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CAPSTONE FINAL REPORT

SMART PARACHUTE SYSTEM I

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LIST OF ABBREVIATIONS

IEEE	The Institute of Electrical and Electronics Engineers
3D	*3- Dimensional*
PSRAM	*Pseudo-Static Random Access Memory*
PIA	*Parallel Interface Adapter*
KgF.cm	*Kilogram-force centimeter*
ESP32	Waveshare ESP32-S3-zero
FSM	*Finite State Machine*
FR	*Functional Requirments*
NFR	*Non-Functional Requirments*
RM	*Responsibility Matrix*
PN	*Project Network*
IMU	*Inertial Measurement Unit*
I^2C / I2C	*Inter-Integrated Circuit*
PWM	*Pulse-Width Modulation*
MCU	*Microcontroller Unit*
Wi-Fi	*Wireless Fidelity*
ODR	*Output data rate*
MPU	*Motion Processing Unit*
BMP	*Barometric Pressure Sensor Fmaily*
g	*Grams of Acceleration*

1. OVERVIEW

The main purpose of this project is to design a functional, low-cost smart parachute deployment system that is able to withstand a variable weight payload of .50 litres of water. From unpredictable heights while safely landing on the ground, from any small projectile when set in motion. The system should be able to detect the optimal time to deploy when the payload is in free fall.

1.1. Identification of the need

In various fields, including experimental physics, aerospace prototyping, and educational activities, the safe recovery of small payloads from unpredictable launches is a persistent challenge. Conventional parachute systems, typically based on timed or manual deployment mechanisms, often fail to adjust dynamically to variations in launch conditions. This creates a clear need for a compact, autonomous parachute system that can intelligently assess real-time environmental data and initiate deployment accordingly. Such a system would offer significant utility in academic experiments, prototype testing, and any context where lightweight payloads must be launched and recovered safely, especially when the launch conditions cannot be standardized.

1.2. Definition of the problem

The primary problem is to design a smart, autonomous parachute deployment mechanism capable of handling variable launch heights, trajectories, and velocities. Unlike traditional systems designed for vertical drops or consistent launch profiles, the device must correctly interpret flight dynamics and trigger the parachute deployment at an appropriate time during the descent phase, regardless of how the projectile was initially set in motion. The design must ensure that the payload remains secure during the launch and flight phases. Deploys the parachute at an optimal point to maximize deceleration and minimize impact forces upon landing. Functions autonomously, while providing an option for manual override if necessary. Collects and records data to validate system performance during testing. The system must also remain lightweight, compact, and robust enough to withstand the stresses induced by launching, flight, and landing.

1.2.1. Functional requirements

There are multiple needs to ensure the success of the solution. Firstly, the body of the device must be able to hold the required payload when set from the projectile; in this case, it will be the bottle holding 0.5 litres of water. In terms of systematic design, it must be able to alert the system to slow the descent of the bottle; therefore, the parachute must be deployed automatically as the height from the ground is being analyzed through the sensors. Real-time data should be analyzed by the system to detect when the payload is descending in free fall. In the case of the projectile of the bottle, the system should not launch until conditions are met, then the parachute must deploy to ensure normal landing conditions. The system of the parachute should be able to have a manual override by receiving a remote command and an automated command to deploy. The calibration of altitude and motion sensors should be able to detect false triggers or delays during a fall. Data collected by the sensor recorder should be detailed to track the state of the system and the conditions that caused the parachute to deploy. Concededly, the functionality of the microcontroller system should synchronously work with the mechanical mechanism of the parachute to deploy at a reasonable time to ensure a safe landing. As the system is signaled to deploy, the sound of a beep will be enabled to alarm of descent. Practicality measures like lightweight and durability of the compact system should be established for the design to be able to perform durably for repeated launches.

1.2.2. Performance requirements

From a mechanical perspective, the system will be ranged with projectile points, the structure must be durable against impact and vibrations. The design should sustain flight during unpredictable conditions to efficiently land and remain intact for all electronic components like microcontrollers, sensors, and batteries to operate through all phases. To ensure a safe landing and protection of internal components, shock absorption mechanisms to withstand collision, like frames made out of 3-D damping frames or rubber mounting, to enclose padding.

Furthermore, to prevent false triggering during ascent or turbulence, the system must be able to identify the change from flight to free fall with high precision and be compatible with aerial drop designs in drone deployment scenarios. Additionally, the sensors and structural housing must endure brief but strong inertial pressures without failing or prematurely deploying, as projectile launches may involve significant initial acceleration. In order to make deployment choices in real time, the system's success also depends on its sensor fusion capabilities, which integrate data from accelerometers, gyroscopes, and possibly barometer sensors. The accuracy and response speed of this sensor processing system directly affect deployment timing, and therefore the integrity of the landing. The parachute deployment mechanism itself must activate in under a second and ensure full canopy expansion within a short vertical drop, making system latency and mechanical release reliability critical performance indicators.

1.2.3. Constraints

Several constraints must be acknowledged and limitations considered to be attended to the design and system of the final product. Economic, environmental, and social factors are all part of sustainability considerations and constraints that must be assessed and taken into account during project research and development. These requirements all have different aspects that are applied to bring the theoretical information into the application in real life.

During the design phase, the aim is to maintain a low-cost model that will sustain a prototype of globally available components that can be purchased on the market. Due to the need for experimentation and the educational system, the results must be maintained while ensuring the ability to replicate. Economically, these implementations can be considered during the selection of the materials and electrical components like sensors, altitude sensors, and microcontrollers. There are multiple complex hardware platforms and available modules that can be utilized to ensure the success of deployment mechanisms. The most important factor is to optimize cost without compromising the essential functionality of the mechanism and system. The main expenses of the design are the motion sensors, the microcontroller, the audible beeper, and the portable battery source. Searching for market products, all of these components are mass-produced, and they can be found on websites for online orders. Compatibility with the application and availability of the product are requirements to ensure that the economic constraint is achieved.

Environmental awareness while designing the product will be considered by minimizing the ecological footprint. Of course, the electrical components will be hard to replace for biodegradable materials, however, it will be encouraged to ensure repairability and recycling of the product to be able to reiterate the components for multiple usages rather than a single-use disposable deployment. Socially achieving further reach to induce educational values, this can be applied as a demonstrative teaching tool in engineering programs. Socially, this is a conceptual system that introduces the concept of real-time calibration, sensor integration, and mechanical actuation all in one product. Principles like dynamics, control systems, microcontrollers, and aerodynamic flight are all implemented within the design to create a working system.

The primary priority of the project must be safety and ethics, taking into consideration the system's responsibility in public areas where the falling payload may be a hazard for bystanders. Safety regulations must be ensured during the open testing period and demonstrations. All designs must have safety measures to reduce damage. The autonomous parachute deployment also must have remote control to ensure overrule if it comes close to crashing when manually monitored. These limitations help to make the system an affordable, instructive, sustainable, and socially responsible option for the smart parachute system in small-scale aerial applications.

1.3. Conceptual solutions

To be able to prepare a functional design plan for autonomous payload recovery, safe conceptual solutions were considered. Multiple things can be implemented from other designs that have been created for other solutions. The core connecting all aspects will be using a microcontroller system that will integrate all aspects of the design to achieve functionality. The environmental sensors that read lifetime conditions like altimeter and accelerometer will be incorporated to monitor the flight and be able to determine the appropriate launch time.

