frac{T}{mV} \left(K_3 + \frac{N_\alpha}{T} \right)$$

$$A_1 = \frac{K_2 T}{mV} \left(M_\alpha + \frac{M_\delta N_\alpha}{T} \right)$$

$$A_0 = B_0$$

For a unit-step wind disturbance of $\alpha_w(s) = 1/s$, we use equation (16) The steady-state value of \dot{Z} can be found as

$$\frac{\dot{Z}}{V} = \lim_{s \rightarrow 0} - \frac{A_2 s^2 + A_1 s + A_0}{s^3 + B_2 s^2 + B_1 s + B_0} = \frac{-A_0}{B_0} = -1$$

The launch vehicle drifts along the wind direction with $\dot{Z} = -V_w$ and also with $\theta = \dot{\theta} = \alpha = \delta = 0$ as $t \rightarrow \infty$ and that could be noticed from fig 2.2.

It is interesting to notice that the steady-state drift velocity (or the flight path angle) is independent of feedback gains provided an asymptotically stable closed-loop system with $B_0 \neq 0$.

If we choose the control gains such that $B_0 = 0$ (i.e., one of the closed-loop system roots is placed at $s = 0$), the steady-state value of \dot{Z} becomes

$$\frac{\dot{Z}}{V} = \lim_{s \rightarrow 0} - \frac{A_2 s + A_1}{s^2 + B_2 s + B_1} = \frac{-A_1}{B_1} = \frac{-1}{1+C}$$

Where

$$C = \frac{mV[M_\delta(K_1 + K_3) - M_\alpha]}{M_\alpha K_2 T + M_\delta N_\alpha / T}$$

For a stable closed-loop system with $M_\delta(K_1 + K_3) - M_\alpha > 0$, and for $C > 1$ we have

$$|\dot{Z}| < V_w$$

A set of full-state feedback control gains, (K_1 , K_2 , and K_3), can be found by using a pole-placement approach or the linear-quadratic-regulator (LQR) control method [21-22], as follows:

$$\min_{\delta} \int_0^{\infty} (x^T Q x + \delta^2) dt \quad (17)$$

Subject to

$$\dot{x} = Ax + B\delta$$

$$\delta = -Kx$$

Where

$$x = [\theta \quad \dot{\theta} \quad \alpha]^T, \quad K = [k_1 \quad k_2 \quad k_3]$$

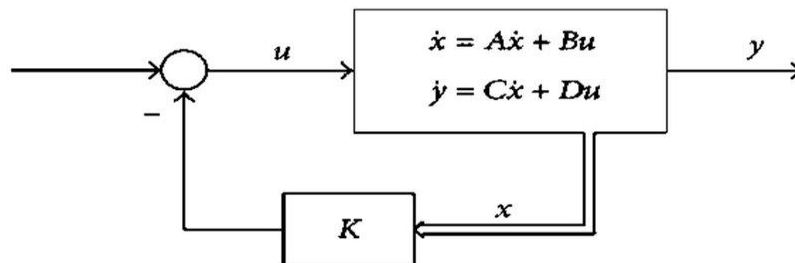


Figure 2. 3 Bloc diagram of LQR controller

2.3 Example

Consider a launch vehicle control design example for the for the Space Shuttle, Ares I[11]:

$$I_y = 2.43E6 \text{ slug-ft}^2, \quad m = 5830 \text{ slug}, \quad T = 341.000 \text{ IB}$$

$$F = 375.000 \text{ IB}, \quad X_{cp} = 38 \text{ ft}, \quad X_{cg} = 32.3 \text{ ft}$$

$$V = 1320 \text{ ft/sec}, \quad V_w = 132 \text{ ft/sec}, \quad \alpha_w = 5.73 \text{ deg}$$

$$N_\alpha = 240.000 \text{ IB/rad}, \quad M_\alpha = 3.75 \text{ s}^{-2}, \quad M_\delta = 4.54 \text{ s}^{-2}$$

The open-loop poles of this example vehicle are:

$$P_1 = -1.9767, \quad P_2 = 0.0488, \quad P_3 = 1.8967$$

Note that the wind-induced angle of attack of 5.73 deg considered for this example is somewhat unrealistic because it will require a maximum gimbal deflection angle of

$$\delta_{\max} > \frac{M_\alpha}{M_\delta} \alpha_w = 4.73 \text{ deg}$$

Most practical thrust vector control systems have a maximum gimbal angle constraint of about ± 5 deg.

Table 2. 2 Summary of rigid-body control analysis and design

Case no	Controller Type	Feedback Gains (K_1, K_2, K_3)	Closed-loop Poles
1	$(\theta, \dot{\theta})$ Feedback control	(2, 0.8, 0)	-1.7488±1.3934j, -0.1596
2	LQR Control	(3.9274, 3.7148, 4.7229e-04)	-1.9767, -1.8967, -0.0488

2.4 Rigid-Body Control

2.4.1 Rocket dynamics with LQR feedback control

Objectives of simulation:

We offset our TVC actuator on 0.2 deg of angle but for pitch rate and the drift on Z axes at 0 we want our vehicle to give a response for 0.01 deg of pitch angle.

And for that we used an LQR controller choosing lowest weight matrix to TVC angle and max to weight for the drift “z” so R is chosen like:

$$R = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 10 \end{bmatrix}$$

And for the cost Matrix Q we chose it to be a drift cost function as follow:

$$K = [K_1, K_2, K_3] \quad Q = \begin{bmatrix} 1 & 0 & \frac{1}{v} \\ 0 & 0 & 0 \\ \frac{1}{v} & 0 & \frac{1}{v^2} \end{bmatrix}$$

$$K_1 = 3.9274, K_2 = 3.7148, K_3 = 4.7229e-04$$

And that helped to determine the controller gains vector “K”

We are aiming in this simulation to have a stable pitch angle response and zero pitch rate but drift on Z axes is not related directly or influenced with our control gains and for this Z is not important in our control objectives because in the end it’s only an altitude description of the vehicle.

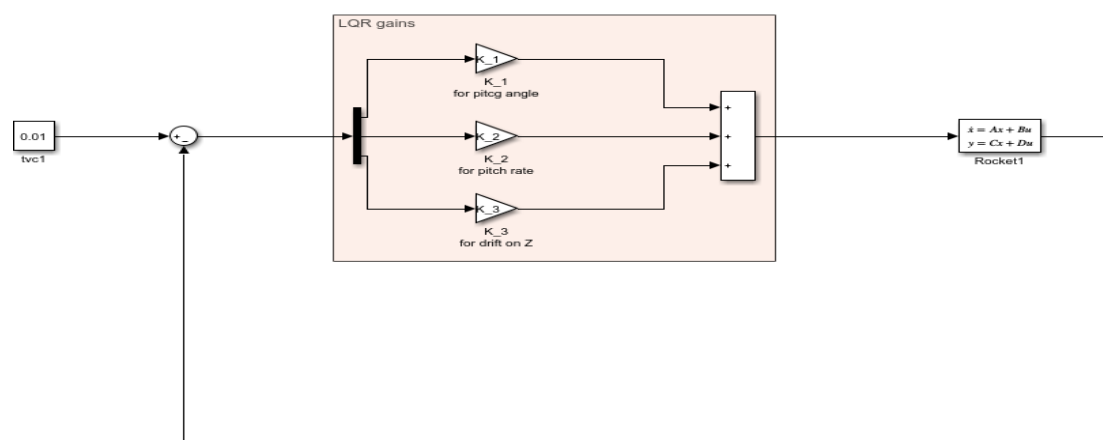


Figure 2. 4 Simulink block with State representation of the dynamics and cinematics of our rocket model with LQR feedbacks controllers

