Design of Self- Stabilization Thrust Vector Control System (TVCs)for Rockets and Missiles

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Abstract - *The sole aim of this project is to design an automatic self-stabilized thrust vector control system for any type of non-air breathing engine such as rocket, missile and an aircraft used for military purpose with short / vertical takeoff and landing ability by employing programmed algorithms for counterfeit trajectory path and flight. The major concern of this project is successful execution of our designed thrust vectoring control system (TVCs) that utilize the thrust given by operational rocket or aircraft engine in order to control the trajectory path by using flight computer and gyroscope which actuate the direction of flight to operate the nozzle for thrust vectoring with self-stabilization program. This new thrust vector control system is integrated with traditional thrust vector control system based on Attitude control thrusters. Here, we are employing gyro and gimbal technology to build our Thrust Vector Control system by using Uno Arduino chip with advance program which helps for deflection of nozzle for trajectory. A C++ advanced algorithm is set in no Arduino with MCU6050 sensor for motion tracking and trajectory control for Thrust Vectoring.*

Key Words: **TVCs, Flight Computer, Uno Arduino, Self-Stabilization, Program, Gyro and Gimbal Technology etc.**

1. INTRODUCTION

Thrust vector control (TVC) is the vital part of Aerospace maneuvering. It is capacity of a rocket, missile, fighter aircraft(S/VTOL) or other vehicle to change or control the direction of the thrust from its engines or motors to control the attitude or angular velocity of the vehicle that leads to them for directional change in respective trajectory path. Aerodynamic control surfaces like Ailerons, Elevators and Rudder are ineffective in context of non-air breathing engine (rocket and missiles) as they fly outside the earth's atmosphere at very high speed, so thrust vectoring is the primary means of attitude control. Recent years have seen an increase in interest in the research and development of Thrust Vector Control System for rocket which would provide self-stabilization and change in Angular velocity for trajectory which leads for precise deviation of Vehicle in Space. So, here we came up with design of self-stabilized Thrust Vector Control system with aid of advanced algorithm and program with simple mechanical modification in manufacturing. During landing manoeuvres to slow down and reach a final soft landing it is employed in lander spacecraft mainly to keep the vector parallel to the velocity of Spacecraft.

2. LITERATURE REVIEW

2.1 Analysis of the fluid mechanics of secondary injection for thrust vector control by James E. Boardwell, May 1963

This paper deals with the interaction of the injected, or secondary, fluid with the primary free-stream; the boundary layer on the nozzle wall is ignored. The boundary layer, of course, makes important modification to the flow, but the results obtained suggest that many of the essential features of the injection process are contained in the "inviscid" analysis. In any case, an understanding of the free-stream injectant interaction would provide a basis for a more general study, including the effect of the boundary layer.

2.2 Thrust vector control analysis and design for solar sail spacecraft by Bong Wie, May-June 2007

This paper presents a comprehensive mathematical formulation as well as a practical solution of the thrust vector control design problems of solar sail spacecraft. Thrust vector control logic is part of an attitude and orbit control system of sail-craft, which maintains the proper orientation of the sail-craft to provide its desired thrust vector pointing or steering. The solar-pressure thrust vector direction of a sail-craft is often described by its cone and clock angles measured with respect to certain orbital reference frames. This paper describes various forms of orbital trajectory equations, which employ two different sets of such cone and clock angles, design, and simulation of solar-sail thrust vector control systems. In particular, quarter ion-based thrust vector control/orbit control system architecture is proposed for solar sails because of its simple computational algorithm for determining the desired sail-craft attitude quarter ions from the commanded cone and clock angles of the solar-pressure thrust vector.

