VISVESVARAYA TECHNOLOGICAL UNIVERSITY
Jnana Sangama, Belagavi - 590 018

MINI PROJECT REPORT ON

AUTOMATED REUSABLE INDIGENOUS AERO-NAVIGATING EXTRATERRESTRIAL VEHICLE

Project submitted in partial fulfillment for the Award of Degree of

Bachelor of Engineering

in

Electronics and Communication Engineering

Submitted by

JASHWANTH K	1RN22EC048
VISHNU JOSHI	1RN22EC142
DHANVI ACHARYA	1RN22EC039
JATHEEN V	1RN22EC049

Under the Guidance of

Mr Sreenivasa Babu M O

Assistant Professor

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
(Accredited by NBA for the Academic years 2022-25)

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Autonomous Institution Affiliated to VTU Recognized by GOK, Approved by AICTE NAAC 'A+'Accredited, NBA Accredited (UG - CSE, ECE, ISE, EIE and EEE) Channasandra, Dr.Vishnuvardhan Road, Bengaluru-560098

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CERTIFICATE

Certified that the project work entitled **"AUTOMATED REUSABLE INDIGENOUS AERO-NAVIGATING EXTRATERRESTRIAL VEHICLE"** is carried out by **JASHWANTH K (1RN22EC048), VISHNU JOSHI(1RN22EC142), DHANVI ACHARYA (1RN22EC039), JATHEEN V (1RN22EC049)** in partial fulfillment for the award of degree of Bachelor of Engineering in **Electronics and Communication Engineering** of Visvesvaraya Technological University, Belgavi, during the year 2024-2025. It is certified that all corrections/suggestions indicated during internal assessment have been incorporated in the report. The project report has been approved as it satisfies the academic requirements in aspect of the project work prescribed for the award of degree of **Bachelor of Engineering**.

....	....	....
Mr. Sreenivasa Babu M O	Dr. Rajini V Honnungar	Dr.Ramesh Babu H S
Assistant Professor	Head of the Department	Principal

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DECLARATION

We here by declare that the entire work emobodied in this thesis titled, **" Automated Reusable Indigenous Aero-Navigating Extraterrestrial Vehicle"** submitted to **Visvesvaraya Technological University**, Belagavi, is carried out at the department of **Electronics and Communication Engineering, RNS Institute of Technology, Bengaluru** under the guidance of **Mr Sreenivasa Babu M O**, Assistant Professor . This report has not been submitted for the award of any Diploma or Degree of this or any other University.

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We are grateful to our Founder Chairman, RNS Group of Institutions, **Late. Dr. R N Shetty**, for providing state of art facilities.We would like to express our gratitude to our honourable **Mr.Satish R Shetty**, Managing Director, RNS Groups of Institutions, for providing state of art facilities.

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Finally, we take this opportunity to extend our earnest gratitude and respect to our parents, teaching and non-teaching staff of the department, the library staff and all our friends who have directly or indirectly supported us.

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Abstract

This project focuses on the development of reusable rockets, a revolutionary step in making space exploration more affordable, efficient, and sustainable. Traditional rockets are designed for single use, which makes space missions very expensive. Reusable rockets, on the other hand, are engineered to be launched, recovered, and launched again multiple times. This significantly reduces costs and increases the frequency of space missions.

The report examines the key technologies required for reusable rockets, including advanced engines, thermal protection systems, and automated landing systems. One of the most critical aspects is the ability to control the rocket during its return to Earth, ensuring it lands safely and can be refurbished for future launches. The study also looks at challenges such as managing high temperatures during reentry and ensuring the durability of materials over multiple flights.

To better understand the concept, this project studies successful examples like SpaceX's Falcon 9, which has demonstrated how reusable rockets can transform space missions. Based on these examples, the project proposes ideas to improve existing designs, such as using lighter materials, improving fuel efficiency, and automating recovery operations.

The project also includes simulations to test the performance of the proposed designs and assess their feasibility. The results show that reusable rockets have the potential to reduce launch costs by up to 50 percent while making space travel more accessible. This is a game-changer for industries like satellite deployment, space tourism, and deep-space exploration.

In conclusion, reusable rockets are the key to making space exploration sustainable and affordable for future generations. This project highlights the importance of innovation in this field and provides recommendations for improving the design and operation of reusable rockets. It aims to inspire further research and development to unlock the full potential of reusable space technology.

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Acronyms

ARIANE : Automated Reusable Indigenous Aero-Navigating Extraterrestrial Vehicle

ESP : Espressif

TVC : Thrust Vector Control

COM: Center of mass

COG: Center of gravity

PWM: Pulse width modulation

GPS: Global Positioning System

IMU: Inertial Measurement Unit

Chapter 1

Introduction

Reusable rockets represent a groundbreaking innovation in the field of space exploration, offering a transformative solution to one of the industry's most significant challenges—high launch costs. Traditional rockets, which are discarded after a single mission, render every launch an expensive and resource-intensive endeavor. The development of reusable rockets, however, is revolutionizing the way we approach space travel by introducing a cost-effective, efficient, and sustainable alternative. These rockets are specifically engineered to return to Earth, undergo refurbishment, and embark on subsequent missions, drastically reducing the cost per launch.

The principle of reusability involves integrating cutting-edge technologies into rocket design and operation. One key component is the precise landing system, which enables rockets to return safely to predetermined locations on land or at sea. This precision is achieved through a combination of advanced navigation systems, gyroscopes, and thrusters that provide fine control over the rocket's descent and landing. Another critical feature is the use of robust propulsion mechanisms, which ensure reliability during both liftoff and landing phases. Additionally, the rockets are equipped with heat-resistant materials to withstand the extreme temperatures experienced during reentry, safeguarding critical components for reuse.

Vertical landing capabilities are one of the hallmarks of reusable rockets. Unlike traditional systems that rely on parachutes or expendable modules, reusable rockets can descend vertically, using their engines to slow down and achieve a controlled touchdown. This capability significantly reduces the wear and tear on the rocket structure, allowing for minimal maintenance between missions. Sea landings, executed on specialized drone ships, further enhance the flexibility and adaptability of these systems, especially for missions that do not permit a return to land-based facilities.

The economic and operational benefits of reusable rockets extend beyond cost savings. By enabling faster turnaround times between launches, these systems increase the frequency of space missions, making space more accessible to various industries. Companies like SpaceX have been at the forefront of this technological revolution.

The Falcon 9 rocket, a prime example of reusable technology, has successfully completed numerous missions with the same hardware, demonstrating the feasibility and reliability of this approach. SpaceX's achievements have paved the way for other organizations to explore similar technologies, fostering competition and innovation in the space sector.

The impact of reusable rockets is already being felt across multiple industries. In satellite deployment, the reduced costs make it more viable for smaller companies and governments to launch their payloads, democratizing access to space. In space tourism, reusable rockets have brought the dream of commercial space travel closer to reality by lowering ticket prices and increasing the frequency of flights. Additionally, reusable systems are critical for interplanetary exploration, as their cost-effectiveness and reliability make ambitious missions to Mars and beyond more attainable.

Despite their advantages, reusable rockets also face challenges. Ensuring the durability of materials, optimizing refurbishment processes, and achieving precise landings in diverse conditions require continuous innovation. Furthermore, the environmental impact of rocket launches must be addressed to ensure sustainable development.

This report explores the principles, challenges, and benefits of reusable rockets in detail. By analyzing current advancements and proposing potential improvements, it aims to contribute to the ongoing development of these systems, laying the foundation for a more sustainable and efficient space economy. Reusable rockets are not just a technological breakthrough; they represent a paradigm shift in humanity's approach to the cosmos, unlocking new possibilities for exploration and discovery.

1.1 Objectives

The objective of this project is to :

1. **Design and Development of a TVC-Controlled Rocket**

   To design and build a 3.5-foot solid propellant rocket with thrust vector control (TVC) for precise maneuverability and stability during flight.