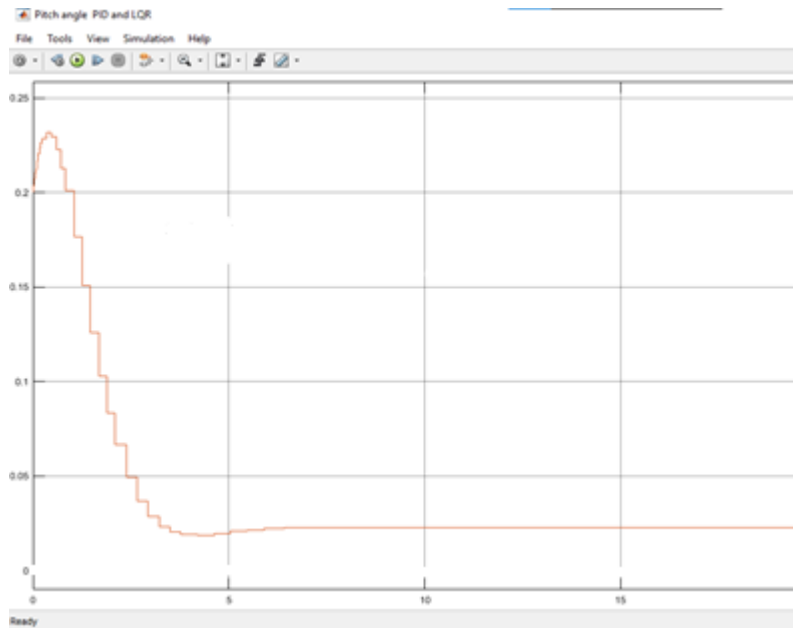


Figure 2. 5 Pitch angle response with an LQR controller

What we grasp her that as the objective was desired the slope went to our angle input with a slightly small margin of error but stability is demonstrated with the LQR feedback

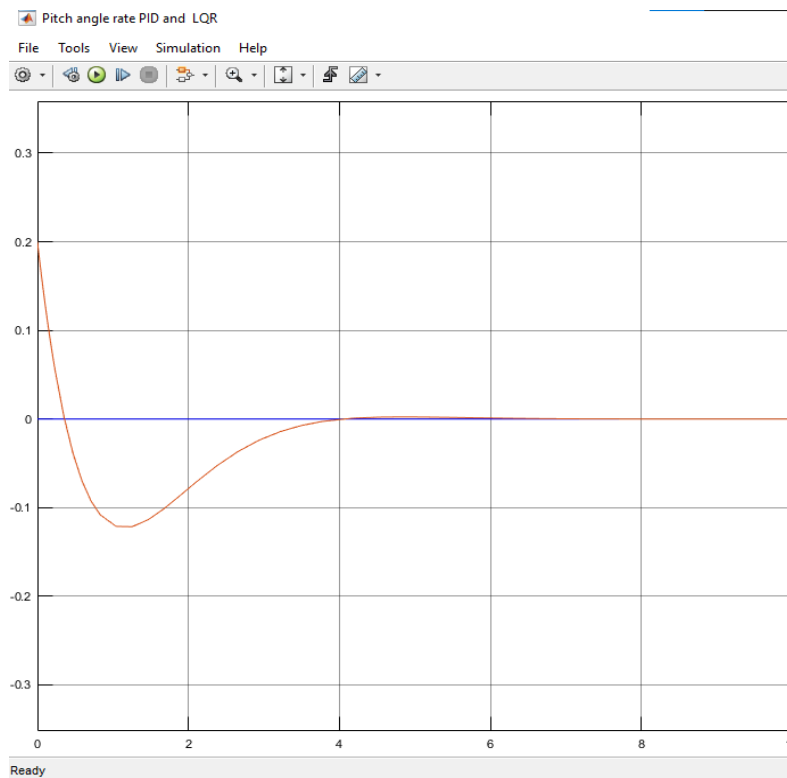


Figure 2. 6 Angular Velocity

The angular velocity even though it was initialized by zero but encountered a minor disturbance due to the primary offset of our TVC actuators ‘servo motors’ and then it return to zero pitch rate as intended

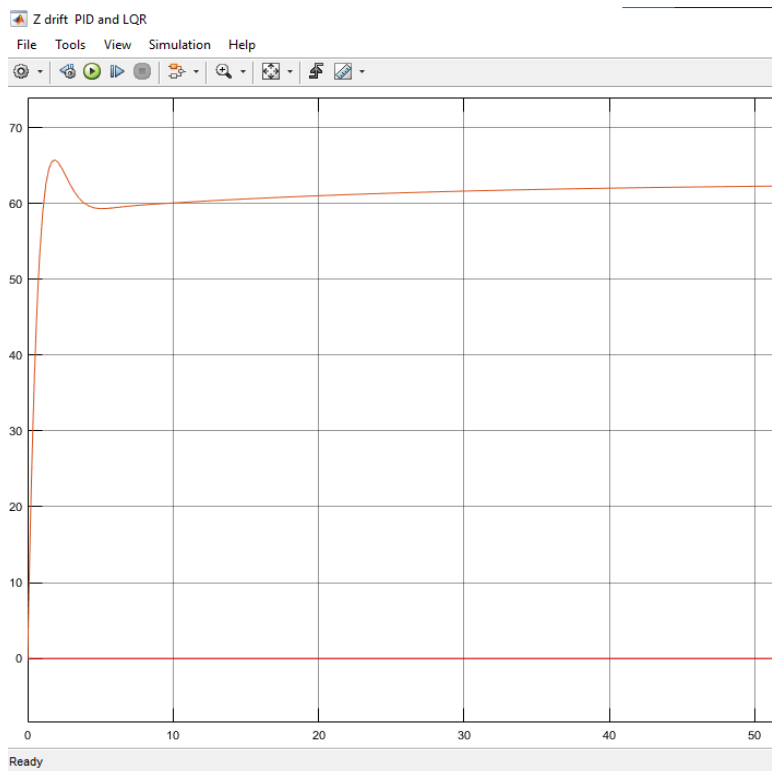


Figure 2. 7 Drift on Z axes

The drift encounters some disturbance at the beginning but it reaches to a peak altitude of roughly 62 Km

2.4.2 Rocket dynamics with PID feedback controller:

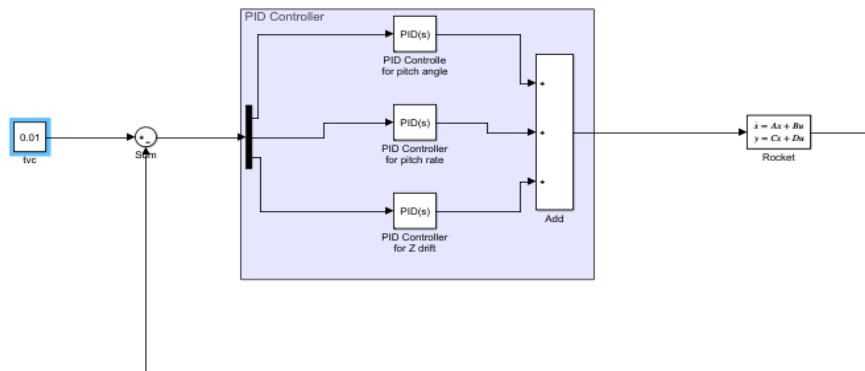


Figure 2. 8 Simulink block with state representation of the dynamics and cinematics of our rocket model with PID feedbacks controllers

Because we have three states in our systems we need to use thre pid Controllers to generate our PID gains we use the tuning block