2.3 An electrical thrust vector control system for the VEGA launcher by Tillo vanthuyne, September 2009

The aim of the TVC is to control the flight of the launcher by controlling the direction of thrust. It is a nested loop (small loop) inside the launcher attitude control. SABCA has developed and is qualifying the TVC system for the four stages of the European launcher VEGA. The VEGA launcher consists of 4 stages called P80, Z23, Z9 and AVUM. The TVCs are optimized while keeping the same architecture. This paper presents the thrust vector control systems designed and currently under qualification for the four stages of the European launcher VEGA. Special attention is given to the design and qualification of the qualification of the electro-mechanical actuators.

2.4 Research on thrust vector control of non-linear solid rocket motor nozzle based on active disturbance rejection technology by Chen Chong Shi and ZhishuXu, 2020

In this paper, based on the auto disturbance rejection control technology, the electromechanical servo system is used as the control actuator, and the thrust vector control of the solid rocket motor nozzle with typical nonlinear friction characteristics is studied and analyzed. In this paper, the realization of the classical PID algorithm and the lack of dynamic performance are analyzed, and then the compensation algorithm based on the auto disturbance rejection control technology is added. The algorithm compensates for the phase lag of the system due to the nonlinear friction characteristics. As a result, the frequency characteristics of the system have been significantly improved.

2.5 Numerical study on rod thrust vector control for physical applications by Dong Li and Kexin Wu,17 November 2021

Mechanical thrust vector control is a classical and significant branch in the thrust vector control field, offering an extremely control technology are numerically investigated in a two-dimensional supersonic nozzle. Complex flow phenomena caused by the penetrating rod in the diverging part of the supersonic nozzle are elucidated with the purpose of a profound understanding of this simple flow control technique for physical applications. Published experimental data are used to validate the dependability of current computational fluid dynamics results. A grid sensitivity study is carried through and analyzed. The result section discusses the impacts of two important factors on steady-state aerodynamic features, involving the rod penetration height and the rod location. Furthermore, unsteady-state flow features are analyzed under various rod penetration heights for 15 the first time. Significant vectoring performance variations and flow topology descriptions are illuminated in full detail. While the rod penetration height increases, the vectoring angle increases, whereas the thrust coefficient decreases. As the rod location moves downstream close to the nozzle exit, the vectoring angle and thrust coefficient increase.

3. SELF-STABILIZATION CHALLENGES

From all above literature review it has been found that, self-stabilizing is the main problem and design challenges for Thrust vector Controlling System. So, the main design challenges require the enormous emphasis while designing the self-Stabilized mechanism technique in Thrust Vector control (TVC) system. The various Parameters that need special attention are appropriate angle of deviation for space vehicle during trajectory in Space by vectoring the thrust and its control during the flight. Hence, TVC system of Rocket, Missile or aircrafts to be designed such that it can control the thrust vectoring by sensing the attitude and altitude of vehicle for directional change and advanced algorithm program needs to develop for self-stabilization in gyro and gimbal mechanism for successful execution.

4. OUR DESIGN

4.1 Thrust Vector Control (TVC) Design

The design of the thrust vectoring system has been the main focus of the presented work. The main challenge, so, has been the design of a system that could respond to attitude changes as fast as possible, trying to reduce the usage of reaction thrusters. To achieve this goal, since the response of the TVC system, clearly, cannot be infinitely fast, some constraints and boundary conditions about the range of action had to be fixed, letting the TVC work within some predefined values of 19 thrust deflection angle and adjusting the attitude with the RCS when the eventual required deflection angle exceeds the limits imposed. It is then clear that the synchronization between the two different attitude control system becomes a crucial point for the overall control logic of the prototype. This synchronization, in terms of hardware, is achieved with a merged system of three different CPUs composed by a main general control unit and two control units dedicated respectively to the RCS and TVC systems, that can work separately and also communicate between each other. The deflection of the gases coming out from the nozzle is typically achieve during external vanes or an external additional nozzle, systems that are independent from the engine and that allow to keep the latter always fixed to the structure. 20 A gimbal ring is a gyroscopic joint composed by a set of concentric rings that can rotate with respect each other, along different directions. This particular joint, when connected around a body, allows the body itself to tilt in any wanted direction. In our particular application, the final design of the gimbal ring provides three concentric rings where the inner one is directly connected to the engine and the outer one is attached to the chassis. The connection between the inner ring and the engine is obtained through particular clamps that are custom designed exactly for this engine and provided by the same company. Thanks to the three-ring configuration we get one degree of freedom with the relative rotation of the inner ring with respect the middle ring and another degree of freedom with the relative rotation of the middle ring with respect the outer one. The rotations are allowed by the presence of particular pins that interconnect the ring and that, at the same time, have the role of axis of rotation.