2. **Implementation of Solid Propellant System**

   To utilize a sugar-based propellant composed of D-Sorbitol and potassium nitrate (KNO_3) for efficient and cost-effective propulsion.

3. **Integration of Thrust Vector Control Mechanism**

   To develop and implement a TVC system that allows controlled vectoring of the rocket's thrust for better flight path adjustments.

4. **Design and Testing of Electronics for Flight Control**

   To create and integrate electronic components, including sensors, actuators, and microcontrollers, for real-time monitoring and control of the rocket's trajectory.

5. **Thermal and Structural Analysis**

   To ensure the rocket's structural integrity and thermal resistance under high temperatures generated during combustion and flight.

6. **Testing and Validation**

   To conduct ground and flight tests to validate the performance of the propulsion system, TVC mechanism, and electronic controls.

7. **Documentation and Analysis**

   To document the entire design, development, and testing process, providing insights and recommendations for future projects.

This project aims to combine engineering principles with practical applications, offering hands-on experience in rocket design, control systems, and electronics.

1.2 Application of ARIANE

1. **Educational and Research Tool**
    - Serves as a practical demonstration of thrust vector control (TVC) technology and solid propellant chemistry for academic purposes.
    - Provides hands-on experience in aerospace systems, integrating propulsion, electronics, and control systems.
2. **Low-Cost Rocketry Development**
    - Showcases a cost-effective approach to building rockets using sugar-based propellants (sucrose and KNO3).
    - Can inspire affordable small-scale rocketry initiatives for educational institutions and hobbyists.
3. **Thrust Vector Control Implementation**
    - Demonstrates the use of TVC for precise rocket trajectory control, a critical technology in modern aerospace systems.
    - Helps in testing and refining control algorithms that can be scaled to larger projects.
4. **Prototype for Advanced Rockets**
    - Acts as a prototype for developing more advanced rockets with improved thrust and stability.
    - The technology can be extended to more sophisticated applications, such as satellite launch vehicles or suborbital experiments.
5. **Data Collection for Performance Analysis**
    - Enables the collection of flight data, such as altitude, speed, and stability, for analyzing rocket performance and optimizing designs.
    - Contributes to research in solid propellant efficiency and flight dynamics.
6. **Inspiration for Space Exploration Projects**
    - Encourages innovation and interest in space exploration technologies among students and aspiring engineers.
    - Provides foundational knowledge for developing reusable or larger-scale rockets.

Chapter 2

Literature Survey

[1] Lars Blackmore "Autonomous Precision Landing of Rockets " :
Summary-
Lars Blackmore's paper on *Autonomous Precision Landing of Rockets* presents an in-depth look into the technology behind vertical rocket landings, particularly focusing on reusability. The research addresses the complexities of guiding rockets back to Earth with high precision, often landing on moving platforms like drone ships or small landing pads. The study emphasizes the critical role of autonomous systems, which use real-time data from sensors to make instantaneous decisions regarding rocket trajectory and stability. Blackmore highlights the development of advanced control algorithms and navigation techniques that manage these precision landings. He discusses the challenges rockets face in unpredictable environments, such as wind gusts, atmospheric variations, and unstable landing sites. His work details the integration of high-performance onboard computers that process flight data, adapt to external conditions, and correct the rocket's descent path to ensure accurate landings. Blackmore's research is essential for understanding how future space missions can reduce operational costs and enhance the safety of reusable rockets, which could significantly impact satellite launches, space tourism, and interplanetary exploration. His contributions are vital in advancing rocket technology and fostering sustainability in space exploration by enabling multiple uses of the same hardware.

[2] Mingyang Huang "Analysis of Rocket Modeling Accuracy and Capsule Landing Safety " :
Summary-
Mingyang Huang's *Analysis of Rocket Modeling Accuracy and Capsule Landing Safety* explores the importance of accurate rocket trajectory models for ensuring safe and predictable landings of capsules. The paper emphasizes that even small errors in the rocket's trajectory prediction can lead to large deviations from the desired landing site, thus compromising the safety of the capsule. Huang investigates various rocket models and simulation techniques to improve the precision of trajectory predictions, considering factors such as aerodynamic forces, burn rates, and environmental conditions.

A key focus of the study is the integration of these models into capsule landing systems, where even slight inaccuracies can result in unsafe landings. Huang discusses the role of real-time data feedback, simulation-based prediction adjustments, and corrective measures that enhance the precision of landing mechanisms. His research suggests that improving the accuracy of rocket models will lead to safer landing procedures, minimizing the risks associated with capsule recovery after reentry. The study underscores the importance of reliable modeling techniques and validation through experimental data to ensure the success and safety of future space missions. Huang's work contributes significantly to advancing the reliability of capsule-based space travel, ensuring safer returns to Earth.

[3] David Gable "Design Development of a Vertically Landed Model Rocket" :

Summary-

Gable's thesis delves into the design, testing, and optimization of solid propellant rockets, focusing on improving propulsion systems for better performance and safety. The thesis examines various components of solid propellant rockets, such as thrust generation, burn rate, and the material properties of propellants, all of which play crucial roles in ensuring efficient propulsion. Gable also investigates the challenges of integrating guidance and control systems with solid rocket motors to achieve stable and accurate flight paths. By analyzing how small deviations in propulsion or control can affect the rocket's trajectory, the thesis offers insights into the optimization of both solid propellant and guidance systems to enhance overall mission success. Gable emphasizes the importance of extensive testing and validation, recommending simulation-based approaches to identify potential failures before actual launches. The thesis also explores the safety measures necessary for solid rockets, particularly in ensuring the structural integrity of the rocket under various flight conditions. Through a detailed study of both theoretical and practical aspects of solid propellant rocketry, Gable's work contributes to the broader field of aerospace engineering by providing practical recommendations for improving rocket design, safety, and reliability. His research is essential for advancing solid propellant technology, particularly in small-scale rockets and new space missions.

[4] Adithya Praveen, Anjith S J, Shiva A, Abraham Mathews, Megha Shaiju, and Sreeja S "Thrust Vector Control of Solid Propellant Model Rocket" :

Summary-

This paper investigates the application of thrust vector control (TVC) in solid propellant model rockets to enhance trajectory stability and precision during flight. The authors explore the integration of TVC systems with solid propellant motors, addressing challenges such as structural vibrations, delayed thrust response, and the precise alignment of thrust vectors. Through simulations and experiments, the study demonstrates how TVC mechanisms, such as movable nozzle actuators and gimbal systems, can improve trajectory correction and landing accuracy. The research highlights the role of control algorithms in achieving effective TVC operation and minimizing deviations caused by environmental factors like wind and aerodynamic instability. By providing a detailed analysis of TVC implementation in solid propellant rockets, this work contributes to the field of small-scale rocketry and lays the groundwork for future advancements in low-cost, reusable systems.

[5] Cong Wang, Zhengyu Song "Trajectory Optimization for Reusable Rocket Landing" :

Summary-

Wang and Song's paper focuses on trajectory optimization strategies for reusable rocket landing systems. The study emphasizes the importance of energy-efficient descent and precise landing capabilities to enhance reusability and cost-effectiveness. The authors propose an advanced optimization framework that integrates nonlinear dynamics, control constraints, and landing accuracy requirements. Simulations demonstrate the effectiveness of their approach in reducing fuel consumption during descent while maintaining robust trajectory control. The paper also explores the impact of external disturbances, such as atmospheric drag and wind, on trajectory deviations and presents strategies to mitigate these effects. By analyzing different descent profiles and optimizing thrust control, the research provides practical solutions for improving the reliability and efficiency of reusable rocket landings, contributing to advancements in sustainable space exploration.