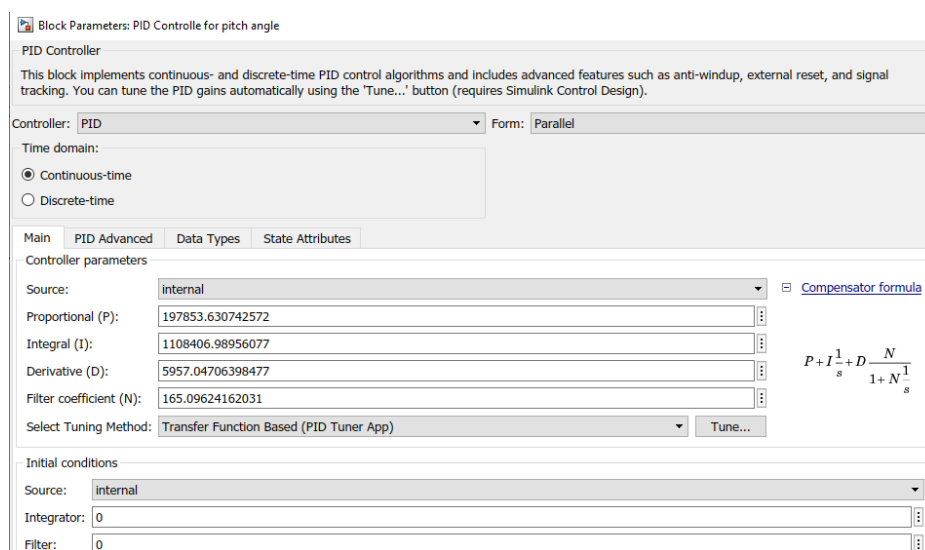


Figure 2. 9 The tuning block of PID

2.4.3 Simulation of rocket dynamics with LQR and PID feedback control

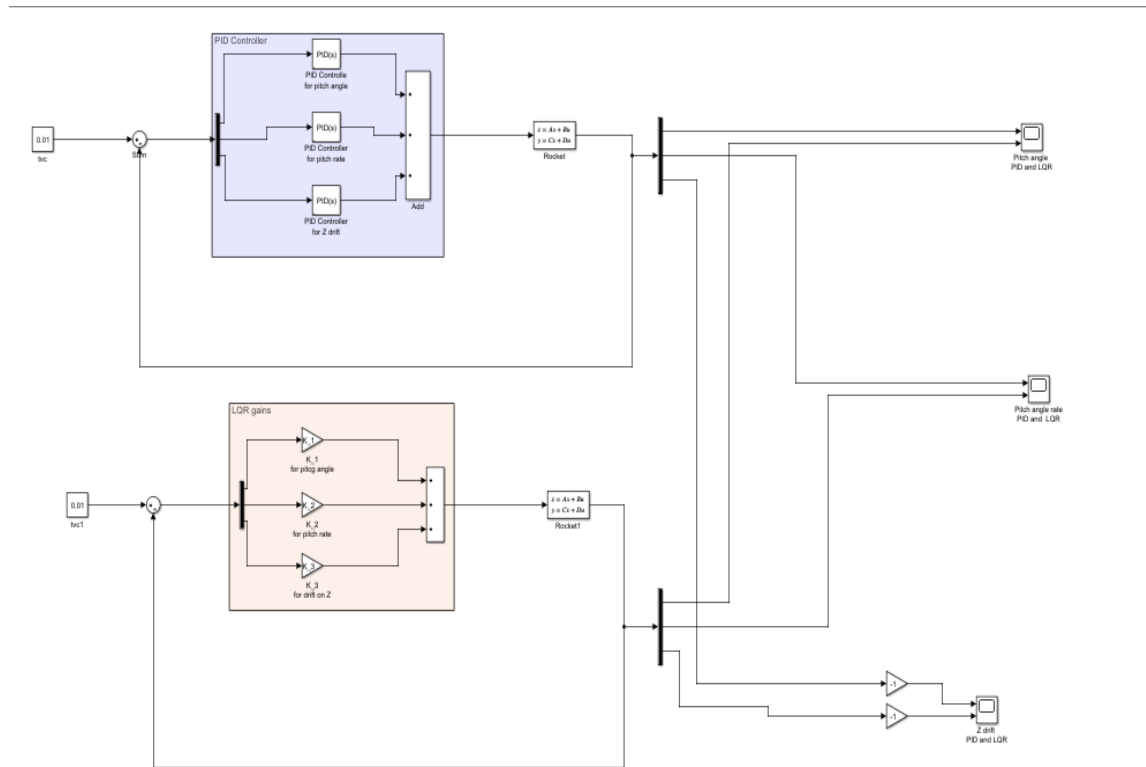


Figure 2. 10 Simulink block with state representation of the dynamics and cinematics of our rocket model with LQR and PID feedbacks controllers

2.4.4 Simulation of different state with LQR and PID controllers:

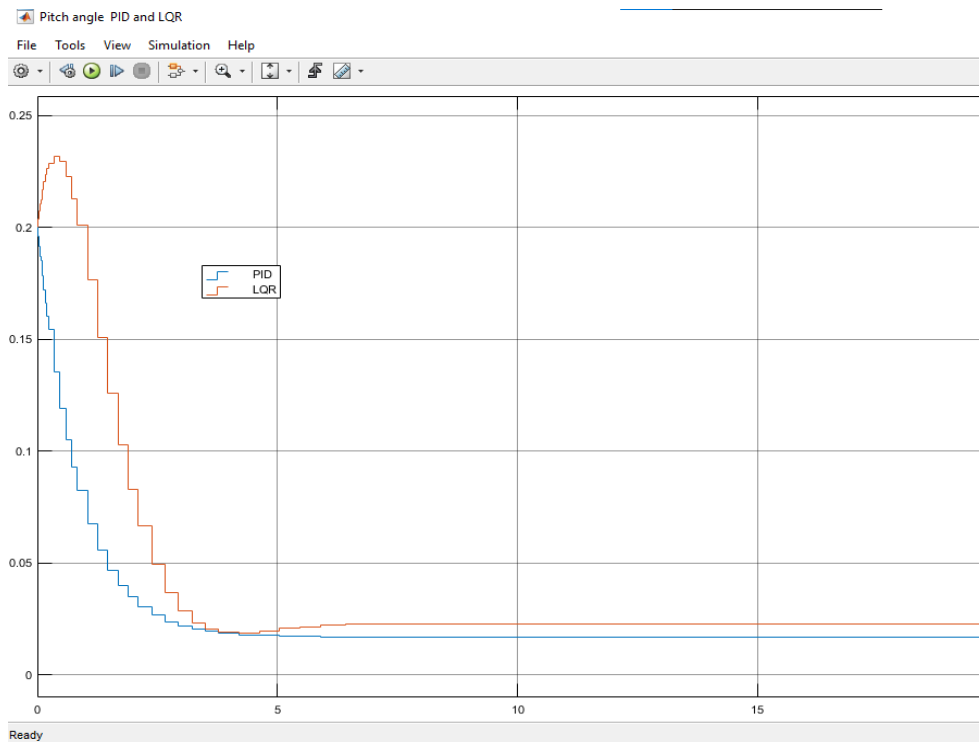


Figure 2. 11 Pitch response with PID and LQR controller

Compared to an LQR response the PID is fast and precise and that due to the fact that PID is more stable controllers than LQR one and robust also concerning how the controllers react with initialized disturbances.

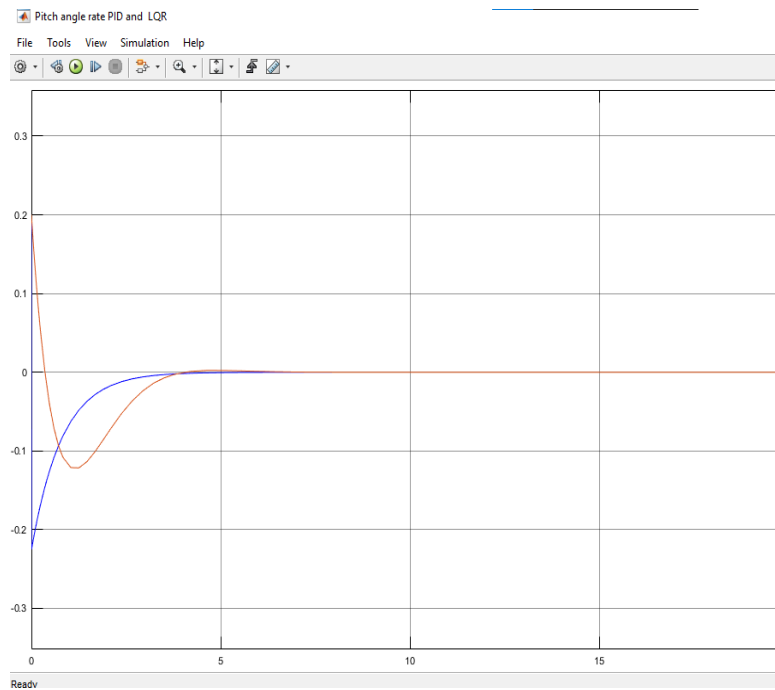


Figure 2. 12 Pitch rate response with PID and LQR controllers

For angular rate the response with the PID controller is faster than the LQR due to high gains coefficients

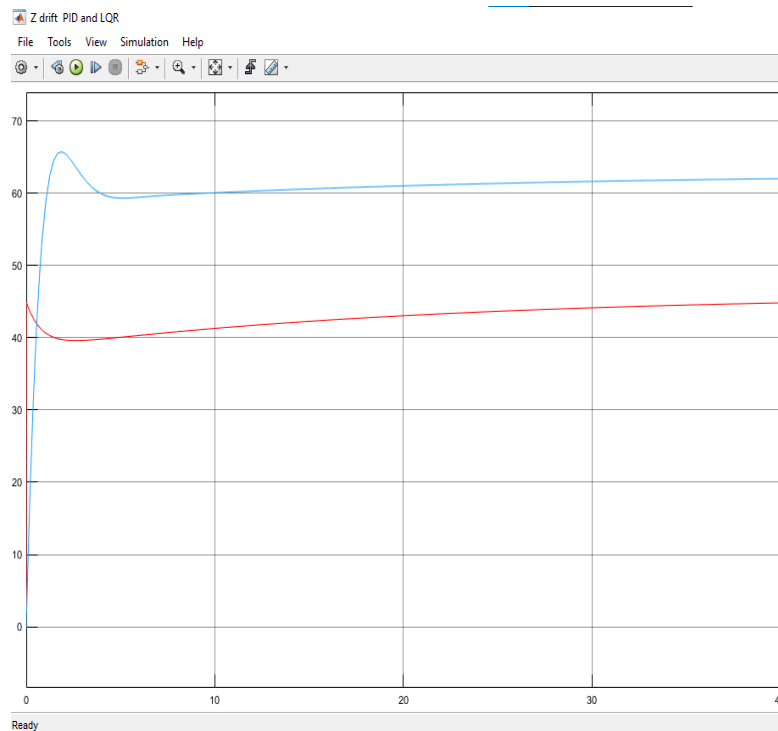


Figure 2. 13 Drift on Z with LQR and PID

As usual the PID response was more robust and with less margin errors compared to the LQR response and due to the fact that this command is not integrated to the testing prototype “rocket” and therefore determining the proper LQR gains will be more difficult