1.3.1. Literature Review

To initialize the design process, multiple references were evaluated for their key points that can be utilized in this design. The following were the acceptable concepts that can be adapted into the parachute system and considered to be included. The final layout of the structure and components of the solution will be used, considering all the information gathered through the references.

Reference [1] states that the purpose of a parachute is to decrease speed while maintaining the stability of a falling vehicle or payload. Before that, the system must be capable of recognizing free fall, or in their case critical failure can be a distinctive problem. Due to the timely detections that have to be made as soon as the actual fall is sensed, because one second can affect the descent, making it too harsh for the system, which will cause a damaging collision with the ground. The article includes multiple solutions for parachute deployment to save drones, which can be applied to this design to establish a recovery method. The same idea of performing a smooth descent is also applied to the smart parachute. Autonomous emergency systems deploy the parachute when signals are lost. To this design, the same mechanism is applied but for the specific purpose of identifying free-falling regardless of axis and angle of fall. The shape of the parachute is chosen with consideration of where the sensitive components are; it can be from the top of the design or the belly, or from the bottom, flipping the whole structure for the parts that need to be protected to avoid direct impact. The placement of the parachute should be designed from the top, considering that the electrical components will be connected to the parachute, meaning the order of mechanical placement will be parachute, electrical components, and the payload will be the first thing touching the ground during landing. This will help ensure the safety of the system and that repeated uses can be done without risk of damaging the electrical components. The parachute shape will also affect the point of landing at different angles, depending on the distance of the drop, and oscillatory movements in flight can present issues of displacement.

In Figure 1, there is a representation of the parachute system as a rigid body this model, the equations of motion can also be extracted, which will be an approximation of how aerodynamic drag can be calculated. The forces that will be considered are all from a free-fall perspective to consider the velocity and angle of fall. The concept of the free-fall design of the parachute is to be able to withstand aerodynamic drag and slow down the fall to safely land.

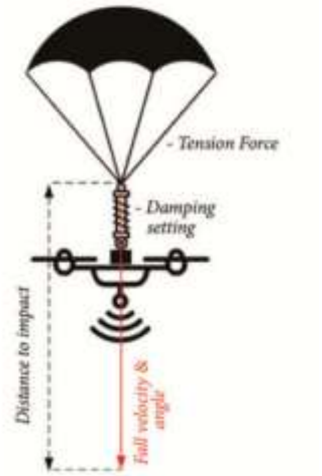

Figure 1An existing model of the parachute system of Reference [1].

In reference [12], the system uses sensor data and inputs it into the microcontroller. An inertial measurement unit (IMU) is utilized to identify a sudden drop in stability by detecting acceleration and angular velocity. To further enable the system to detect the rapid descent altitude threshold, a barometric pressure sensor is utilized. Through these sensors, the real-time acceleration data is used to detect free-fall conditions. Furthermore, the autonomy of the parachute deployment system must be decided based on calibrations that are taken from the sensors implemented in the system. The microcontroller will execute a deployment sequence based on these inputs by triggering a servo motor to release the parachute. The threshold conditions are predefined and already implemented into the controls of the microcontroller.

This provides a successful design that proves the validation of using either a motion or environmental sensor for autonomous safety. The function of the parachute is also highlighted to be able to follow a particular pattern when unfolding to enable the parachute to expand to enter the air. If the folding is not done properly, then the material might be blocked inside the container, which is a risk that should be assessed. The strength and weight of the material should be able to offer resistance to environmental conditions.

1.3.2. Concepts

The mechanical mechanism of the deployment of the parachute can be established through different conceptual designs. Firstly, the shape of the parachute and the material can be a critical determining factor of the speed of the descent and the performance of unfolding of the parachute can complicate the mechanism, ultimately limiting its deployment time if not considered properly.

However, this will all depend on the center of the system application, which will be the microcontroller. Any physical aspect can be altered easily during the development phase.

Two conceptual solutions were most closely paired with the basic deployment methodology of the system. Concept 1 will include an Arduino Uno [14] microcontroller with the addition of basic deployment method triggers of a fixed timer or manual override. The sensors in this case that will integrate the data will be a barometer and/or an accelerometer. The advantages of this system will be the simple mechanism, easy control, and budget-friendly. However, it does lack required attributes that will need to be added with more electrical components, like the WiFi or Bluetooth for manual remote control. Furthermore, the real-time data will not be fused, also all logic will be timer-based, causing premature or delayed triggers to set deployment in action. Finally, the size of the Arduino is bulky, which will be a factor to consider since the goal is to create a design as light-weight as possible. This will also be a further issue since it consumes high amounts of power, which will require a larger energy source.

Concept 2 will use ESP32 Mini [13] for a microcontroller, and for the sensors, a barometer and gyroscope (IMU), with built-in WiFi communication. The flight dynamics will be autonomously monitored till the trigger is detected, and deployment will be at the optimal time in flight. The only disadvantages of this system design would be that the ESP32 is more complicated to program, unlike the Arduino and it has very high sensitivity the power will have to be managed, and sensor calibration will need to be accurate to develop an efficient system.

Table 1 [15] [16] compares different microcontrollers that can all act as conceptual solutions concerning the six most important requirements for the system to function according to the purpose of the design. The ESP32 Mini will be chosen as the microcontroller for this project due to its low cost, built-in Wifi communication, and Compact build. There are multiple advantages for each application of a microcontroller, however, our main goal is to be able to find a compact microcontroller that won't affect the weight of the design and add more to the payload. Additionally, the input of the Wi-Fi application will establish manual override and remote control communication with the device. The first concept would be applicable more for vertical launches it will be underperforming when the variable conditions are not controlled.

Table 1 Comparison of the Microcontrollers

	Arduino Uno (Concept 1)	ESP32 D1 Mini (Concept 2)	Raspberry Pi Pico	STM32 Blue Pill
Cost	highest	Low	low	medium
Size/Form Factor	bulky	Compact	medium	small
Wi-Fi	None	Built-in	Needs add-on	None
Power Efficiency	Poor	Low-power modes	Good	Moderate
Real-Time Capability	Weak	Moderate	Moderate	Strong
Built-in Data Logging	None	With SD/Flash mod	None	None

1.4. Physical architecture

Considering the concept solution decided on the focus is to create a system solution coinciding with the requirements that the product must fulfil. In Figure 2, the interactions between the components of the smart parachute system are divided into two subsystems. Firstly, the whole of the system will be powered electrically by a power source. The application of all of the needed core components of the system should be distributed and all connected to the microcontroller to receive the needed signals. The electrical subsystem consists of the sensors that will interpret the position of the mechanism, record the data, and detect real-time movement. The microcontroller is the core of the system; it will function as the control unit, and all the input will be received by the microcontroller. The decision to wait or trigger parachute deployment will be decided based on threshold critical values, signals will be sent to the actuators, which will execute the system response. The mechanical subsystem is the mechanism components includes the servo motor that will deploy the parachute and the buzzer that will emit an audible alert. The arrows denote the direction of the flow of the data or control flow. Any signals will be established by the microcontroller and any data will be received by the microcontroller. Furthermore, the mechanism of manual communication will be through wifi, the commands will also be received by the microcontroller to overrule and stop calibration to deploy the mechanism.