[5] David Tönqvist, Anders Helmersson, Fredrik Gustafsson "Window-Based GPS Integrity Test Using Tight GPS/IMU Integration Applied to a Sounding Rocket" :

Summary-

This paper presents a novel approach to enhancing the reliability of navigation systems in sounding rockets by implementing a window-based GPS integrity test integrated with an Inertial Measurement Unit (IMU). The authors propose a tight coupling of GPS and IMU data to improve accuracy and robustness in high-dynamic environments where traditional GPS solutions often fail. The window-based integrity test method ensures continuous monitoring of navigation performance, detecting potential anomalies and correcting them in real time. The system was applied to a sounding rocket to validate its effectiveness under dynamic flight conditions, including rapid accelerations and varying atmospheric disturbances. Experimental results demonstrate significant improvements in trajectory estimation and robustness against signal degradation or loss, which are common in rocket flights. The study highlights the advantages of integrating GPS and IMU data tightly, offering a reliable solution for precise navigation in aerospace applications. This research contributes to advancing guidance and control systems for rockets, paving the way for safer and more accurate missions.

Chapter 3

Hardware and Software Requirements :

This chapter deals with the hardware and software components used in our project.

Hardware :

1. Teensy 4.1
2. Adafruit Ultimate GPS FeatherWing
3. Adafruit Adalogger FeatherWing
4. Adafruit Servo FeatherWing
5. SparkFun ICM20948 IMU
6. DFRobot BMP388 Pressure Sensor
7. 1500mAh 3S LiPo Battery

Software :

1. Teensy 4.1 Firmware
2. Adafruit GPS Library
3. Adafruit Servo Library
4. SparkFun ICM20948 Library
5. DFRobot BMP388 Library
6. Adafruit RTC Library
7. Data Logging Software

3.1 Hardware

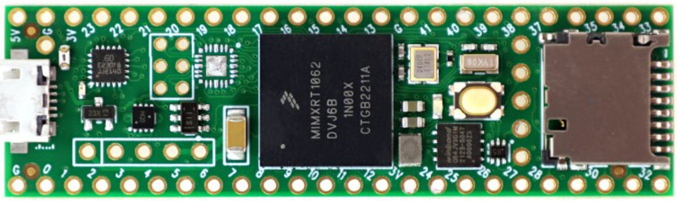

Figure 3.1: Teensy 4.1

Teensy 4.1: The Teensy 4.1 is the newest iteration of the astoundingly popular development platform that features an ARM Cortex-M7 processor running at 600 MHz. It is powered by an NXP IMXRT1062 chip and boasts four times larger flash memory compared to the Teensy 4.0, along with two new locations to optionally add more memory. The Teensy 4.1 retains the same size and shape as the Teensy 3.6 (2.4 inches by 0.7 inches) while providing enhanced I/O capabilities, including an Ethernet PHY, SD card socket, and USB host port, as shown in ”Figure 3.1”.

When running at 600 MHz, the Teensy 4.1 consumes approximately 100mA current and provides support for dynamic clock scaling. Unlike traditional microcontrollers, where changing the clock speed causes wrong baud rates and other issues, Teensy 4.1 hardware and Teensyduino’s software support for Arduino timing functions are designed to allow dynamically speed changes. Serial baud rates, audio streaming sample rates, and Arduino functions like delay() and millis(), and Teensyduino’s extensions like Interval Timer and elapsed Millis, continue to work properly while the CPU changes speed. Teensy 4.1 also provides a power shut off feature. By connecting a pushbutton to the On/Off pin, the 3.3V power supply can be completely disabled by holding the button for five seconds and turned back on by a brief button press. If a coin cell is connected to VBAT, Teensy 4.1’s RTC also continues to keep track of date time while the power is off. Teensy 4.1 also can also be overclocked, well beyond 600MHz!

Teensy 4.1’s Cortex-M7 processor includes a floating-point unit (FPU) that supports both 64 bit ”double” and 32-bit ”float”. With M4’s FPU on Teensy 3.5 3.6, and also Atmel SAMD51 chips, only 32-bit float is hardware accelerated. Any use of double, double functions like log(), sin(), cos() means slow software implemented math. Teensy 4.1 executes all of these with FPU hardware.

Specifications

- ARM Cortex-M7 at 600 MHz
- Float point math unit, 64 & 32 bits
- 7936K Flash, 1024K RAM (512K tightly coupled), 4K EEPROM (emulated)
- QSPI memory expansion, locations for 2 extra RAM or Flash chips
- USB device 480 Mbit/sec & USB host 480 Mbit/sec
- 55 digital input/output pins, 35 PWM output pins
- 18 analog input pins
- 8 serial, 3 SPI, 3 I2C ports
- 2 I2S/TDM and 1 S/PDIF digital audio port
- 3 CAN Bus (1 with CAN FD)
- 1 SDIO (4 bit) native SD Card port
- Ethernet 10/100 Mbit with DP83825 PHY
- 32 general purpose DMA channels
- Cryptographic Acceleration & Random Number Generator
- RTC for date/time
- Programmable FlexIO
- Pixel Processing Pipeline
- Peripheral cross triggering

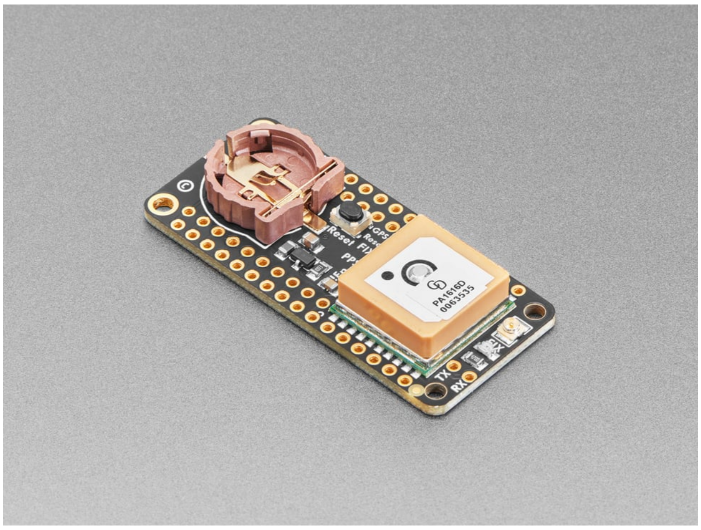

Figure 3.2: Adafruit Ultimate GPS FeatherWing

Adafruit Ultimate GPS FeatherWing: The Wing is built around the MTK3333 chipset, a no-nonsense, high-quality GPS+GLONASS module that can track up to 33 satellites on 99 channels, has an excellent high-sensitivity receiver (-165 dB tracking!), and a built-in antenna. It can do up to 10 location updates a second for high speed, high sensitivity logging, or tracking. Power usage is incredibly low, only 30 mA during navigation. "Figure 3.2" above illustrates the Adafruit Ultimate GPS FeatherWing, highlighting its compact design and onboard components.

Specifications

- Satellites: 33 tracking, 99 searching
- Update rate: 1 to 10 Hz
- Velocity Accuracy: 0.1 meters/s
- Warm/cold start: 34 seconds
- Acquisition sensitivity: -145 dBm
- Tracking sensitivity: -165 dBm
- Maximum Velocity: 515m/s
- MTK3333 Operating current: 29mA tracking, 35 mA current draw during navigation
- Output: NMEA 0183, 9600 baud default

Figure 3.3: Adafruit Adalogger FeatherWing

Adafruit Adalogger FeatherWing: This FeatherWing will make it real easy to add datalogging to any of our existing Feathers. You get both an I2C real time clock (PCF8523) with 32KHz crystal and battery backup, and a microSD socket that connects to the SPI port pins (+ extra pin for CS). Tested and works great with all of our Feathers. "Figure 3.3" above shows the Adafruit Adalogger FeatherWing, showcasing its compact design and integration-ready features.