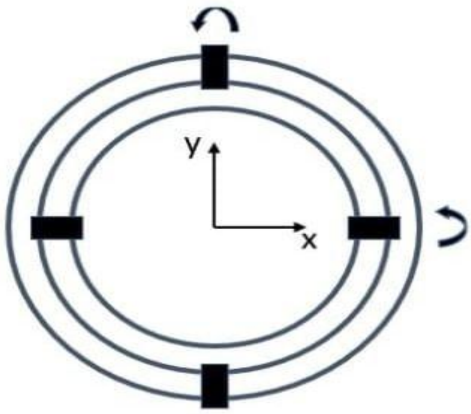

Fig -1: Conceptual design of gimbal ring

As we can see from above fig. 1 the gimbal's axis of rotation is perfectly aligned with the principal axis of inertia of the vehicle (x and y in the figure). The choice is related to a simpler actuation procedure since, in case of pure pitch or pure roll motion, we can provide the control torque by rotating only one of the rings so, as will be described later on, activating only one linear actuator. Once decided the method to use to obtain the TVC, the second phase of the work regarded the mechanical design of the gimbal ring.

4.2 Gimbal Joint Design

Gimbal rings are very particular joints that are custom designed for the applications they're intended for. The particular geometry of the prototype, combined with the engine used, required a newly designed joint. The design of the gimbal ring had been driven by some requirements that can be summarized as follows:

- Overall component as light as possible, so not to add a too much extra mass to thevehicle
- Enough resistance in order to withstand the thrust given by the engine
- Use of PLA (Poly Lactic Acid) material, in order to keep the cost sufficiently low
- Not too complicated geometry in order to allow an in-lab machining and fabrication with the machinery available.

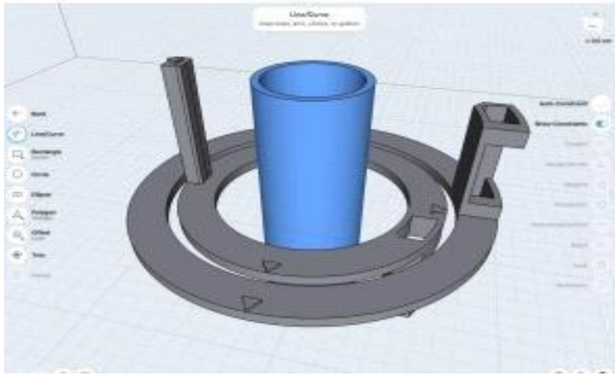

Fig -2: 3D design of Gimbal joints

The gimbal ring with a different material is the inter-connecting pins since they're carrying both the weight of the rings and both the thrust of the engine. For this reason, the pins are characterized by a stainless -steel screwed shaft where a couple of bushings are placed in order to facilitate the rotation. The distance between rings is kept through the usage of spacers. The final shape recalls the geometry of the lower layer of the chassis in order to get easier attachments between the two parts. In addition, the inner ring of the joint also hosts two vertical plates that run along the sides of the engine and that are used as aconnection point for the actuators.