Conclusion:

An LQR controller make it easy to generate the gains using MATLAB codes that help us to solve the Ricatti equation but in other hand it requires that we know all the state of our system and that’s means if we wanted to integrated to a testing prototype, we need to have a reliable sensor for all the state of the system an LQR is also considered as a modern way of control compared to PID but in general modern doesn’t means better, taking the fact of disturbance LQR is not robust as PID.

Not forgetting to mention that the LQR is proportional regulator that means errors will always accrued and to solve that we need to add an integral control the LQR approach

Chapter 03: Manufacturing of Gyro stabilized Rocket

Introduction

In this chapter we conducted a static thrust vector control teste or hold down test using solid rockets propellant.

In amateur rocketry the basics are making a decent thrust motor and a reliable TVC design that could deliver a decent control over the desired axes and for the body of the rocket it's left to the designers to choose their preferable final prototype shape.

Our prototype is similar in concept to regular solid rocket which mainly are composite from big cello containing main propellants (oxidizer + fuel) and sometimes are separate; an engine which is a complex part and an important one as well.

Solid rocket motors are compound from a compact propellant grains a combustion chamber a nozzle and an igniter in the case of the solid motor the grains and the combustion chamber take the same space [10] .

For the nozzle an important part which is formed from divergent and convergent section and a throat that allow a high performance of the combustion exhaust; as much as the nozzle is well perfected the speed of the exhaust is faster and thus, we have more thrust for the rocket.

3.1 Rocket Motor Component and Design

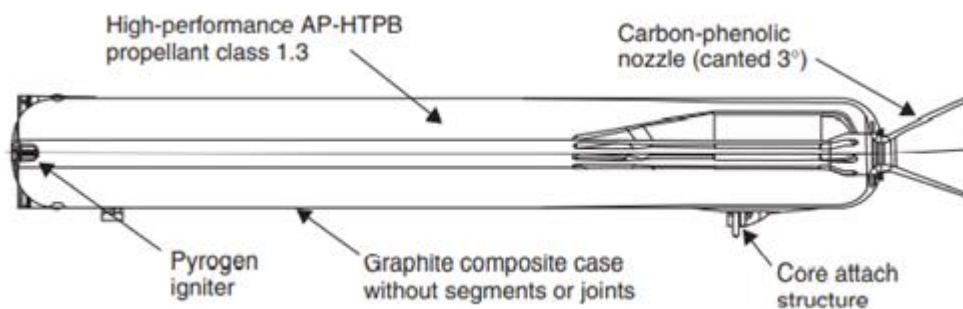


Figure 3. 1 Atlas V solid rocket booster (SRB) cross-sectional view.

“This motor has a large monolithic carbon-composite case and other novel features representative of modern solid boosters. The grain has tapered aft slots. (Courtesy of Aerojet Rocket dyne)”

3.1.1 Motor Case

The case not only contains the propellant grain, but also serves as a highly loaded pressure vessel. Case design and fabrication technology has progressed to where efficient and reliable motor cases can be produced consistently for any solid rocket application. Most problems arise when established technology is used improperly or from improper design analysis, understating the requirements, or improper material and process control, including the nondestructive tests at critical points in the fabrication process is highly recommended.

In our case we choose a PVC case for many reasons first that they are available everywhere and cheap and as important criteria they are very light weighted and could handle the pressure and temperature caused by a rocket candy propellant "KNO₃ +sugar".

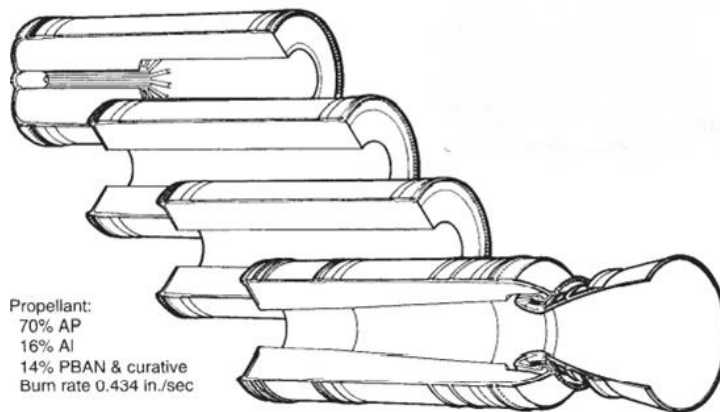


Figure 3. 3 Simplified diagram of the four segments of the historic Space Shuttle solid rocket booster motor



Figure 3. 2 Motor case



Figure 3. 4 Motor case contain propellants with circle grain form

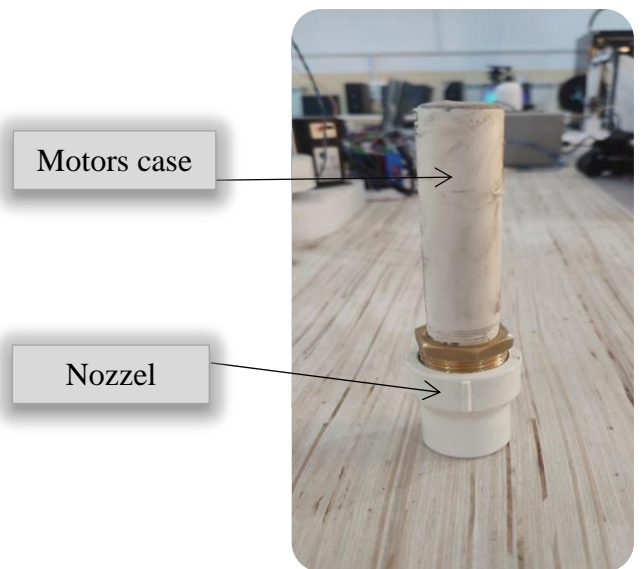


Figure 03: solid motor

3.1.2 Nozzles

The supersonic nozzle provides for the expansion and acceleration of the hot gases and has to withstand the severe environment of high heat transfer and erosion. Advances in material technology have allowed substantial mass reductions and performance improvements [12].

3.1.2.1 Classification Nozzles

Nozzles for solid propellant rocket motors can be classified into five categories as listed below and shown in Fig 3.6

- **Fixed Nozzle** Simple and used frequently in tactical weapon propulsion systems for short-range air-, ground-, and sea-launched missiles, also as strap-on propulsion for space launch vehicles such as Atlas and Delta, and in spacecraft motors for orbital transfer.
- **Movable Nozzle.** one movable nozzle can provide pitch and yaw control and two are needed for roll control.
- **Submerged Nozzles.** A significant portion of the nozzle structure is submerged within the combustion chamber or case. Submerging the nozzle reduces the overall motor length somewhat, which in turn reduces the vehicle length and its inert mass.
- **Extendible Nozzle.** Commonly referred to as an extendible exit cone, or EEC, although it is not always exactly conical. It is used on strategic missile propulsion upper-stage systems and upper stages for space launch vehicles to maximize motor-delivered specific impulse, it has a fixed low-area-ratio nozzle section which is enlarged to a higher area ratio by mechanically adding a nozzle cone extension piece.
- **Blast-Tube-Mounted Nozzle.** Used with tactical air- and ground-launched missiles with diameter constraints to allow space for aerodynamic fin actuation or TVC power supply systems.