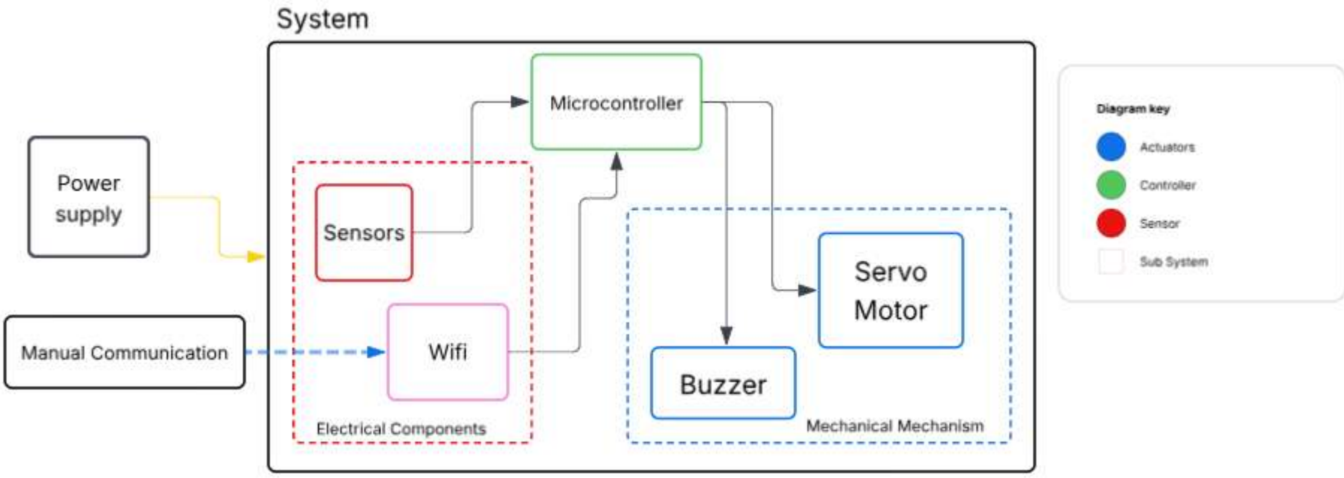

Figure 2 Interface diagram for the system.

This system design will receive the information input as seen in Figure 3, where the calibration is sent to the microcontroller to be authorized for the critical trigger. If the system does not classify input as critical, the system will stay put and monitor real-time input. If the calibration is below the threshold, then critical motion is detected and the parachute deployment mechanism is implemented. Another decision is made if manual command is sent to the microcontroller to stop monitoring the overruling system and release the mechanism. The microcontroller will send the signal for the servo motor to release the mechanism, and the buzzer will be activated synchronously. Finally, the system will stop monitoring as landing is successful and go into safe mode.

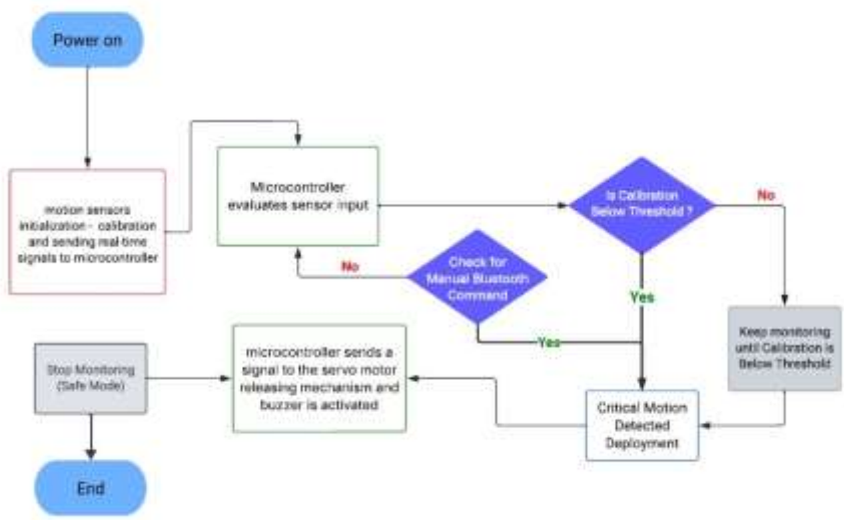

Figure 3 Process chart for the system

2. WORK PLAN

This section outlines the plan for implementing the Smart Parachute System I initiative. The goal is to design a microcontroller-based parachute deployment mechanism that activates autonomously in free-fall situations, prevents accidental deployment during normal handling operations, and provides telemetry and control functionalities through wireless communication. A team of four students sets out to embark on this challenge:

- Abdulla Ahmed Mohammed– Mechanical systems design and integration

- Amr Nasser benhalim – Sensor and power distribution systems wiring.

- Ghiath Abdul aziz – Communication and Control Systems

- Habiba Hassan Ahmed – Data analysis and documentation

Materialisation is projected to be completed within a 15-week after the second semester has started.

The next subsections shall explain Work Breakdown Structure (WBS), Responsibility Matrix (RM), Project Network (PN), Gantt chart, and the risks involved.

2.1. Work Breakdown Structure (WBS)

In the figure below, the tasks are broken out hierarchically. There are five main groups within it:

1.1 Hardware Design

1.2 Electronics & Sensors

1.3 Communication & Control

1.4 Testing & Optimisation

1.5 Documentation

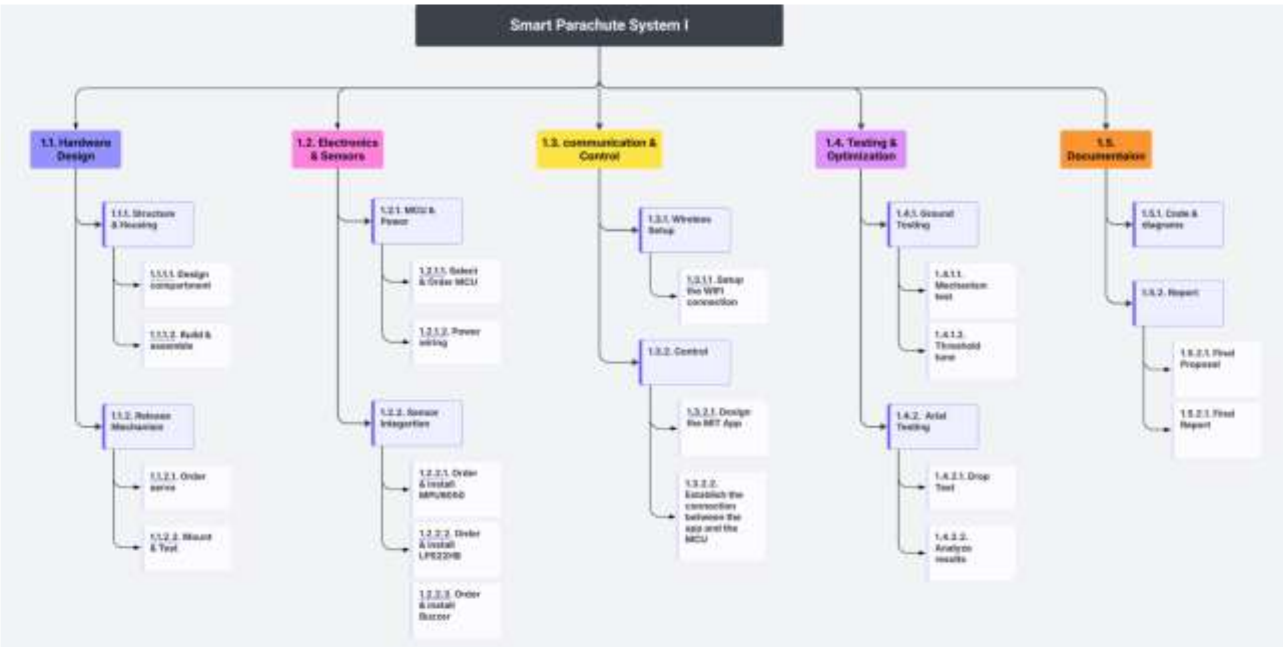

Figure 4 Smart Parachute system WBS.