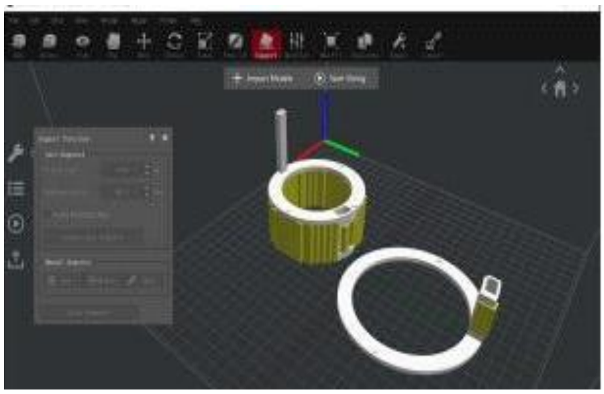

Fig -3: 3D design of Gimbal Parts

Fig -4: CAD model

5. SENSOR AND PROGRAMMING

5.1 Flight Computer

The flight computer is an electronic component of amateur rocket that processes signals from various sensors and issues commands to maintain the correct position and orientation of the rocket. As the name suggests, flight computer serves as the central control and flies with the thrust. In our case, it brings “intelligence” to thrust vectoring and enables self-stabilization and landing. Since one essence of the project is the thrust vector control (TVC), we focus on designing and building a flight computer that enables active TVC. Key components of a flight computer include the brain (the central processor), the sensor (a gyroscope that obtains information on acceleration, and thus altitude) as well as interconnects (pins that connect the processor, the gyroscope, the servo motors and the battery. Following instructions of the code stored in the processor, the flight computer reads data from the gyroscope, processes it with the central processor, and then sends commands to the servo motors to maintain the position and orientation of the vectoring.

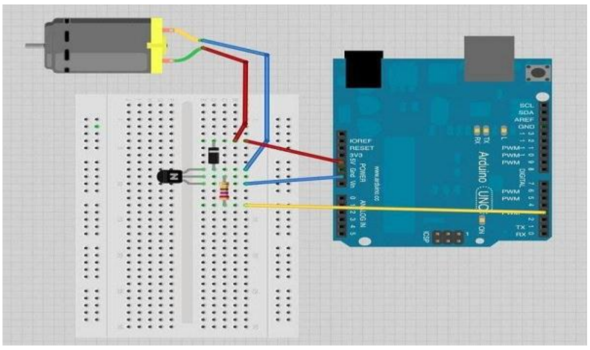

Fig -5: Full look of the flight computer

5.2 Arduino UNO Microcontroller

Arduino is an open-source platform used for building electronics projects. It consists of both a physical programmable circuit board (often referred to as a microcontroller) and a piece of software, or IDE (Integrated Development Environment) that runs on your computer, used to write and upload computer code to the physical board. Arduino allows users a simple pathway to creating interactive objects that can take input from switches and sensors, and control physical outputs like lights, motors, or actuators.

Fig -6: Arduino UNO

5.3 MPU6050 interfacing with Arduino UNO

MPU6050 sensor module is an integrated 6-axis Motion tracking device. It has a 3-axis Gyroscope, 3-axis Accelerometer, Digital Motion Processor and a It can accept inputs from other sensors like 3-axis magnetometer or pressure sensor using its Auxiliary I2C bus.

If external 3-axis magnetometer is connected, it can provide complete 9-axis Motion Fusion output.

A microcontroller can communicate with this module using I2C communication protocol. Various parameters can be found by reading values from addresses of certain registers using I2C communication.

Gyroscope and accelerometer reading along X, Y and Z axes are available in 2’s complement form. Temperature reading is also available in signed integer form. Gyroscope readings are in degrees per second (dps) unit; Accelerometer readings are in g unit; and Temperature reading is in degrees Celsius.