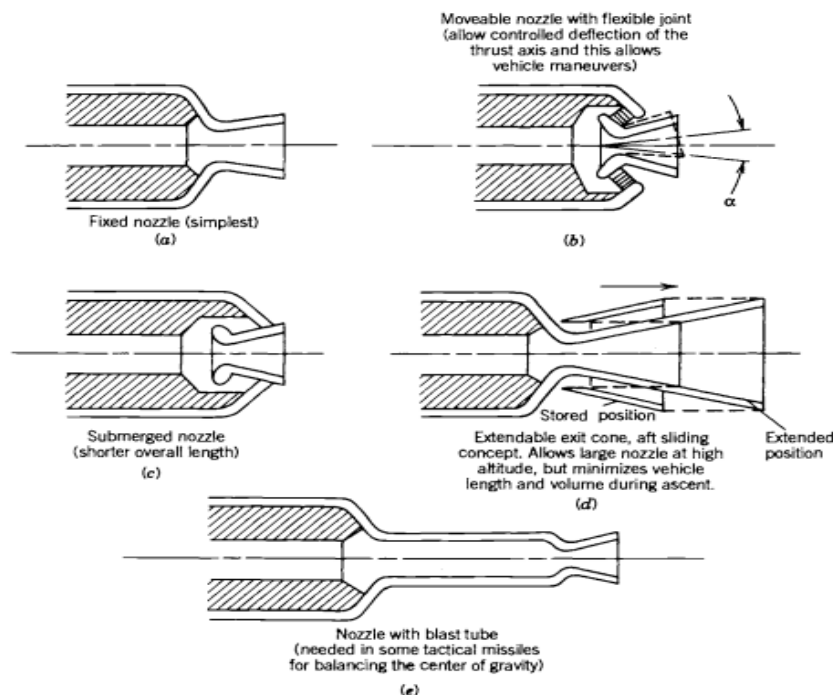


Figure 3. 5 Simplified diagrams of five common nozzle configurations.

3.2 PIECES FABRICATION

3.2.1 3D Design Fusion 360

Fusion 360 is a cloud-based CAD/CAM tool for collaborative product development that combines industrial design, mechanical engineering, and machine tool programming into one software solution.

- **Thrust vector control :**

The outer gimbal in the left is attached to the rocket body and holds the x axes servo ,the inner gimbal in the middle is to hold the y axes servo and the motor mount tube in the right side is to hold the rocket motor and to be attached with the two servos using a linkage

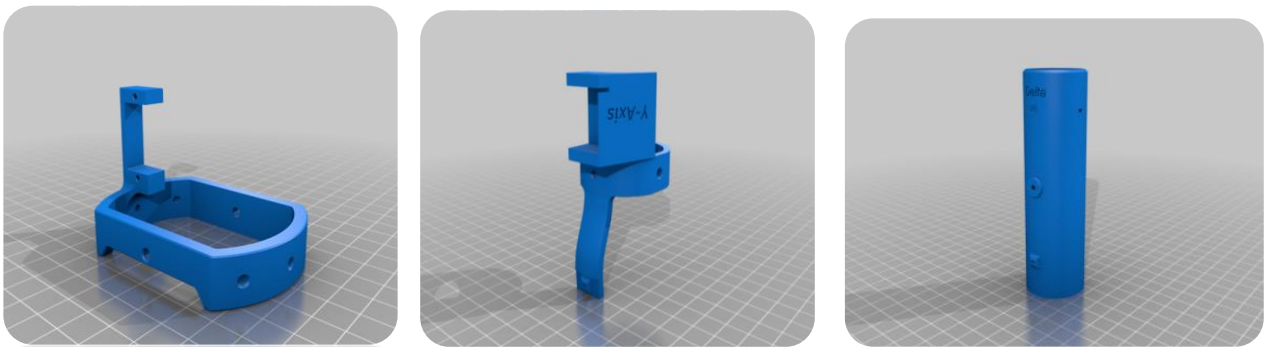


Figure 3. 6 3D design of outer gimbal, inner gimbal and motor tube

- **The Nose:**

Is the tip part of the rocket its help to get a better aerodynamically performance during flight phase



Figure 3. 7 3D design of the nose

- **The Holders:**

They guarantee to fix the rocket without neglecting its attitude dynamics basically it's a hold down design



Figure 3. 8 3D design of the holders

3.2.2 3D Impression

3D printing is a so-called additive manufacturing technique which proceeds by adding material, unlike techniques proceeding by removing material such as machining. 3D printing makes it possible to produce everyday objects, spare parts or even prototypes intended for testing. The starting point is a computer file representing the object in three dimensions, broken down into slices. This information is sent to a 3D printer which will carry out the manufacturing by adding successive layers [17].

- **Thrust vector control**



Figure 3. 9 printed parts of Outer gimbal, Inner gimbal and Motor tube

- **The Nose**



Figure 3. 10 printed nose

- **The Holders**

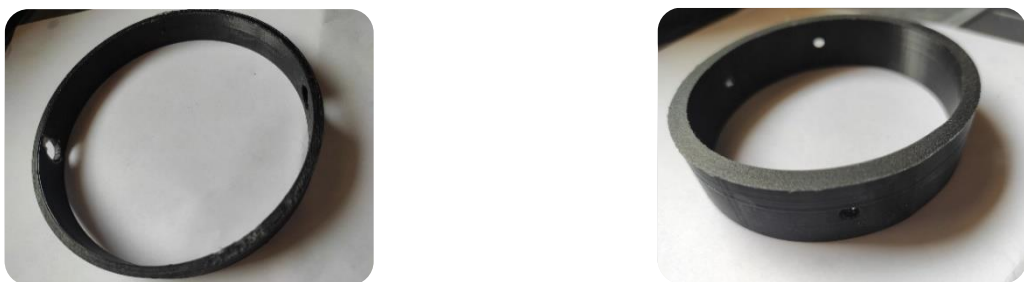


Figure 3. 11 printed holders

- **The Nozzle:**



Figure 3. 12 preparing the nozzle conceived with cement

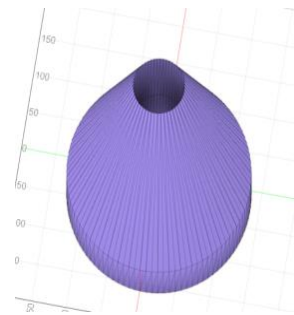


Figure 3. 13 Nozzle divergent section type 'd' made from cement formed with 3d printed mold

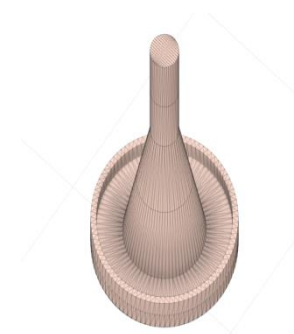


Figure 3. 14 nozzle convergent section type 'd' made from cement formed with 3d printed mold

3.3 Materials:

- **Servo 9g:**

The Micro Servo Module is made up of an electric motor mechanically linked to a potentiometer. The Servo Library is used to easily control this module with an Arduino kit, The electronics inside the servo motor transform a PWM pulse width into a physical position: When the servo is commanded, the motor will be driven until it reaches the potentiometer value corresponding to the requested position.



Figure 3. 15 micro servo 9g

- **Arduino Uno:**

Is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator (CSTCE16M0V53-R0), a USB connection, a power jack, an ICSP header and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery 9v to get started.



Figure 3. 16 Arduino Uno

- **wireless relay**

A relay is an electrically operated switch. They usually use an electromagnet (coil) to operate their internal mechanical switching mechanism (contacts). When a relay contact is opened, it will energize a circuit when the coil is activated.

Relays allow a low current circuit to control one or more higher current circuits raised.



Figure 3. 17 Wireless Relay [19]

- **MPU6050**

MPU6050 sensor module is complete 6-axis Motion Tracking Device. It combines 3-axis Gyroscope, 3-axis Accelerometer and Digital Motion Processor all in small package. Also, it has additional feature of on-chip Temperature sensor. It has I2C bus interface to communicate with the microcontrollers. It has Auxiliary I2C bus to communicate with other sensor devices like 3-axis Magnetometer, Pressure sensor. It can measure angular momentum or rotation along all the three axes, the static acceleration due to gravity, as well as dynamic acceleration resulting from motion, shock, or vibration. [18]

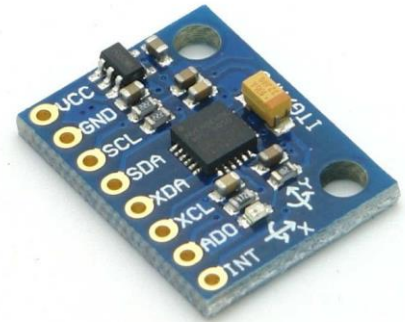


Figure 3. 18 MPU6050 device

- **Measuring Acceleration**

The MPU6050 can measure acceleration using its on-chip accelerometer with four programmable full scale ranges of $\pm 2g$, $\pm 4g$, $\pm 8g$ and $\pm 16g$

It has three 16-bit analog-to-digital converters that simultaneously sample the 3 axis of movement (along X, Y and Z axis)

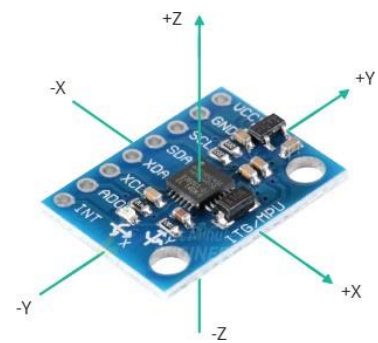


Figure 3. 19 Acceleration Axes

- **Measuring Rotation**

The MPU6050 can measure angular rotation using its on-chip gyroscope with four programmable full-scale ranges of $\pm 250^\circ/s$, $\pm 500^\circ/s$, $\pm 1000^\circ/s$ and $\pm 2000^\circ/s$.