Specifications

- DS3231 RTC chip for high accuracy with ±1 minute per year
- I2C communication interface for integration with Feather boards
- Coin-cell CR2032 battery for backup power to maintain time during power loss
- MicroSD card slot supports up to 32GB storage (FAT16/FAT32 file systems)
- SPI interface for communication with microSD card
- Powered by Feather microcontroller via 3.3V or 5V supply
- Low current consumption for long-duration data logging
- Size: 2.0 x 0.9 inches, compatible with all Feather boards
- Integrated libraries for easy use with Adafruit RTC and SD card functionalities

servo.jpg

Figure 3.4: Adafruit Servo FeatherWing

Adafruit Servo FeatherWing: The 8-Channel PWM or Servo FeatherWing is an add-on board designed for Feather microcontroller boards, enabling the control of up to 8 servos or motors simultaneously. It utilizes I2C communication, allowing for easy integration into various projects requiring precise motion control, such as robotics or UAVs. This board offers adjustable PWM frequency and high-resolution control, making it ideal for applications like controlling multiple actuators or managing thrust vector control (TVC) systems in rockets. With its compact size and external power support, it is a versatile solution for enhancing the capabilities of Feather-based projects. "Figure 3.4" above illustrates the 8-Channel PWM or Servo FeatherWing, showcasing its layout, connection ports, and compact design.

Specifications

- **PWM Channels**: 8 independent PWM channels for controlling servos or motors
- **PWM Frequency**: Adjustable frequency, default 50Hz (ideal for servos)
- **Interface**: I2C communication with Feather microcontroller
- **Power Supply**: External power supply required for servos or motors (5V to 12V)
- **Power Consumption**: Low current consumption for the Feather board itself, servos powered externally
- **Resolution**: 12-bit PWM resolution (4096 steps)

- **Voltage**: Operates at 3.3V or 5V logic levels, depending on Feather board

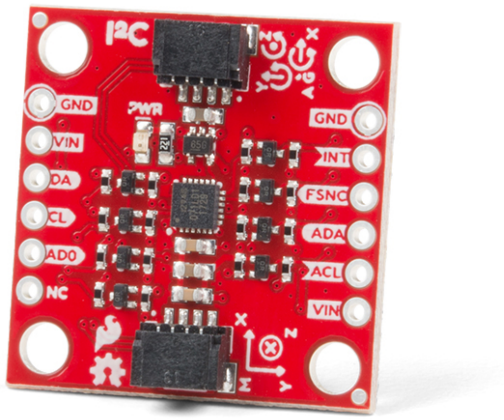

Figure 3.5: Sparkfun ICM20948 IMU

Sparkfun ICM20948 IMU: In addition to the 3-Axis Gyroscope with four selectable ranges, 3-Axis Accelerometer, again with four selectable ranges, and 3-axis magnetometer with an FSR to ±4900µT, the ICM-20948 also includes a Digital Motion Processor that offloads the computation of motion sensing algorithms from the detectors, allowing optimal performance of the sensors. We've also broken out all the ICM-20948 pin functionality to GPIO and labeled them I2C on the front, SPI on the back for ease of identification. "Figure 3.5" above illustrates the ICM-20948 breakout board, showing the labeled pin functions for both I2C and SPI interfaces.

Specifications

- 1.95 V to 3.6 V supply voltage
- Triple-axis MEMS gyroscope with user-programmable full-scale range of ±250 dps, ±500 dps, ±1000 dps, and ±2000 dps
- Triple-axis MEMS accelerometer with programmable full scale range of ±2g, ±4g, ±8g, and ±16g
- Triple-axis silicon monolithic Hall-effect magnetic sensor with full scale measurement range to ±4900 µT
- I2C at up to 100 kHz (standard-mode) or up to 400 kHz (fast-mode) or SPI at up to 7 MHz for communication with registers

- On-board digital motion processor (DMP)
- Digital-output temperature sensor

Figure 3.6: DFRobot BMP388

DFRobot BMP388: The barometric pressure is usually used to measure barometric pressure and temperature. But besides that, we can also use the sensor to measure the altitude and the relative floor height due to the fact that there is a certain relationship between altitude and barometric pressure. What's more, BMP388 enables accurate GPS tracking. So with an IMU sensor and BMP388, we can experience 3D indoor positioning and navigation.

BMP388 is based on Bosch's mature Piezo resistive pressure sensor technology featuring high accuracy as well low power consumption and high EMC robustness. "Figure 3.6" above illustrates the BMP388 barometric pressure sensor, showcasing its compact design and key features.

Specifications

- Operating Voltage: 3.3V-5.5V
- Operating Current: 0.5mA
- Operating Range: 300-1250 hPa
- Relative Accuracy: ±8 Pa (equivalent to ±0.50m @700-900hPa, 25℃-40℃)
- Absolute Accuracy: ±50 Pa0℃-65℃@300-1100hPa

- Temperature Coefficient Offset: ±0.75 Pa/K-20℃-65℃@700-1100hPa
- Absolute Accuracy Temperature: ±0.5℃@0℃-65℃
- Operating Temperature: -40℃~80℃ (more accurate in 0℃-65℃)
- Interface: Gravity-I2C 4Pin or SPI (SPI is only used at 3.3V)

Figure 3.7: 1500mAh 3S LiPo Battery

1500mAh 3S LiPo Battery(fig 3.7):

Specificatios

- Voltage(V): 11.1
- Configuration: 3S
- Capacity (mAh): 1500
- Discharge Rate: 35C

3.2 Software

- Teensy 4.1 Firmware: The firmware for the Teensy 4.1 microcontroller is the core software that controls all the hardware components of the rocket. Developed using the Arduino IDE with the Teensyduino add-on or PlatformIO, this firmware implements real-time algorithms for stabilization, data acquisition, and thrust vector control (TVC). It facilitates seamless communication between the various sensors, actuators, and other hardware components.

- Adafruit GPS Library:

  This library is designed to interface with Adafruit's GPS modules, providing tools to parse and extract positioning data, such as latitude, longitude, and altitude. The library simplifies integration of GPS data into the system, ensuring accurate navigation and telemetry.

- Adafruit Servo Library:

  The Adafruit Servo Library is used for generating PWM signals to control servo motors. It enables precise adjustments to the TVC system, ensuring accurate stabilization and maneuvering during the rocket's flight.

- SparkFun ICM20948 Library:

  This library provides access to the ICM20948 9-axis IMU, offering tools for reading accelerometer, gyroscope, and magnetometer data. It supports sensor fusion algorithms for calculating orientation and motion, critical for flight stability and control.

- DFRobot BMP388 Library:

  The library enables integration with the BMP388 barometric pressure sensor, offering accurate readings of atmospheric pressure and altitude. This data is essential for tracking the rocket's ascent and descent in real time.

- Adafruit RTC Library:

  Designed for the DS3231 real-time clock, this library provides accurate timestamping for data logging. It ensures that every piece of flight data is synchronized with precise timing, aiding in post-flight analysis.

- Data Logging Software:

  This software facilitates the storage of critical flight data, such as sensor readings and telemetry, onto a microSD card in formats like CSV or JSON. It supports real-time data logging, ensuring that every parameter is recorded for detailed analysis and system optimization post-flight.

Chapter 4

Methodology

This chapter gives an explanation regarding the physical connections and codes used in building ARIANE. The approach begins with a detailed analysis of the project's requirements and the selection of appropriate components, ensuring compatibility with the rocket's goals. The design phase incorporates the mechanical structure, propulsion system, flight control mechanisms, and avionics, all while adhering to principles of efficiency, safety, and performance. Following the design phase, the development of hardware and integration of various subsystems, such as sensors, actuators, and the microcontroller, is carried out.