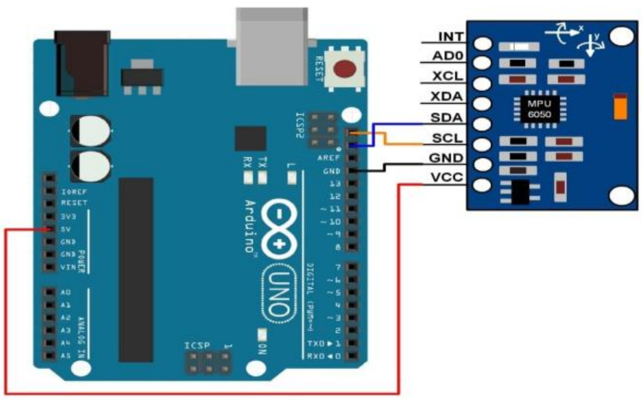

Fig -7: Interfacing MPU6050 Module with Arduino UNO6

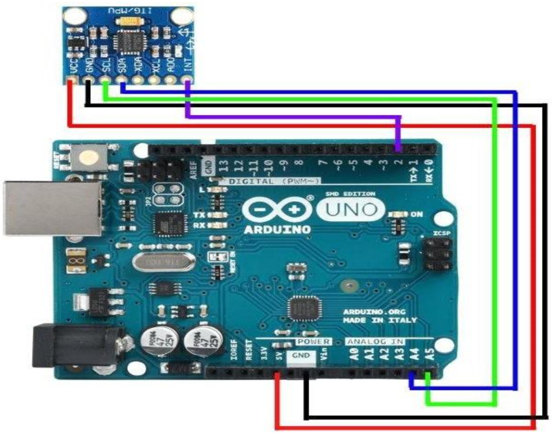

Fig -8: The circuit schematic diagram of the flight computer dubbed"Vector"

6. SELF-STABILIZATION COADING

For self-stabilization we have developed advanced algorithm program in C++ script which helps the nozzle to change the direction with its strong artificial intelligence. Here below we present the coding we have coded in Uno Arduino with MPU6050 sensor with gyro to control the thrust vector during the trajectory of space vehicle.

6.1 Sensor programming for gyroscope

```
#include
#include
#include
//#include 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 ledBLU = 14; // LED
connected to digital pin 9 int ledGRN = 16; // LED
connected to digital pin 9 int ledRED = 15; // LED
connected to digital pin 9 int mosfet = 24; int valueX =
110; int valueY =150; Servo servoX;
Servo servoY;
float elapsedTime, currentTime, previousTime; float
kp = 1; float ki = 1; float kd = 1; int pos;
//KalmanFilterkalman(0.001, 0.003, 0.03); 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);
pinMode(mosfet, OUTPUT);
pinMode(ledBLU, OUTPUT);
pinMode(ledGRN, OUTPUT);
pinMode(ledRED, OUTPUT);
digitalWrite(ledBLU, HIGH);
delay(500); digitalWrite(ledBLU,
LOW); digitalWrite(ledGRN, HIGH);
delay(500); digitalWrite(ledGRN,
LOW); digitalWrite(ledRED, HIGH);
delay(500); digitalWrite(ledRED,
LOW); digitalWrite(ledBLU, HIGH);
delay(500); |
digitalWrite(ledBLU, LOW)
digitalWrite (ledGRN, HIGH);
delay(500); digitalWrite (ledGRN,
LOW); digitalWrite (ledRED, HIGH);
delay(500); digitalWrite (ledRED,
LOW);
Serial.begin(9600);
//120 minutes
//delay(7200000);
//digitalWrite(ledBLU, HIGH);
//delay(5000);
//digitalWrite(ledBLU, LOW);
} 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 )
```

```
180 / PI) + 1.58; //
Wire.beginTransmission(MPU);
Wire.write(0x3B);
Wire.endTransmission(false);
Wire.requestFrom(MPU,12,true);
AcX=Wire.read()<<<<<<
```