Every one of these branches has distinct subtasks that correspond to activities related to design, assembly, coding, and validation. Figure [Smart Parachute WBS] already displays the entire WBS diagram (see previous image).

2.2. Responsibility Matrix (RM)

This matrix ensures that each subsystem has a clear owner and backup support. Ghiath manages control logic and planning, Abdulla handles mechanical implementation, Amr ensures electronics function correctly, and Habiba prepares all documentation.

Table 2 Responsibility Matrix for the team

	Abdulla ahmed	Ghiath	Habiba	Amr nasser
Mechanical	R		S	
Electrical		S		R
Communication		R		
Control		R		
Planning		R	S	
Report	S	S	R	S
Integartion	R			S

R = Responsible; S = Support

2.3. Project Network (PN)

The Project Network (Figure 2) illustrates dependencies and sequencing of tasks.

For example:

-Tasks 1.1.1.1 and 1.2.1.1 must be completed before integration begins.

-App communication (1.3.2.2) relies on wireless installation (1.3.1.1) and complete integration of sensors.

-Test activities (1.4) require all sensor and deployment systems installation and checkout.

The network's graph presents parallelizable operations and bottlenecks.

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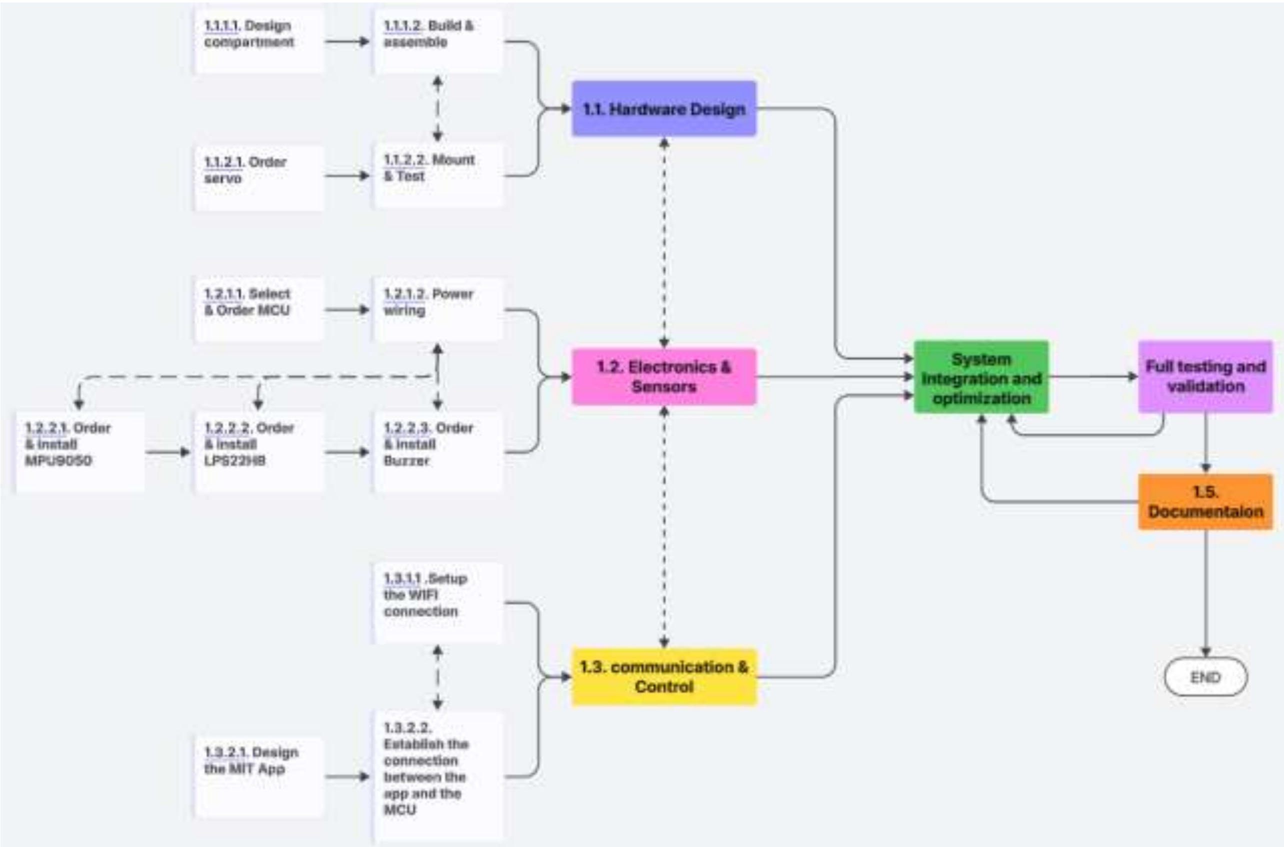

Figure 5 The project network.