To ensure proper functionality, rigorous testing and calibration of all components take place, including bench testing of the propulsion system and the flight control system. Finally, the rocket undergoes a series of test flights to evaluate its performance, analyze the data collected, and refine the design for future iterations.
The block diagram of our project is shown below in fig 4.1

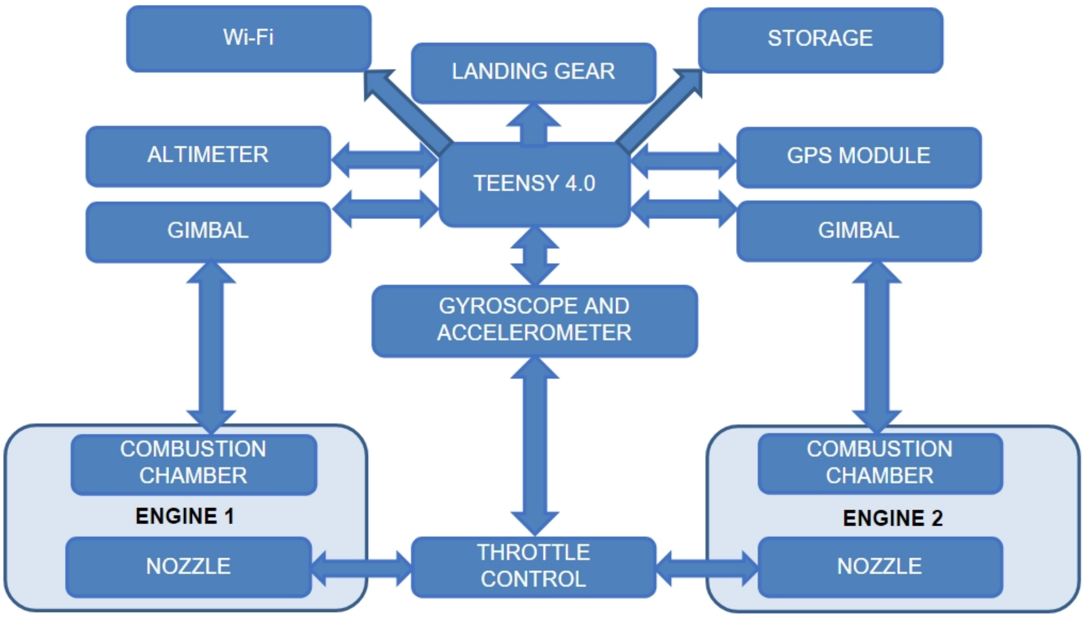

Figure 4.1: Block Diagram

4.1 Overview of I2C Communication:

I2C (Inter-Integrated Circuit) is a communication protocol that enables multiple devices to connect to a microcontroller using only two wires:

- SDA (Data Line): For data transfer.
- SCL (Clock Line): For timing synchronization.
- I2C supports multiple devices on a single bus, identified uniquely by their addresses.

4.2 Assigning I2C Devices and Address Mapping:

Each connected device has a unique I2C address. Here's the address mapping for the components used:

- Adafruit GPS FeatherWing: Connects via UART, not I2C. However, it's added for data fusion.
- Adafruit RTC FeatherWing (DS3231): Default address: 0x68
- SparkFun ICM20948 IMU: Default address: 0x68 or configurable to 0x69
- DFRobot BMP388 Pressure Sensor: Default address: 0x76 or configurable to 0x77 Adafruit Servo FeatherWing: Default address: 0x40

4.3 Hardware Connections:

All components share the same I2C bus. The connections are as follows:

- SDA (Data): Connect to Teensy 4.1 SDA pin (default pin 18).
- SCL (Clock): Connect to Teensy 4.1 SCL pin (default pin 19).
- Power and Ground:
  - Connect VCC of all devices to Teensy 4.1 3.3V pin.
  - Connect GND of all devices to Teensy 4.1 ground pin.

4.4 Appendix

The code provided is for an autonomous rocket control system that integrates GPS, IMU (Inertial Measurement Unit), barometric pressure sensor (BMP388), and a servo driver to control the Thrust Vector Control (TVC) system. This system utilizes a **Kalman filter** for altitude estimation and a **PID controller** for TVC. The code features a **real-time clock**, IMU data processing, GPS tracking, and an ignition system based on altitude. Below is an explanation of the key components and the structure of the code.

4.4.1 Libraries and Definitions

```
#include <Wire.h>
#include <Adafruit_GPS.h>
#include <Adafruit_PWMServoDriver.h>
#include <SparkFun_ICM_20948.h>
#include <Adafruit_BMP3XX.h>
#include <RTClib.h>

#define IGNITION_PIN 9
```

- `Wire.h`: Used for I2C communication with sensors. - `Adafruit_GPS.h`: Library for interacting with GPS modules. - `Adafruit_PWMServoDriver.h`: Library to control PWM servos via I2C. - `SparkFun_ICM_20948.h`: Used for interacting with the ICM-20948 IMU. - `Adafruit_BMP3XX.h`: Library to interface with the BMP388 barometric pressure sensor. - `RTClib.h`: Real-time clock library for time tracking.

```
#define IGNITION_PIN 9
```

- `IGNITION_PIN`: Defines the pin for triggering the ignition system.

4.4.2 Global Variables

```
Adafruit_GPS GPS(&Serial1);
Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver();
ICM_20948_I2C imu;
Adafruit_BMP3XX bmp;
RTC_DS3231 rtc;
```

These objects are used to interface with various hardware modules such as the GPS, PWM servo driver, IMU, BMP388 sensor, and RTC.

4.4.3 Kalman Filter Variables

```
float kalman_altitude = 0.0;
float kalman_velocity = 0.0;
float kalman_bias = 0.0;
float kalman_P[2][2] = {{1, 0}, {0, 1}};
float kalman_R = 1;
float kalman_Q[2][2] = {{0.1, 0}, {0, 0.1}};
```

- **Kalman filter** is used for accurate altitude estimation based on noisy barometric pressure readings.

4.4.4 PID Control Variables

```
float pid_kp = 1.0;
float pid_ki = 0.1;
float pid_kd = 0.5;
float pid_setpoint_x = 0.0;
float pid_setpoint_y = 0.0;
```

- **PID controller** variables are used to control the movement of the TVC servos based on IMU accelerometer data.

4.4.5 Servo and Pressure Sensor Variables

```
const int SERVO_MIN = 150;
const int SERVO_MAX = 600;
int tvc_x = 0;
int tvc_y = 0;
float ground_level = 0.0;
float current_altitude = 0.0;
float ignition_altitude = 5.0;
```

- **Servo control** for TVC and **pressure sensor** variables for altitude monitoring.

4.4.6 Setup Function

```
void setup() {
  Serial.begin(115200);
  while (!Serial);
  Wire.begin();
```

```
  GPS.begin(9600);
  GPS.sendCommand(PMTK_SET_NMEA_OUTPUT_RMCGGA);
  GPS.sendCommand(PMTK_SET_NMEA_UPDATE_1HZ);
  if (!rtc.begin()) {
    while (1);
  }
  if (imu.begin(Wire, 0x68) != ICM_20948_Stat_Ok) {
    while (1);
  }
  if (!bmp.begin(0x76)) {
    while (1);
  }
  bmp.setTemperatureOversampling(BMP3_OVERSAMPLING_8X);
  bmp.setPressureOversampling(BMP3_OVERSAMPLING_4X);
  bmp.setIIRFilterCoeff(BMP3_IIR_FILTER_COEFF_3);
  bmp.setOutputDataRate(BMP3_ODR_50_HZ);
  ground_level = bmp.readPressure();
  pwm.begin();
  pwm.setPWMFreq(50);
  pinMode(IGNITION_PIN, OUTPUT);
  digitalWrite(IGNITION_PIN, LOW);
}
```

The `setup` function initializes the GPS, IMU, barometric pressure sensor, RTC, and PWM servo driver. It also configures the BMP388 sensor for pressure and temperature readings and sets up the servo motor frequencies.