It has another three 16-bit analog-to-digital converters that simultaneously samples 3 axes of rotation (around X, Y and Z axis). The sampling rate can be adjusted from 3.9 to 8000 samples per second.

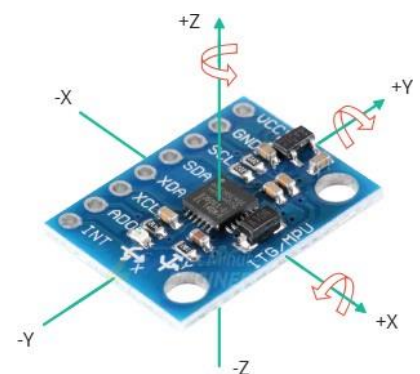


Figure 3. 20 Rotation Axes

- **MPU6050 Module Pin out**

The pin descriptions of the MPU6050 module are as follows :

INT: Interrupt digital output pin.

AD0: I2C Slave Address LSB pin. This is 0th bit in 7-bit slave address of device.

XCL: Auxiliary Serial Clock pin. This pin is used to connect other I2C interface enabled sensors SCL pin to MPU-6050.

XDA: Auxiliary Serial Data pin. This pin is used to connect other I2C interface enabled sensors SDA pin to MPU-6050.

SCL: Serial Clock pin. Connect this pin to microcontrollers SCL pin.

SDA: Serial Data pin. Connect this pin to microcontrollers SDA pin.

GND: Ground pin. Connect this pin to ground connection.

VCC: Power supply pin. Connect this pin to +5V DC supply

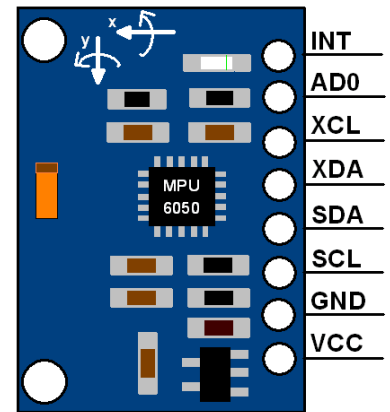


Figure 3. 21 MPU6050 Module Pin out

3.3.1 Wiring Servos and MPU6050 Module with Arduino

The following pictures shows you how to wire everything

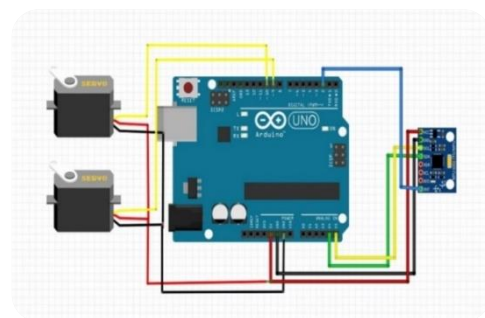
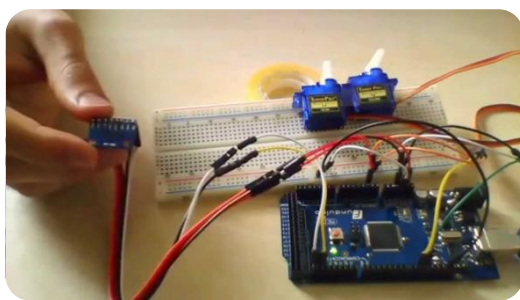


Figure 3. 22 Schema of Wiring Devices

3.4 PROPELLANT MIXING:

For this motor we will need to mix up 100g of dry propellant. The ratio is 65/35. 65% KNO_3 and 35% Sorbitol.

- **Potassium Nitrate (KNO_3):** Potassium nitrate appears as a white to dirty gray crystalline solid. Water soluble. Noncombustible, but accelerates the burning of combustible materials. If large quantities are involved in fire or the combustible material is finely divided an explosion may result.

May explode under prolonged exposure to heat or fire. Toxic oxides of nitrogen are produced in fires. Used in solid propellants, explosives, fertilizers.[12]

- **Sugar:** Sugar propellants (SP) or rocket candy is a type of rocket propellant for model rockets made with sugar as a fuel, and containing an oxidizer. The propellant can be divided into three groups of components: the fuel, the oxidizer, and the additive(s). The fuel is a sugar; sucrose is the most commonly used.

- **Motor propellant:** typical sugar propellant formulation is typically prepared in a 65:35 oxidizer to fuel ratio. However, this formulation is slightly fuel rich. This ratio allows for the formulation to be more fluid in its melted state. Additives could take up between zero and ten percent of the total fuel. There are many different possible formulations that will

allow for flight in model rocketry.

The original SP's utilized sucrose (ordinary table sugar) as the fuel to combine with the potassium nitrate oxidizer. While this provides an excellent propellant, fructose fuel provides excellent working time while melted and provides a slightly longer burn time than sucrose motors. It also melts at a relatively low 250°F. A more readily available and cheaper fuel alternative is dextrose. This is also easy to work with and provides good burn characteristics as well.



Figure 3. 23 Potassium Nitrate (KNO_3)

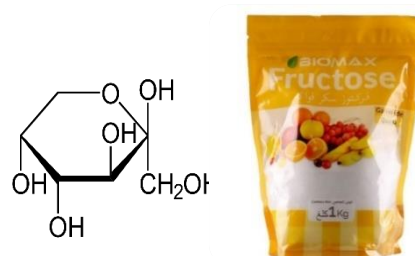


Figure 3. 24 Sugar Fructose



Figure 3. 25 Sugar Preparation and Mixing Motor Propellant

3.4.1 Solid Propellant Functions

A solid propellant is a monopropellant fuel, a single mixture of several chemicals i.e., the oxidizing agent and the reducing agent or fuel. This fuel is in its solid state and has a preformed or molded shape. The propellant grain, this interior shape of the core is an important factor in determining a rocket's performance. The variables determining grain-relative performance are core surface area and specific impulse. [16]

Surface area is the amount of propellant exposed to interior combustion flames, existing in a direct relationship with thrust. An increase in surface area will increase thrust but will reduce burn-time since the propellant is being consumed at an accelerated rate. The optimal thrust is typically a constant one, which can be achieved by maintaining a constant surface area throughout the burn.

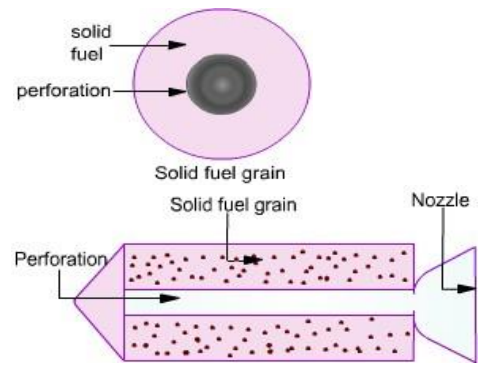


Figure 3. 26 Prototype of rocket engine



Figure 3. 27 Rocket Engine

3.5 Igniter Hardware

If a rocket motor is unexpectedly ignited and starts combustion, the very hot exhaust gases may cause burns and local fires, or ignition of adjacent rocket motors. Unless the motor is constrained or fastened down, its thrust will accelerate it to unanticipated high velocities or erratic flight paths that can cause much severe damage. Its exhaust can be toxic and corrosive

Since the igniter propellant mass is small (often less than 1% of the motor propellant) and burns mostly at low chamber pressure, it contributes very little to the motor overall total impulse. It is the designer's aim to reduce the igniter propellant mass and the igniter inert hardware mass to a minimum, just big enough to assure ignition under all operating conditions.