2.4. Gantt chart

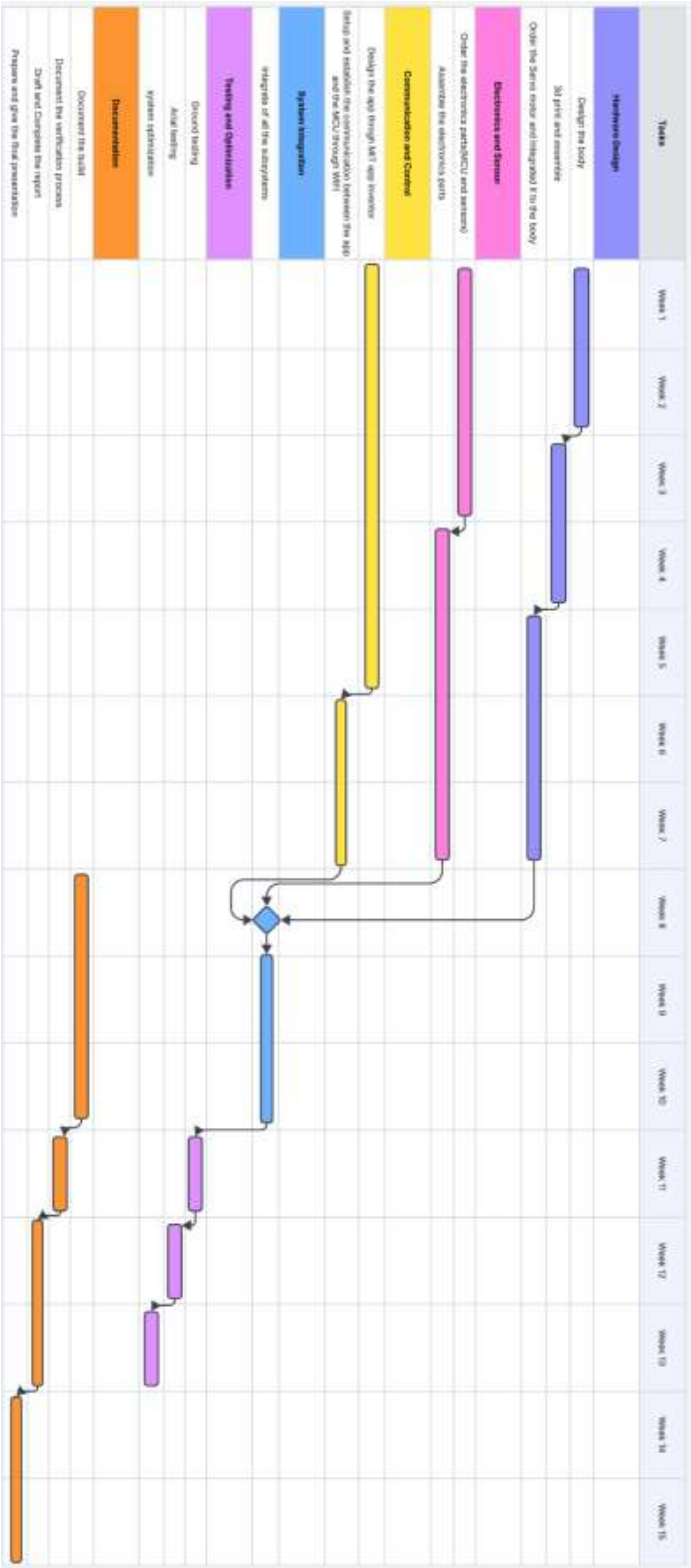

Figure 6 Gantt Chart

2.5. Costs

As a measure of the viability of the Smart Parachute System I, we performed an analysis of the necessary specifications and materials at the initial planning phase. The detailed estimation of costs includes essential sensors, control electronics, mechanical components, and provisions for testing and improvement.

Table 3 Costs

Electro-mechanical	
D1 mini Esp32	320 ₺
MPU9250	450 ₺
SG90-RC serve-motor	50 ₺
Adafruit LPS22 Pressure Sensor	280 ₺
Buzzer	15 ₺
other materials	300 ₺
3d printing	It depends on the volume of our design (Capstone II)
parachut	800 ₺
Total	**2215 ₺**
System Total	**2215 ₺**

2.6. Risk assessment

Various risks are expected to impact the effective development and assessment of the Smart Parachute System I. This section examines such risks based on their likelihood and impact, with suggested measures for mitigation. The risk matrix used for classifying purposes is shown in Table 5, and Table 6 lists project-specific risks.

RISK LEVEL		**Severity** of the event on the project success		
		Minor	Moderate	Major
Probability of the event occuring	Unlikely	VERY LOW	LOW	MEDIUM
	Possible	LOW	MEDIUM	HIGH
	Likely	MEDIUM	HIGH	VERY HIGH

VERY LOW	This event is very low risk and so does not require any plan for mitigation. In the unlikely event that it does occur there will be only a minor effect on the project.
LOW	This event is low-risk; a preliminary study on a plan of action to recover from the event can be performed and noted.
MEDIUM	This event presents a signficant risk; a plan of action to recover from it should be made and resources sourced in advance.
HIGH	This event presents a very signficant risk. Consider changing the product design/project plan to reduce the risk; else a plan of action for recovery should be made and resources sourced in advance.
VERY HIGH	This is an unacceptable risk. The product design/project plan must be changed to reduce the risk to an acceptable level.

Figure 7 Risk Matrix

Table 4 Risk Assessment

No.	Failure Event	Probability	Severity	Risk Level	Plan of Action
R1	delay in component delivery	Possible	Major	MEDIUM	Order early in Week 1; prepare alternate suppliers
R2	Poor Wi-Fi conditions during demo/testing	Possible	Moderate	MEDIUM	Change the testing date or location
R3	Team member unavailability or illness	Poss ible	M oderate	ME DIUM	Cross-train members on tasks.
R4	Limited access to a safe drop testing location	Possible	Major	HIGH	Reserve test sites in advance (rooftops, stairwells); coordinate with advisor
R5	Parachute fails to deploy at the correct time	Unlikely	Major	MEDIUM	Simulate multiple deployment scenarios in ground tests before flight tests
R6	Sensor noise affects deployment decisions	Poss ible	M oderate	ME DIUM	Apply digital filters; validate sensor data patterns
R7	Power fluctuations are causing a system reset	Poss ible	M ajor	HI GH	Use voltage regulation, capacitors, and low-dropout regulators

3. SUB-SYSTEMS

3.1. Electrical Components and Sensors

The electrical subsystem functions as the central decision-making unit for the Smart Parachute System. Through its functionality, the system detects motions while interpreting environmental conditions to make deployment decisions, performs data recording and activates remotely, and issues audible alerts [1], [2]. The subsystem consists of motion sensors, a microcontroller, as well as a motor controller for mechanical release actuation, a sound module for alerts, a telemetry system for logging, and a dependable power source to operate the entire setup[3].

The electrical system needs real-time functionality to achieve safe, precise parachute deployment. Different movement patterns need to be distinguished by the system between a fall and regular handling[5]. The system requires secure remote command response capabilities in addition to keeping records for analysis purposes[6]. The system performs essential operational functions through its decision-making abilities while assuring safe procedures and enabling reuse[7]

The control

3.1.1. Requirements

Several functional and performance-based requirements must be fulfilled by the electrical system. The system needs to possess the capability to recognize deployment times for the parachute. The system needs to detect all three scenarios, including free-fall and downward throws and angled trajectories, yet avoid activating during normal handling sessions[5]. The sensors need to operate with high sensitivity while their calibration capabilities enable distinction between regular operating states and emergencies.

The system needs to analyze sensor information through a microcontroller for instant decision-making.[3]. The system will activate the actuator motor through servo or solenoid signals when all deployment conditions are fulfilled.

A wireless remote deployment capability must be included in the system design to enable users to activate parachute deployment at specific moments when manual intervention[6] becomes necessary. The system requires data logging functionality to record information about altitude and acceleration measurements along with precise deployment conditions. Users need audible alerts from the system to track status through sound during flight and after deployment, since visual access is limited.

A portable rechargeable power supply needs to drive all components while operating throughout the entire mission[10] without interruption.

While choosing an ideal barometer sensor for the parachute system, selecting a suitable sensor that provides precision along with quick responsiveness is essential. Standard sensors commonly used, including BMP388 & BMP280, are well-suited for common purposes, yet are limited concerning high-resolution altitude measurement and noise tolerance. However, LPS22HB is far superior to such alternatives, with an incredible sensitivity of 0.024 Pa, which is equivalent to about 0.15 cm for altitude resolution, compared with 0.16 Pa (1 cm) for BMP280 and 1 Pa (8 cm) for BMP180. In addition, it has a far lower RMS noise rating (0.75 Pa compared to 1.3–3 Pa), making it more reliable for sensing minute variations in pressure. With a wide range of measurements [11]. With the capability of pressure and with low power consumption, LPS22HB provides the accuracy & reliability needed for applications including altitude tracking, meteorological surveys, or any device that requires real-time, high-accuracy measurements of pressure[11].