4.4.7 Kalman Filter Function

```
void kalmanFilter(float measured_altitude, float dt) {
  kalman_altitude += dt * kalman_velocity;
  kalman_P[0][0] += dt * (dt * kalman_P[1][1] -
  kalman_P[0][1] - kalman_P[1][0] + kalman_Q[0][0]);
  kalman_P[0][1] -= dt * kalman_P[1][1];
  kalman_P[1][0] -= dt * kalman_P[1][1];
  kalman_P[1][1] += kalman_Q[1][1] * dt;
  float y = measured_altitude - kalman_altitude;
  float S = kalman_P[0][0] + kalman_R;
  float K[2];
```

```
  K[0] = kalman_P[0][0] / S;
  K[1] = kalman_P[1][0] / S;
  kalman_altitude += K[0] * y;
  kalman_velocity += K[1] * y;
  kalman_P[0][0] -= K[0] * kalman_P[0][0];
  kalman_P[0][1] -= K[0] * kalman_P[0][1];
  kalman_P[1][0] -= K[1] * kalman_P[1][0];
  kalman_P[1][1] -= K[1] * kalman_P[1][1];
}
```

The **Kalman filter** function refines altitude measurements from the BMP388 sensor by filtering out noise, providing more accurate altitude data.

4.4.8 PID Control Function

```
float pidControl(float setpoint, float measured, float &prev_error,
                 float &integral) {
  float error = setpoint - measured;
  integral += error;
  float derivative = error - prev_error;
  prev_error = error;
  return pid_kp * error + pid_ki * integral + pid_kd * derivative;
}
```

PID control is used to calculate the servo positions for TVC based on the accelerometer readings from the IMU. It adjusts the servo's position to achieve the desired setpoint.

4.4.9 Loop Function

```
void loop() {
  char c = GPS.read();
  if (GPS.newNMEAreceived()) {
    if (!GPS.parse(GPS.lastNMEA())) {
      return;
    }
  }
  if (imu.dataReady()) {
    imu.getAGMT();
    float accel_x = imu.accX();
```

```
    float accel_y = imu.accY();
    tvc_x = constrain(map(pidControl(pid_setpoint_x, accel_x,
    pid_prev_error_x, pid_integral_x), -5, 5, SERVO_MIN, SERVO_MAX),
    SERVO_MIN, SERVO_MAX);
    tvc_y = constrain(map(pidControl(pid_setpoint_y, accel_y,
    pid_prev_error_y, pid_integral_y), -5, 5, SERVO_MIN, SERVO_MAX),
    SERVO_MIN, SERVO_MAX);
    pwm.setPWM(0, 0, tvc_x);
    pwm.setPWM(1, 0, tvc_y);
  }
  if (bmp.performReading()) {
    float pressure = bmp.readPressure();
    float measured_altitude = bmp.readAltitude(ground_level);
    float dt = 0.1;
    kalmanFilter(measured_altitude, dt);
    current_altitude = kalman_altitude;
  }
  if (current_altitude <= ignition_altitude) {
    digitalWrite(IGNITION_PIN, HIGH);
  } else {
    digitalWrite(IGNITION_PIN, LOW);
  }
  Serial.print("Altitude: ");
  Serial.print(current_altitude);
  Serial.println(" m");
  delay(100);
}
```

The `loop` function continuously reads sensor data from the GPS, IMU, and BMP388 sensor. It processes the data with the Kalman filter and PID control. When the rocket reaches the desired altitude (ignition altitude), the ignition pin is triggered to initiate the rocket's launch.

4.4.10 Appendix Summary

This code integrates various sensors and algorithms to control an autonomous rocket system. It uses GPS, IMU, barometric pressure, and real-time clock modules, along with Kalman filtering and PID control, to manage the rocket's flight and thrust vector control (TVC). The system is designed to handle dynamic changes in altitude and perform accurate motion control using high-quality sensors.

4.5 Code

```
#include <Wire.h>
#include <Adafruit_GPS.h>
#include <Adafruit_PWMServoDriver.h>
#include <SparkFun_ICM_20948.h>
#include <Adafruit_BMP3XX.h>
#include <RTClib.h>

#define IGNITION_PIN 9

Adafruit_GPS GPS(&Serial1);
Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver();
ICM_20948_I2C imu;
Adafruit_BMP3XX bmp;
RTC_DS3231 rtc;

float kalman_altitude = 0.0;
float kalman_velocity = 0.0;
float kalman_bias = 0.0;
float kalman_P[2][2] = {{1, 0}, {0, 1}};
float kalman_R = 1;
float kalman_Q[2][2] = {{0.1, 0}, {0, 0.1}};

float pid_kp = 1.0;
float pid_ki = 0.1;
float pid_kd = 0.5;
float pid_setpoint_x = 0.0;
float pid_setpoint_y = 0.0;
float pid_error_x = 0.0, pid_error_y = 0.0;
float pid_prev_error_x = 0.0, pid_prev_error_y = 0.0;
float pid_integral_x = 0.0, pid_integral_y = 0.0;

const int SERVO_MIN = 150;
const int SERVO_MAX = 600;
int tvc_x = 0;
int tvc_y = 0;

float ground_level = 0.0;
```

```
float current_altitude = 0.0;
float ignition_altitude = 5.0;

void setup() {
  Serial.begin(115200);
  while (!Serial);
  Wire.begin();
  GPS.begin(9600);
  GPS.sendCommand(PMTK_SET_NMEA_OUTPUT_RMCGGA);
  GPS.sendCommand(PMTK_SET_NMEA_UPDATE_1HZ);
  if (!rtc.begin()) {
    while (1);
  }
  if (imu.begin(Wire, 0x68) != ICM_20948_Stat_Ok) {
    while (1);
  }
  if (!bmp.begin(0x76)) {
    while (1);
  }
  bmp.setTemperatureOversampling(BMP3_OVERSAMPLING_8X);
  bmp.setPressureOversampling(BMP3_OVERSAMPLING_4X);
  bmp.setIIRFilterCoeff(BMP3_IIR_FILTER_COEFF_3);
  bmp.setOutputDataRate(BMP3_ODR_50_HZ);
  ground_level = bmp.readPressure();
  pwm.begin();
  pwm.setPWMFreq(50);
  pinMode(IGNITION_PIN, OUTPUT);
  digitalWrite(IGNITION_PIN, LOW);
}

void kalmanFilter(float measured_altitude, float dt) {
  kalman_altitude += dt * kalman_velocity;
  kalman_P[0][0] += dt * (dt * kalman_P[1][1] -
  kalman_P[0][1] - kalman_P[1][0] + kalman_Q[0][0]);
  kalman_P[0][1] -= dt * kalman_P[1][1];
  kalman_P[1][0] -= dt * kalman_P[1][1];
  kalman_P[1][1] += kalman_Q[1][1] * dt;
  float y = measured_altitude - kalman_altitude;
```

```
  float S = kalman_P[0][0] + kalman_R;
  float K[2];
  K[0] = kalman_P[0][0] / S;
  K[1] = kalman_P[1][0] / S;
  kalman_altitude += K[0] * y;
  kalman_velocity += K[1] * y;
  float P00_temp = kalman_P[0][0];
  float P01_temp = kalman_P[0][1];
  kalman_P[0][0] -= K[0] * P00_temp;
  kalman_P[0][1] -= K[0] * P01_temp;
  kalman_P[1][0] -= K[1] * P00_temp;
  kalman_P[1][1] -= K[1] * P01_temp;
}

float pidControl(float setpoint, float measured, float &prev_error,
float &integral) {
  float error = setpoint - measured;
  integral += error;
  float derivative = error - prev_error;
  prev_error = error;
  return pid_kp * error + pid_ki * integral + pid_kd * derivative;
}

void loop() {
  char c = GPS.read();
  if (GPS.newNMEAreceived()) {
    if (!GPS.parse(GPS.lastNMEA())) {
      return;
    }
  }
  if (imu.dataReady()) {
    imu.getAGMT();
    float accel_x = imu.accX();
    float accel_y = imu.accY();
    tvc_x = constrain(map(pidControl(pid_setpoint_x, accel_x,
    pid_prev_error_x, pid_integral_x), -5, 5, SERVO_MIN,
    SERVO_MAX), SERVO_MIN, SERVO_MAX);
    tvc_y = constrain(map(pidControl(pid_setpoint_y, accel_y,
```

```
    pid_prev_error_y, pid_integral_y), -5, 5, SERVO_MIN,
    SERVO_MAX), SERVO_MIN, SERVO_MAX);
    pwm.setPWM(0, 0, tvc_x);
    pwm.setPWM(1, 0, tvc_y);
  }
  if (bmp.performReading()) {
    float pressure = bmp.readPressure();
    float measured_altitude = bmp.readAltitude(ground_level);
    float dt = 0.1;
    kalmanFilter(measured_altitude, dt);
    current_altitude = kalman_altitude;
  }
  if (current_altitude <= ignition_altitude) {
    digitalWrite(IGNITION_PIN, HIGH);
  } else {
    digitalWrite(IGNITION_PIN, LOW);
  }
  Serial.print("Altitude: ");
  Serial.print(current_altitude);
  Serial.println(" m");
  delay(100);
}
```