And thus we may find a several type of ignition hardware:

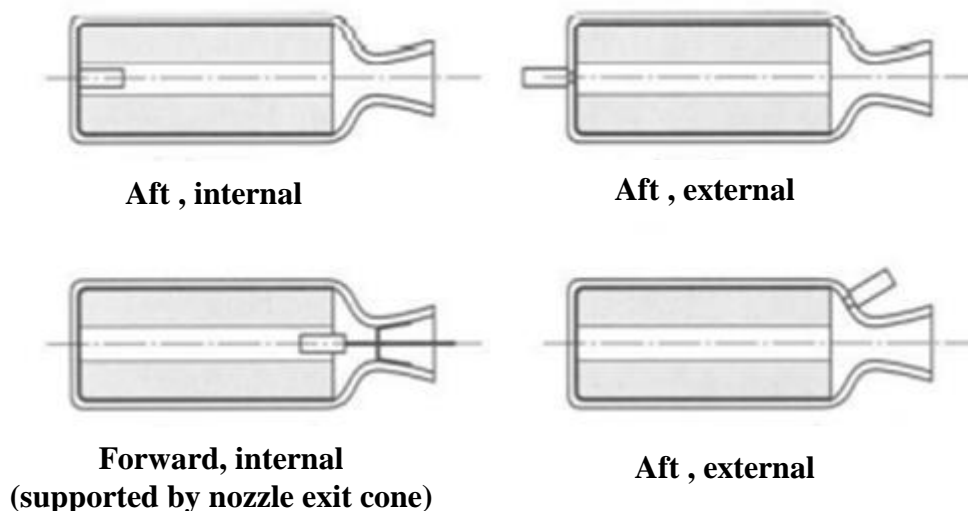


Figure 3. 28 Simplified Diagrams of Five Common Nozzle Configurations.

3.5.1 The ignition system

Model rockets, like professional rockets are launched electrically. This provides both safety and realism. A launch system must provide adequate electrical current to cause engine ignition. The electrical current accomplishes engine ignition by heating the igniter which produces enough heat to cause the solid propellant to ignite.

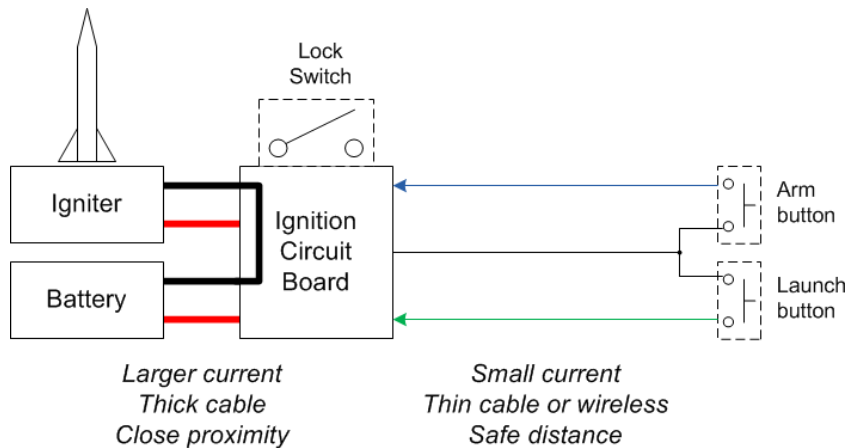


Figure 3. 29 Prototype of Ignition System

3.5.2 Wireless ignition system:

In our launching, we need an ignition system that will be safe and easy to use. At this time, we came with the idea of a wireless ignition system in which we use a means to remotely light things on fire via wireless relay and an RF. This system is mainly intended to launch model rockets, and can do so from over a hundred feet away! It's also able to light things like thermite, fireworks, explosives..., anything you need on fire, and would want to stand far away from.

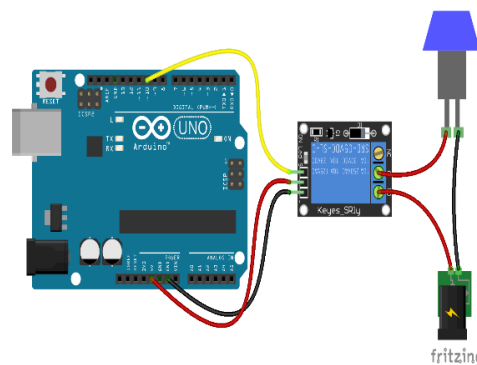


Figure 3. 30 Prototype of Ignition System with Fritzing [20]

3.6 Arduino code for the TVC:

- **Libraries included:**

we used an SPI which stand for “synchronous serial data protocol” which is a full duplex communication better than the half duplex I2C type and use 4 wires protocol of only one master and this choice comes in handy one we use one peripheral device that send large amount of data like an MPU6050 “gyroscope”, and for wire library it comes in use when we are dealing with SDA, SCL inputs, servo library is necessary to control RC motors.

```
#include <SPI.h>
#include <Servo.h>
#include <Wire.h>
```

- **Constant and variable implementation:**

We have many variables from acceleration along X, Y, Z axes to rotational acceleration along those three axes to tow angles of control Pitch and yaw that send data to our servos referenced as servo X, Y.

```
const int MPU=0x68;
int16_t AcX,AcY,AcZ,Tmp,GyX,GyroY,GyroZ;
int pitch;
int accAngleX;
int accAngleY;
int yaw;
int GyroX;
int gyroAngleX;
int gyroAngleY;
int valueX = 110;
int valueY = 150;
Servo servoX;
Servo servoY;
float elapsedTime, currentTime, previousTime
```

- **Setup function:**

In the setup function we initiate the communication between the MPU and Arduino board and we attach our servo motors to the desirable pins.

```
void setup(){
  Wire.begin();
  Wire.beginTransmission(MPU);
  Wire.write(0x6B);
  Wire.write(0);
  Wire.endTransmission(true);
  Serial.begin(9600);
  servoX.attach(5);
  servoY.attach(6);
  Serial.begin(9600);
```

- **Loop function:**

In the loop function we defined the transitory acceleration upon X and Y acceleration with an estimated error of 0.5 for X axes and 1.6 on Y axes also we defined gyro angle on x and y even thou those angles inherit a lot of disturbance due to the fact that the MPU collect acceleration data and do not measure the angle directly which oblige us to use some type of filter.

```
void loop() {
  filter();
  map();
  previousTime = currentTime;
  currentTime = millis();
  elapsedTime = (currentTime - previousTime) / 1000;
  accAngleX = (atan(AcY / sqrt(pow(AcX, 2) + pow(AcZ, 2))) * 180 / PI) - 0.58; //
  AccErrorX ~(0.58) See the calculate_IMU_error()custom function for more details
  accAngleY = (atan(-1 * AcX / sqrt(pow(AcY, 2) + pow(AcZ, 2))) * 180 / PI) + 1.58; //
  Wire.beginTransaction(MPU);
  Wire.write(0x3B);
  Wire.endTransmission(false);
  Wire.requestFrom(MPU,12,true);
  AcX=Wire.read()<<8|Wire.read();
  AcY=Wire.read()<<8|Wire.read();
  AcZ=Wire.read()<<8|Wire.read();
  GyroX=Wire.read()<<8|Wire.read();
  GyroY=Wire.read()<<8|Wire.read();
  GyroZ=Wire.read()<<8|Wire.read();
  gyroAngleX = gyroAngleX + GyroZ * elapsedTime; // deg/s * s = deg
  gyroAngleY = gyroAngleY + GyroY * elapsedTime; }
```

- **Complementary filter**

We used a math filter that merges the signals returned by the gyroscope and the accelerometer

its common that the gyroscope drift and in few times returns wrong values and in the other hand accelerometers even though it returns true values when the acceleration is progressive it cannot handle vibrations.