3.1.2. Technologies and methods

The electrical subsystem will accomplish its goals through proven accessible technologies. The system will use a microcontroller board, which includes options between Arduino Nano and ESP32 as its controlling component. This component receives sensor information and then uses logical programming to control system outputs as well as handle data storage requirements[1], [3].

The system will employ either an MPU-9250 accelerometer for detecting motion, together with orientation and acceleration measurements. The sensor data contains x, y, and z-axis [5] information, allowing the system to distinguish between falling motion, moving upward, and regular passing movements. Some versions of this system include a gyroscope addition, which enhances angled throw accuracy by tracking[12]. angular velocity data.

The microcontroller requires a servo motor driver to operate the mechanical actuator through a motor controller circuit. The microcontroller deploys the servo or solenoid-operated parachute through the controller after validating an appropriate deployment condition[3].

The implementation of remote control requires the connection of either an HC-05 Bluetooth module, an NRF24L01, or wifi between the microcontroller and the control station. The secure remote signal functions through this system to activate deployment.

The device will operate using two rechargeable Lithium-ion batteries (3.7 Voltage – 2200 mAh each) that suit its component requirements while providing a combination of lightweight design and strong power output[10].

3.1.3. Conceptualization

A basic flight control system replicates the function to sense motion and interpret conditions so that it can react appropriately through compact, low-cost, efficient electronics. Key ideas for this system originate from drone technology and rocket controls, along with miniature telemetry methods[13].

The microcontroller maintains its position as the main processing point for handling both sensor data inputs and remote signals, alongside controlling actuators, generating audio alerts, and storing data[1]. The accelerometer will operate in real-time to detect both acceleration and orientation shifts. The system uses threshold-based logic to detect falls by identifying three movement patterns of upward motion, downward motion, and being stationary[5].

When receiving a remote command, the microcontroller will activate parachute deployment after dismissing sensor data[6]. The buzzer utilizes its system to communicate flight status or landing status to individuals who are near the observer[9].

The system logs all recorded information either through an onboard storage chip or by sending wireless[2]. signals to a receiving device. Timing data, along with acceleration values and deployment trigger events, are among the recorded information.

3.1.4. Physical architecture

The electrical subsystem design will achieve maximum efficiency through optimized physical arrangements of components. The Waveshare ESP32-S3-zero board will receive its installation position in the central part of the system[3]. Breadboard jumper wires will serve as connectors between the electrical components, as well as the communication module, buzzer, four-leg push button, and battery[14]. The accelerometer and pressure sensor have a secure installation within the breadboard to deliver precise motion data[5] about the entire system. A correct orientation reading requires the alignment of this device, and a vent will be in proximity of the pressure sensor to be able to provide a precise reading. The buzzer will be internally fixed with the rest of the electrical components to produce audible sounds. The servo motor connection will lead to the mechanical release hatch.

The power slot contains the battery, which connects to a distribution circuit through its power connectors. Every wire will receive a secure attachment to prevent movement or disconnections that could occur during operational periods. Heat-shrink tubing, together with a plastic casing will provide insulation for safety purposes.

3.1.5. Materialization

The components required for physical construction need to meet three primary requirements: lightness, reliability, and mutual compatibility. The ESP32 is a suitable choice for the application because of its small dimensions while offering enough Input and output terminals[1][3]. It also combines two telecommunication types, BLE5.0 (Bluetooth) and the integration of wifi. has 4.5 MB flash and 2MB in its PSRAM.[17] In the hardware incription all of the digital signature modules meet the safety requirements of IoT and provide peripheral interfaces.

The MPU-9250 accelerometer serves as the motion sensor because it achieves a suitable combination of precision and simplicity when working with the ESP32. The accelerometer we used was chosen due to its great precision and accessibility in the market. It has a wide range of library support, and it has 9-axis performance, which will be crucial for our data accuracy, for the system to be able to calibrate all angles to determine free-fall. [18] Furthermore, to reduce weight we must obtain a lower power system, and the MPU-9250 stands at only 9.3µA consumption.

Additionally, the barometric pressure sensor is BMP388 due to its compatiablity to the breadboard we will be using because of its separate input and output domains. During active measurmenet the device can internally regulate its voltage consumption, and its digital interface lines have a standard open-drain and push-pull signaling. [19]There is also an important factor of temperature measurement, which will help maintain a safe temperature within the system. This will ensure reliable operation in our battery-powered system while maintaining reliable data configuration.

The project requires a standard servo motor; the SG90 was utilized to perform as the actuating component. It has the appropriate operating voltage for the used system and a torque of 1.6 kg.cm to 1.8 kg.cm, which is enough for the release mechanism. [20] It is also very compact, and the ulterations that will be needed in the body to ensure that the motor is in place will not be complicated. Furthermore, the buzzer module maintains a compact size to easily integrate it into microcontroller systems.

The buzzer module installed within the device will produce audible sounds. Through the microcontroller, the buzzer will activate various beep sequences both while the drone is in flight and after the parachute opens.

The push button's main function is to switch between the two primary states: the armed and disarmed state.

The breadboard will serve as the main attachment for all the electrical wiring and components. A breadboard was the most optimal choice due to its light weight and solid security for wiring. The wiring system will receive color coding treatment while receiving bundling operations to create a neat arrangement that minimizes interference[14].

The device will operate using two rechargeable Lithium-ion batteries (3.7 Voltage – 2200 mAh each) that suit its component requirements while providing a combination of lightweight design and strong power output[10]. The maximum input Voltage is 5 this must be maintained within our circuit. This will be achieved by using a Lm2596 buck converter. The two batteries together will result in 7.4 volts, then the buck converter will reduce this voltage to 5 volts.

The protocol used to connect the sensors is I2C, which is a two-wire serial communication that utilizes a data line and a serial clock line. There are multiple sensor modules used to support the multiple target devices. This creates a communication bus to send and receive commands and data. This creates less wire traffic and allows each device to have a unique address to turn communication into a single line.

3.1.6. Evaluation

To evaluate the electrical subsystem performance, we had both unit tests and integrated system trials. The functionality of each component, including the sensor, the buzzer, the motor, and the overall satisfaction of controlled commands. The main concern while testing the electrical component is its ability to work synchronously in connection and on its own. This consides with then testing of the controls and software updates that will need to be designed and fed to the system to ensure smooth operation.

An analysis of the isolation and fusion algorithms, respectively, of each module was made with component-level tests before they were verified to work independently. The reliability of the ESP32 microcontroller to be able to upload firmware, run stably, and communicate serially was evaluated using its built-in programming interface. Successful code installation and execution without halting confirmed its adequacy as a computing core. The MPU-9250 sensor was also characterized separately to verify the input for acceleration, gyroscope, and magnetometer along the x, y, and z axis, which leads to precise motion and orientation measurement. The operation of the BMP388 barometric pressure sensor was addressed with the I²C communication to verify pressure and temperature stability under continuous conditions.

Quantitative assessment of the electrical subsystem consistently verified real-time operation across sensing, processing and actuation cycles. The MPU-9250 sensor worked at 1 kHz sampling frequency and provided stable acceleration and orientation readings with no noticeable packet loss. Even for the BMP388 barometric sensor, the pressure resolution was up to 0.18 Pa, which is related to sub-meter altitude resolution applicable for deployment detection. From the time threshold detection on the sensors was reached until a command to actuate the servo and cut free of the flight string (end-to-end system latency) was less than 50 ms, well within parameters for timely parachute deployment. The SG90 servo achieved mechanical release in about 0.1–0.12 s per rotation of 60° under the nominal load. Based on power consumption tests, an average system draw of less than 120 mA was measured from active sensing and processing; peak current was observed during servo initialization. These findings support the fact that the EDS satisfies real-time, accuracy, and power consumption necessities for safe and reliable parachute opening.