4.6 Flowchart

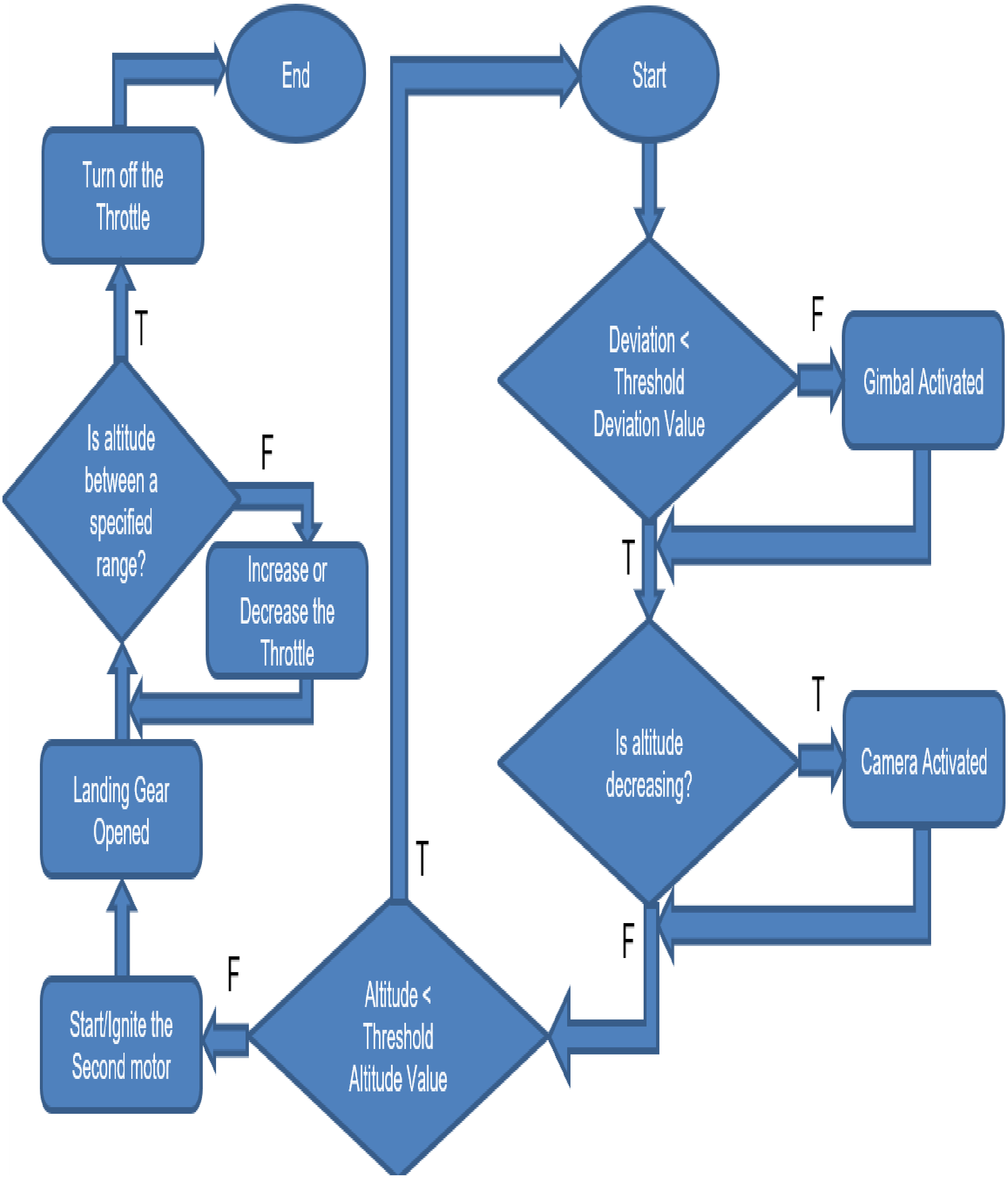

Figure 4.2: Flow Chart

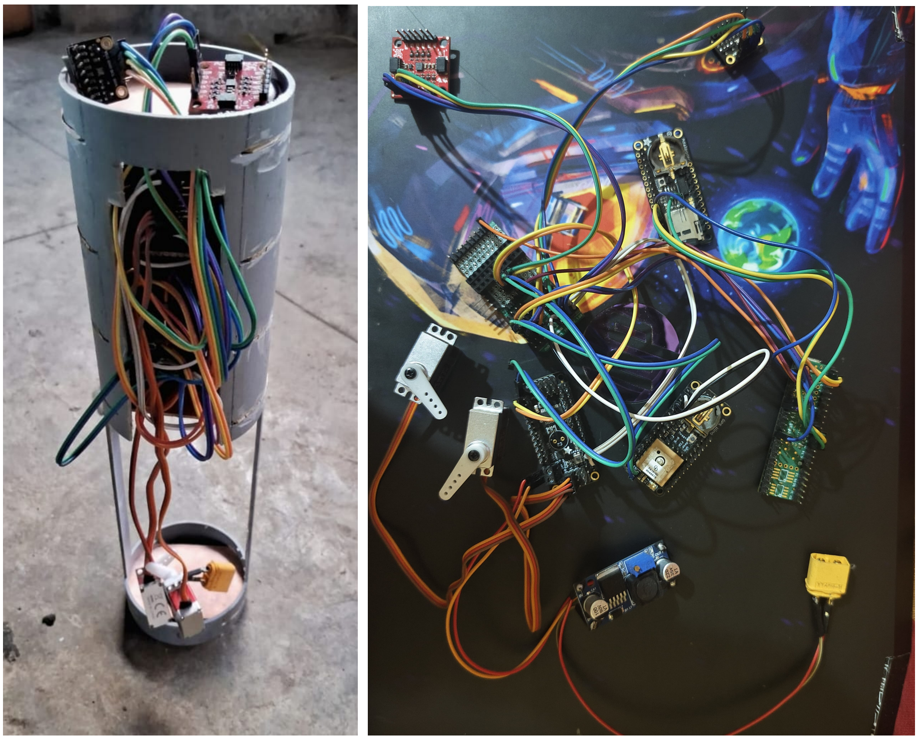

Figure 4.3: Mounting

The figure 4.2 illustrates the detailed wiring and mounting of the components used in the TVC-controlled rocket system. At the core of the system is the Teensy 4.1 microcontroller, which acts as the primary control unit. It is connected to multiple sensor modules and actuators to ensure precise operation and control of the rocket's flight.

1. Sensor Connections:

   The Adafruit Ultimate GPS FeatherWing is linked to provide real-time location and velocity data during the flight. The SparkFun ICM20948 IMU supplies critical information on the rocket's orientation, angular velocity, and acceleration, essential for stability and trajectory correction. The DFRobot BMP388 Pressure Sensor monitors atmospheric pressure and altitude, aiding in accurate flight data logging and performance evaluation.

2. Actuator Connections:

   The Adafruit Servo FeatherWing is interfaced with the microcontroller and servos to manage the Thrust Vector Control (TVC) system. This system allows the nozzle to adjust its angle dynamically based on flight conditions, ensuring trajectory correction and stability.

Figure 4.4: TVC

3. Data Logging:

   The Adafruit Adalogger FeatherWing is integrated to record flight data, such as sensor readings and control outputs, for post-flight analysis and design optimization.