7. CONCLUSION

The design of the presented Self Stabilizing Thrust Vector Control System (TVCs) can be the largest improvement for all types of Aerospace Vehicle as it can increase its maneuverability and also can decrease the propellent loss due to its precise movement of nozzle to change the angular velocity for directional change for all type of Aerospace vehicle in space. This Thrust Vector Control system can have a very good stabilization at a very high disturbance during its flight. Hence, the most important conclusion from this project in our opinion is that for controlling disturbance for Stabilization of Thrust Vector Control in Space, it is pie in the sky, hope of flame for Aerospace industry. Keeping the above conclusions in consideration, we made an approach to put all our efforts and try our level best for solving this matter of Stabilized Thrust Vectoring system with our impeccable Design of Self Stabilization Thrust Vector Control System (TVCs).

ACKNOWLEDGEMENT

This Project became a reality with the kind support and help of many individuals, we are deeply grateful to our Project Guide, M.G. Rajagopal for his guidance, patience and support. We are much obliged to our Head of the Department Dr. S.P. Venkatesan and Project coordinators Dr. P. Karunakaran and K. Vijaybabu along with faculty members of Department of Aeronautical Engineering, Excel Engineering College for their enlightening suggestions and encouragements which motivated us throughout our project. We owe many thanks to our classmate Mr. Rakesh Kumar Shah and all of our colleagues. They always helped us in exchanging ideas regarding research and gave the enjoyable environment for our project. We are most grateful to our parents; they have always loved us and supported our every choice which helped us in successful completion of this project.

REFERENCES

1. Alvi FS, Stryknowski PJ, Krothapalli A, et al (2000)'Vectoring thrust in multiaxes using confined shear layers' J Fluids Eng
2. Asbury SC and Capone FJ (2002)'Multi-axis thrust-vectoring characteristics of a model representative of the F-18 high-alpha research vehicle at angles of attack from 0 to 70' NASA Technical Paper 3531
3. Thrust vectoring. Wikipedia
4. www.poly lactic acid 3D PRINTING.com
5. www.arduino.cc
6. Andrew Ball, James Garry, Ralph Lorenz, and Viktor Kerzhanovich

   (2007)'Planetary Landers and entry probes' Cambridge University Press
7. Tillo vanthuyne (2009) 'An electrical thrust vector control system for the

   VEGA launcher'
8. Ferlauto M and Marsilio R (2009)'Numerical simulation of fluidic thrust vectoring' J Aerosp Sci Technol Syst
9. Shin CS, Kim HD and Setoguchi T. A (2010) 'computational study of thrust vectoring control using dual throat nozzle' J Therm Sci
10. Heo JY and Sung HG (2012) 'Fluidic thrust-vector control of supersonic jet using co-flow injection' J Propul Power
11. Oosthuizen PH and Carscallen WE (2013) 'One-dimensional isentropic flow' In: Introduction to compressible fluid flow. 2th ed
12. Song MJ, Park SH and Lee Y (2014) 'Application of back step flap for supersonic co-flowing fluidic thrust vector control' AIAA J
13. R Deng and HD Kim (2014) 'A study on the thrust vector control using a bypass flow passage'
14. Deng RY and Kim HD (2015) 'A study on the thrust vector control using a bypass flow passage' Proc IMechE, Part G: J Aerospace Engineering
15. Lee Y, Park SH and Kim YS (2016)'Thrust vectoring of sonic jet by using Coanda flap and solenoid valve' AIAA J 2016
16. Bong Wie (2017) 'Thrust vector control analysis and design for solar sail spacecraft'

17. Arun Sebastian, Polly Thomas, and Sophy Alex (2017) 'Servo design and analysis of thrust vector control of launch vehicle'

18. Kexin Wu and Heuy Dong Kim (2019) 'Fluidic thrust vector control using shock wave concept'

19. Emanuele Resta, Roberto Marsilio, and Michele Ferlauto (2021) 'Thrust vectoring of a fixed axis-symmetric supersonic nozzle using the shock-vector control method'

BIOGRAPHIES

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