The math filters or complementary filter can managed both low and high pass filters at the same time producing a good signal; in other case Kalman filter would be the best suitable filters but they are complicated and this is way is better for our case to use a math filter.

```
void filter () {
  Serial.print(GyroX);
  pitch = 0.9 * gyroAngleX + 0.1 * accAngleX;
  yaw = 0.9 * gyroAngleY + 0.1 * accAngleY;
}
```

- **Plots using simple command and serial plotter tool:**

```
Serial.print(valueX);

Serial.print("Accelerometer: ");
Serial.print("X = "); Serial.print(AcX);
Serial.print(" | Y = "); Serial.print(AcY);
Serial.print(" | Z = "); Serial.println(AcZ);
//Serial.print("Gyroscope: ");
//Serial.print("X = "); Serial.print(GyX);
// Serial.print(" | Y = "); Serial.print(GyroY);
// Serial.print(" | Z = "); Serial.println(GyroZ);
}
```

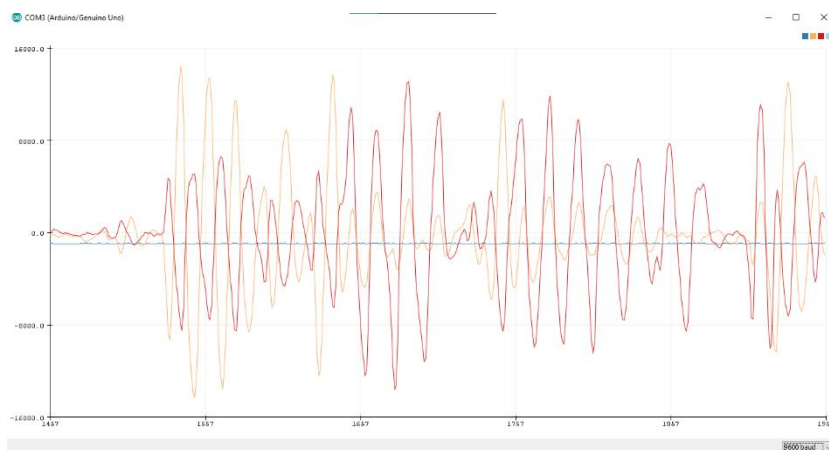


Figure 3. 31 Rotational acceleration along x, y, z

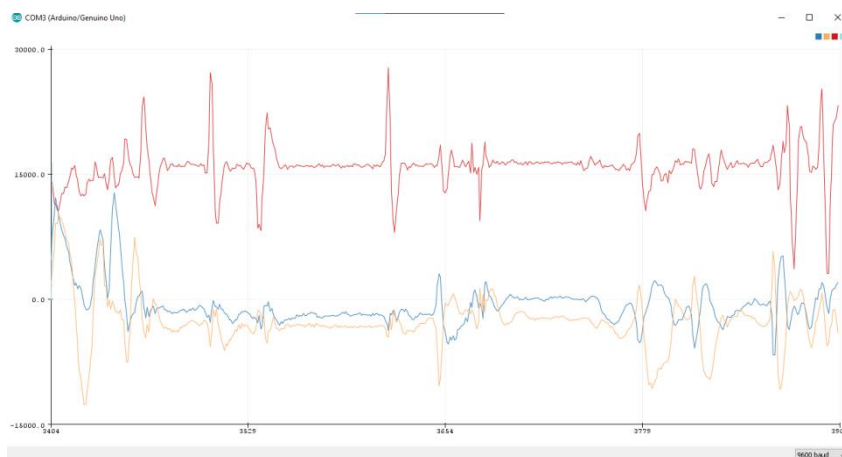


Figure 3. 32 Linaire acceleration on x, y, z

3.7 TVC assembly

We combine our inner and outer gamble with motor mount and we place the x and y servos.



Figure 3. 33 TVC assembly

3.8 Rocket assembly

The final product contained from top a printed nose in the middle we have the main buddy made carton containing the Arduino board plus the meme MPU6050 and the power bank attached from outside with rotative holders and in bottom the TVC plus servos and motor are joined making fully rocket prototype.



Figure 3. 34 SI-Rocket prototype

3.9 Static Test

The engine(s) are fired for a few seconds while the launch vehicle is held firmly attached to the launch mount. This tests engine startup while measuring pressure, temperature and propellant-flow gradients, and can be performed with or without payload. The data gathered in such tests may be used to form a unique (rocket- and engine-specific) set of criteria as part of the go/no-go decision tree in the launch software that is used on launch day. Some static fire tests have fired the engines for twelve and even twenty seconds, although shorter firings are more typical.

In our case static test is mandatory for many reasons the most important one related to security purposes and law conduction in Algeria, the law clear out that no flying vehicle is allowed to bypass the altitude of 2 meters and those law must be obeyed and for that we preferred to make static test that could help also to show the real attitude of our rocket.

Test 01:

Wireless ignition system:

Using a relay module integrated with infrared receiver we put on teste a circuit to ignite our motor for the purpose of security and safety.



Figure 3. 35 Wireless ignition system

Test 02:

Motor Static test without the nozzle:

In this test we tried our own mixture of propellant with a slight ratio deviation to decrease the regression rate, the motor generated a thrust that could lift only 200 g and that due to the lake of a nozzle a part that would help to accelerate the exhaust gases and thus more speed is produced for the motor case.



Figure 3. 36 Motor Static test without the nozzle

Test 03:

Motor Static test with the nozzle:

As expected, more thrust was induced and significantly better than the former due to the nozzle effect making the gases which are more pressurized in the case less pressurized in the convergent section but with more velocity and if the exhaust velocity increases, the thrust which is a function of force will also increase and this underlies under the famous Bernoulli principle.



Figure 3. 37 Motor Static test with the nozzle

Test 4:

First Static control test for pitch angle:

We fixed the yaw axes and provided movability only for the pitch axes, we noticed that the thrust wasn't enough to create perturbation as was planned even though we offset our TVC angle with a slight deviation just to cause disturbances, because if we had some oscillation the TVC will eventually correct them as we saw in the "Free TVC test".

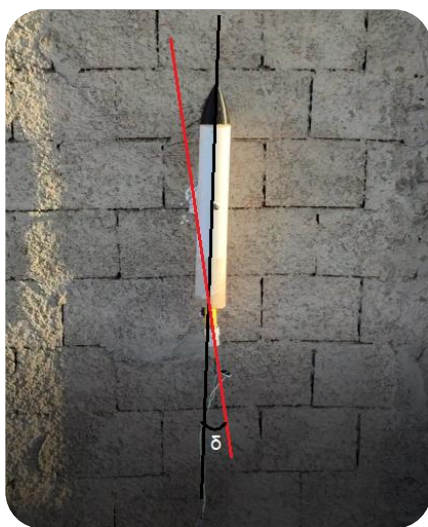


Figure 3. 38 First Static control test for pitch angle

Test 5:

Second Static control test for pitch angle:

Because offsetting our TVC angle wasn't enough to cause disturbance we tried to offset largely the pitch angle of the rocket and also, we add gunpowder to the rocket propellant roughly 10% from the total of oxidizer and fuel composite but unfortunately unexpected exploding accrued damaging our TVC and we decide to end the experimentation for the moment.



Figure 3.39 Second Static control test for pitch angle

3.10 Discussion of results:

The stabilization test was demonstrated in last few seconds of the burnout, even though the rocket motor didn't generate enough thrust, but at least we encounter a slightly attitude disturbance from it that eventually the disturbance has been corrected with the TVC.

Because we have phase shifting between the moment of initialization of the TVC system and the ignition of the rocket taking for granted there is no easy way to negate that effect, a huge disturbance will be noticed in the first few seconds of the burnout.

The complementary filter is not the best way to control our rocket, a mother control technique would be more suitable but with decoupled axes control.

Servo motors 9g type are not delivering the necessary torque to steer our rocket a better choice will be the MG995 servos not forgetting to make a suitable change in the TVC design for the new servos to fit in.

Conclusions and future work

Rocket propulsion and control is an ocean of research and experimentation from developing rocket boosters and engines that work on sea level or vacuum to constraining the perfect navigation and control computers in ascent or descent modes and creating a reusable rocket engine that make extraordinary maneuvers to go back to land and to be reissued again helping to scale down the rocket industry annual coast.

The aim of the presented work was the demonstration of a thrust vector controlling system for a small scaled rocket vehicle using 2 axes (pitch yaw) gimbaled design, and we simulated the control of Ares 1 as a linear model with a linear quadratic regulator and PID tuning technique. Results have shown that both controllers displayed a good performance but the PID shows better performance concerning accuracy.

Adding a roll control will help to fully control the rocket attitude instead of only pitch-yaw control, an optimal and feedforward control should be conduct because they are the most reliable and recent control ways used in rocket industry; and a nonlinear approach with quaternion presentation will be the most robust way to modulate the attitude of rockets and to avoid any problems like the gambled lock issue accord when dealing with Euler representation.

In our TVC design we gimbaled all the motor (chamber + nozzle) a better design would be controlling only the nozzle and thus will oblige us to change the structural material of the motor to aluminum instead of PVC.

The complementary filters generated in the Arduino control script are less reliable then a Kalman filter, so a full study of this filter theory should be conducted to ensure better results concerning how to get angle data directly and more accurately from an MPU6050 module.

In future work we will try to change the type of the engine to a liquid engine and that to granite better thrust performance and control; compared to solid motors type because they are dangerous and not controllable.

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