4.7 Outcome

Outcome- The project aimed to develop a reusable TVC (Thrust Vector Control) solid-propellant rocket, integrating advanced control systems for stability and precision. The rocket achieved an apogee of 100 feet, showcasing the effectiveness of the implemented hardware and software systems.

Apogee Achievement:
The successful attainment of the 100-foot apogee was a milestone, demonstrating the combined functionality of the thrust vector control system and the solid-propellant composition using sorbitol and KNO3. The TVC system ensured stability during ascent, while the Kalman filter provided accurate altitude estimation, enhancing real-time adjustments to maintain the desired trajectory.

Hardware Performance:
The Teensy 4.1 microcontroller, in conjunction with the Adafruit GPS module, enabled precise positional tracking, while the BMP388 pressure sensor contributed to reliable altitude measurements. The IMU (ICM20948) played a crucial role in detecting angular displacements, which were counteracted by the PID control algorithm. The Adafruit Servo FeatherWing efficiently controlled the servos for TVC, allowing for accurate thrust alignment within $\pm 5°$ on the X and Y axes.

Delay in Second Motor Ignition:
A minor delay was observed in the ignition of the second motor during descent. This was attributed to a lag in the altitude estimation algorithm and the ignition circuitry. While this did not compromise the mission's success, it highlighted areas for improvement in synchronization between the Kalman filter output and the motor ignition signal.

Software Integration:
The system employed multiple libraries, including the Adafruit GPS, Servo, RTC, SparkFun ICM20948, and DFRobot BMP388 libraries. These enabled seamless communication between components over the I^2C interface. The Kalman filter and PID control algorithms were crucial in achieving system stability, with the former filtering sensor noise for accurate state estimation and the latter maintaining precise thrust vectoring.

Structural Performance:
The aluminum 6065 TVC mount demonstrated high durability and stability under thrust loads. The rocket's structural integrity remained uncompromised throughout the flight, validating the design and material selection.

Lessons and Future Improvement:
The delay in the second motor ignition underscores the need for refining the synchronization between altitude estimation and actuation commands. Implementing a

higher-speed communication protocol or optimizing the existing control loop could minimize latency. Additionally, integrating real-time feedback from multiple sensors could enhance decision-making accuracy during critical events like motor ignition.

"Overall, the project successfully met its primary objectives. The rocket's ability to achieve a 100-foot apogee with accurate thrust vectoring validates the design and integration of the system components. The minor delay in the secondary motor ignition presents an opportunity for iterative improvement, paving the way for future advancements in reusable rocket technologies".

Figure 4.5: Team

Figure 4.6: Final product

Figure 4.7: Ascending

Chapter 5

Conclusion and Future scope

5.1 Conclusion

The development and successful testing of the TVC-controlled solid propellant rocket represents a significant achievement in the field of aerospace engineering, particularly in small-scale rocketry. Throughout this project, the integration of cutting-edge components, including the Teensy 4.1 microcontroller, various sensor modules, and a customized thrust vector control (TVC) system, has allowed for the creation of a functional and efficient rocket capable of autonomous flight control and navigation.

The use of D-sorbitol and KNO3 as propellants, known for their simplicity and reliability, demonstrated promising results in terms of thrust and propulsion. By carefully optimizing the fuel mixture and adjusting the combustion chamber design, the rocket's propulsion system achieved a balance between performance and safety. The TVC system, which plays a crucial role in stabilizing and controlling the rocket's trajectory during ascent, was successfully designed using the Teensy 4.1 microcontroller, servo motors, and a set of sensors. The servo-controlled nozzle adjustments, based on feedback from the onboard sensors, allowed for precise direction control, ensuring a stable flight profile.

In conclusion, this project serves as a testament to the power of practical engineering and innovation. By merging theoretical knowledge with hands-on experimentation, it has contributed to the growing field of rocketry and has provided the necessary foundation for more complex future projects in the aerospace domain. The lessons learned during this project will serve as an invaluable resource for future engineers seeking to push the boundaries of flight technology.

5.2 Future Scope of ARIANE

The development of the TVC-controlled solid propellant rocket is an important milestone in the field of rocketry and aerospace engineering. Although the project has reached its initial goals, the scope for further innovation and improvement is vast, with many potential advancements in both technology and application. Several avenues can be explored to enhance the rocket's design, capabilities, and efficiency, while also expanding the use of the technology to other industries and applications.

- Enhancement of Propulsion Systems:
  The current propulsion system using D-sorbitol and KNO3 is simple, cost-effective, and reliable, but its performance can be further optimized. Future developments could focus on experimenting with alternative propellant compositions to increase specific impulse, which would result in higher efficiency and more powerful thrust. The use of hybrid propulsion systems, which combine solid and liquid propellants, could also be explored for better controllability and performance. The development of advanced nozzles and combustion chambers that optimize fuel combustion could provide more thrust and improve overall rocket performance.

- Advancement in Thrust Vector Control (TVC) Mechanisms:
  The TVC system, which was central to the rocket's flight stability, can be enhanced by employing more sophisticated control methods. Implementing an active guidance system with better sensors and algorithms can provide real-time adjustments to the rocket's trajectory with even greater precision. The current mechanical servo systems for nozzle adjustment could be replaced with more efficient, lightweight, and responsive systems, such as piezoelectric actuators or electromechanical systems. Further miniaturization of the control mechanisms could also reduce the overall weight of the rocket and improve its efficiency.

- Improved Flight Data Analysis and Control:
  While the existing sensors provided essential data during flight, the future scope lies in integrating more advanced sensors and data processing systems. The use of higher-resolution IMUs and additional sensors, such as magnetometers and accelerometers, could improve the rocket's ability to track its orientation and velocity with greater precision.

Implementing machine learning algorithms for data analysis and control optimization could significantly enhance the decision-making process, allowing for more accurate real-time control adjustments based on flight conditions. Moreover, the development of cloud-based data analysis platforms could enable more efficient processing of flight data, providing insights into system performance and areas for optimization.

- Autonomous Flight and Guidance Systems:
  The future direction of TVC-controlled rockets could involve the integration of fully autonomous flight systems. By employing advanced guidance and navigation algorithms, the rocket could be programmed to execute more complex flight profiles and missions, such as orbital insertion or controlled re-entry. The development of AI-driven flight control systems would allow for better adaptability to changing environmental conditions, such as wind speeds or atmospheric pressure, during flight. These advancements could be vital for future space missions and satellite launches, where precisio and reliability are paramount.

- Reusability and Sustainability:
  The concept of reusable rockets, such as those demonstrated by companies like SpaceX, is becoming increasingly relevant in the aerospace industry. Future rockets based on this project could explore reusability by incorporating modular designs that allow for easy recovery, refurbishment, and re-launching. Additionally, there could be an increased focus on sustainability by using environmentally friendly propellants and reducing the waste produced during launches. Innovations in recovery systems, such as parachute deployment, controlled gliding, or even vertical landing systems, could extend the lifespan of rockets and reduce the cost of operations.

- Applications Beyond Aerospace:
  The technologies developed in this project could have broader applications outside of traditional aerospace. The TVC-controlled system and the propulsion technology can be adapted for use in autonomous drones, small spacecraft, or even defense applications. The lightweight materials and design principles used in this rocket can also contribute to advancements in other fields such as robotics, where high-precision control mechanisms are required. Furthermore, the data logging and tracking systems developed for this project could be applied to other industries that require accurate real-time monitoring and data collection, such as environmental monitoring, agriculture, and logistics.

- Educational and Research Contributions:
  The research and development conducted in this project have the potential to benefit both the academic and industrial sectors. The detailed data, methodologies, and findings could serve as a valuable resource for future research projects focused on small-scale rocketry, propulsion systems, or flight dynamics. Collaborations with universities and research institutions could lead to the development of new theories, experimental techniques, and practical applications that contribute to the broader aerospace community.

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