Upon successful verification of the unit validation, the system performance was evaluated during integration. Both the MPU-9250 and BMP388 sensors were used simultaneously on the same I²C bus, demonstrating correct address assignment and stable two-wire communication. This arrangement allowed to simplify the wiring and keeping stable data readings. The servo motor actuator was evaluated under microcontroller control to verify proper signal timing and the presence of adequate torque for the parachute release mechanism. The buzzer module was evaluated by sounding predefined alert patterns to confirm auditory indications of system status during operation.

System-level testing evaluated synchronization between the sensing, processing, and actuation stages. The collection of data from the sensors, decision-making logic, sensor actuator activation, and alarm generation were found to execute in real-time with no apparent lag or contention. Manually iterative software upgrades were sent while testing to stabilize the control logic and the system performance. The electrical subsystem has been evaluated to verify that it meets the functional requirement and can operate reliably in standalone and integrated mode.

3.2. Mechanical Aspect: Flight mechanics

The physical operation of the Smart Parachute System depends on its mechanical subsystem to execute a safe water bottle descent. The mechanical subsystem consists of three main elements: a protective body structure that carries the payload and electronics, a parachute selection process, and a reliable actuator-powered release mechanism. The separate system parts need to collaborate in harmony to allow the parachute deployment during the correct timing while guarding against system harm [3][7][12].

A body structure needs to combine strength against landing impacts with weight minimization to support descent control. The correct size of the parachute should match the 0.5L water bottle's weight parameters, while the command-responsive yet accident-proof release mechanism must function properly. The reliable and precise actuator functions either as servo motors or solenoids since they must activate promptly upon command. The mechanical system development will prioritize simplicity, together with reliability and robustness.

3.2.1. Requirements

The mechanical subsystem has to guarantee both safety and controlled descent of a 0.5L water bottle. A lightweight yet durable structure should make up the body of the system, which will keep the parachute safely in place. A trustworthy release system must be incorporated to activate the parachute exactly when needed. The actuator requires fast operation and immediate response to directives from the electronic system so that it opens the parachute completely during free fall. To achieve balance and minimize pre-deployment air resistance, the mechanical parts require durability, a lightweight and compact design.

For automatic deployment during free fall and remote activation, the mechanical system needs to function effectively with sensors and electronics. The system should operate securely when people handle it regularly, and the parachute should not deploy by mistake.

3.2.2. Technologies and methods

The system's mechanical components will be constructed by using a mix of contemporary production methods and standard mechanical fabrication techniques. ABS plastic or thin aluminum sheets will form the body structure. ABS plastic works well because it delivers robustness alongside dependable durability, alongside weight reduction properties, and enables easy 3D printing fabrication. Additional strength comes from the use of this material, which adds some weight to the system.

The ripstop nylon material will serve as parachute fabric because it fulfills the requirements of being lightweight while remaining strong and resistant to tearing. A compartment inside the body will receive the parachute for careful folding, which enables smooth deployment when the trigger is activated.

Small hooks operated by servo motors will function as the release mechanism. The microcontroller sends deployment signals to the servo motor after detecting a fall[7][12], thus enabling the servo to move and release the parachute's latches. Digital design using SolidWorks or Fusion 360 will precede physical manufacturing of the body and release mechanism through CAD. Part accuracy depends on this method, while the deployment movement gets simulated precisely.

The 3D printing technology for prototyping enables the quick development of different mechanical designs, which can be tested rapidly to generate rapid performance improvements.

3.2.3. Conceptualization

The mechanism derives its operation concept from both drone parachutes and model rocket systems. The parachute system contains compacted parachutes in a compartment under a simple mechanical locking system[5][12]. The lock mechanism opens rapidly to allow the parachute deployment, which in turn reduces the falling speed of the object.

This project design divides the body structure into two primary sections, which contain the parachute compartment above the payload and the electronics section beneath it. The parachute will receive proper folding before being secured beneath a lid or hatch that operates through servo-controlled locking mechanisms. Through the microcontroller, the servo receives instructions to open the hatch when the correct conditions of free fall or remote signal activation occur.

The servo motor actuator needs installation next to the latch so mechanical responses stay minimal. A spring-loaded mechanism may assist the parachute deployment through the hatch opening after it opens. A proper design must allow the parachute to open without any entanglement since this prevents safe and effective descents.

3.2.4. Physical architecture

The mechanical subsystem's physical structure is divided into sections to achieve organization and functional purposes. The parachute storage area in the upper section is fitted with a lightweight door or hatch that can be secured by the servo mechanism. Openings on the door need to face toward the outside to allow the parachute a free path for deployment.

The essential electronic components, including sensors and a microcontroller, as well as a motor controller and power system, will be secured to mounting brackets found in the middle section of the body. The system needs secure attachments, which will stop components from moving inside during flight and impact events.

The 0.5L water bottle payload will be placed in the bottom part of the design. The bottle holder requires a tight grip that enables simple bottle exchange. Elements of rubber and foam padding should be incorporated as protective layers that reduce shock impacts on the payload during landing operations.

In the design stage, the aerodynamic form of the system exterior reduces air drag until the parachute activates. The design employs smooth contours and prevents all superfluous protuberances, which reduce both entanglement potential and descent irregularity.

3.2.5. Materialization

Lightweight and durable materials will be selected as the main choice for producing mechanical parts. The main components are made through 3-D Printing utilizing PLA. The structure was split into three main sections: the parachute compartment, the release mechanism, and the main body. This provides enough mechanical and physical characteristics to maintain a solid structure and shield the electrical components from appropriate impact resistance. Additionally, its is a cost-efficient material that will lower our bill of materials in our prototype.

Ripstop nylon functions as the material choice for the parachute because it delivers tested results in comparable deployments. Professional stitches at fundamental stress areas will prevent tearing incidents during deployment. The chosen servo motor for the release mechanism will come from a reliable standard model range, which includes the SG90 and its equivalents, because it provides swift, accurate operation with enough torque of 1.8 kgf.cm. Considering that the weight impacts the aerodynamic drag that the parachute will be facing, the weight of the system has to be considered and obtained at the lowest possible value. The total resulting weight of each component in the structure, split by compartments, totals to 145.57 grams as seen in Table 8.

Table 1 Weight of components

Parachute compartment	Right shell	22.75 grams
	Left shell	22.75 grams
Release Mechanism	Deployment pen	2.88 grams
	Gear	1.04 grams
	Top plate	9.43 grams
Main Body		86.72 grams
	Total	145.57 grams

Screws and small bolts, as well as snap fits, serve to join the mechanical components. (Screw measurements) Non-permanent fasteners will serve as the preferred option for all points to enable convenient maintenance as well as repairs. Surface finishing operations were done through the 3-D printing operation called ironing this minimized our step process and provided a finished component straight after printing. The final surface effect was applied by utilizing a printing plate that is custom laser-engraved to build with a custom smooth surface finish. The drawing design was created through Solid-Works [C Figure 12345]. These files were sent to the 3-D printer and took approximately 7 hours to print the final version. Many prototypes had to be printed and disqualified from the final consideration due to their lack of accuracy.

The release mechanism design was created through a snap-in feature crearing a spring effect when the mechanism is activated. The left shell and the right shell snap in together through internal hooks that, when the deployment pin is in the right position they are separated through the hook feature. The unreleased form of the mechanism is already in a pull phase, where both shells are ready to separate. The bottom of the shell structure has an in-bound line on the inside in a fillet shape to provide extra strength to maintain a durable resistance to the shells to ensure that they don’t release without command.

The main body of the structure is a cylindrical shape made to preserve the electrical components so that when the release mechanism is alerted the electrical components are secured and remain attached to the structure.

3.2.6. Evaluation

The mechanical evaluation is done through laboratory tests, which took place under various operational scenarios. The first set of tests aims to verify parachute deployment after the system receives a manual signal to release the mechanism. Release time, along with smoothness, was measured during testing to identify any deployment delays or mechanical failures. We have tested the parachute system manually by sending a signal, and the mechanism satisfied the criteria when 10 out of 10 signals were successfully released. The efficiency was achieved after multiple testing and tweaking of the top plate and its thickness, and the pin length to ensure real-time accuracy with no delays to the mechanical aspect. This test could only be achieved after connecting the motor to the mechanism itself.

The durability assessment requires dropping the system from standard heights, which include tabletop levels to verify that the release mechanism operates safely. This also tests the durability and impact resistances fo the structure, and the weight tests check that the complete system maintains proper mass values to guarantee strong parachute function. We drop tested the whole structure from inside our testing labs instead of crop testing, and just ensured that the structure is durable in gravitational force and under parachute resistance. We used minimal human force by throwing the structure against the floor to ensure it remains compact when actual arm force is applied to it. When the design was fully assembled, the electronic components were internalized. Then, more testing was required, where drop tests were conducted from the first floor of about 3.5 meters. The rate of success of the electrical components not being affected without the parachute system releasing was 9 out of 10 drops after some alterations, including the whole body initially being 2 millimeters in thickness. This testing helped us determine that the specifications and requirements of the design were being overachieved; therefore, we decided to print another main body that was 1 millimeter in thickness, and this achieved a prototype that was both durable and a light structure without harming the success of our system.

The success criteria include reliable parachute deployment under proper conditions, together with durable system components and secure water bottle safety throughout descent. All the testing criteria that were used in the mechanical components were mainly ensure durability and efficiency of the release mechanism. The testing was repeated until an appropriate and approved success rate was gathered through our ten trial tests.

3.3 Communication and Control

To be able to combine the mechanical efficiency and optimal usage of the electrical components, the control and communication between the electrical components must be maintained through a solid coded implementation. The deployment system functions will have different operaitonal state of the payload: Disarmed, Armed, In-Flight, and Deploy. Each function will record and transmit telemetry that will reconstruct the triggering conditions and control transitions between states. The prioritized logic control in drop detection and release a timely deployment, while maintaining an alert for possible manual override. The control logic must maintain two main goals: the first being the detection of a drop or free fall to initiate the release mechanism, and identifying normal-handling to keep false triggers at a minimum rate.

3.3.1 Requirments

The control and communication requirements include recording and calibrating sufficient telemetry to be able to time deployment appropriately and reconstruct sensor values. Efficiency in manual override of the release mechanism on command when the armed state is in action. The calibration must withstand any false deployments when normal handling or short drops are detected by rejecting release. Additionally, when a drop is detected by barometric and IMU data, the release mechanism should be deployed within bounded uncertainty to open before impact.

All operational states must be determined and managed by the commands and be able to be distinguished by the beeper and through the wireless transmissions.

3.3.2 Technologies and methods

This subsystem, which includes three devices, firstly, the Waveshare ESP32-S3-Zero is a Wi-Fi/BLE device that uses hardware timers and real-time control. Secondly, the IMU MPU-9250 and BMP388 will communicate with the controller through a common I²C bus, providing immediate access to acceleration data. Finally, a finite State Machine (FSM) for the subsystem was programmed in C/C++ using the ESP32 Arduino framework. The FSM includes protected transitions that only activate after the corresponding sensors have been confirmed as valid. The way free-fall detection is implemented is by using both low-magnitude acceleration readings and steady altitude trends from the sensors. The detection of false triggering for the EOS is implemented by the use of threshold windows plus the delay time required to either arm or settle the EPS. The servo motor is controlled using PWM signals, and the buzzer will provide audible signals to indicate the system state.

3.3.3 Conceptualization

The control system is a central controller that receives information from many sources, such as sensors, mechanical actuators, and user commands. It uses a finite state machine approach to guarantee predictable operation regardless of workload or ambient conditions. Using a finite state machine approach allows the control system to be able to transition to the armed state only from the disarmed state after specific user input. In addition, during the in-flight phase of flight monitoring for low-G events or other types of dynamic motion, the control system also transitions to a state of in-flight The control system deployment will occur only once sustained descent has been confirmed by both an IMU and telemetric reporting of altitude change; thus, the control system deployment cannot occur until the vehicle is frozen If the user enters an authenticated manual override command, it will still require that the control system be in armed state prior to executing the command. Event-driven methodology minimizes latency and enables control systems to respond to events as they occur in real-time. Additionally, the telemetry from each test provides the ability for evaluators to recreate the changes to the control systems' states and, from that, compile statistics regarding trends from each test.

3.3.4 Physical architecture

The Control Subsystem is housed inside the center of the structure to protect it from impacts, while ensuring that the sensors remain accurately aligned as a result of its physical location. The top board of ESP32 is mounted on stand-offs. Although electrical noise is reduced by having the I²C wires to the IMU and barometer be the shortest possible, the push button for arming/disarming is recessed inside the enclosure to prevent accidental activation while being easily accessible, The RGB LED as well as the buzzer are located behind small holes on the enclosure to provide users with an adequate level of visual and audible feedback. The wires that connect the transmitter to the release mechanism are routed cleanly through the enclosure, remaining bundled together and secured together to avoid any interference with the parachute deployment. The LM2596 buck converter provides a dependable and stable 5V output for powering the servo, and the circuit supplying this voltage to the servo is kept electrically isolated from the logic supply of the ESP32 board to avoid brown-out resets. Lastly, good cable management, good grounding connection integrity, and decoupling capacitors provide reliable operation of the servo even under the conditions of a momentary large current draw associated with activation of the servo.

3.3.5 Materilization

The communication and control section of this project embodied through the ESP32-S3 microcontroller creating a FSM that allows for the four states of operation; the four operational states are the DISARMED state, the ARMED state, the IN-FLIGHT State, as well as the DEPLOYED State. All of these states govern the behavior of the system and all support the safe operation of the system. Upon powering the system on (when it first becomes powered on), the system starts in the DISARMED state. With the actuator locked mechanically in DISARMED state preventing unintentional deployments, the transition from the DISARMED state to the ARMED state can only be made with deliberate inputs through the use of a push button so that the system may be safely handled prior to the testing stage.

For the acquisition of sensor data, both the MPU-9250 accelerometer and BMP388 barometric pressure sensor were interfaced with the ESP32-S3, each using a common I²C bus. The magnitude of acceleration and the trending of altitude were processed in real-time to validate that the system was in free fall while filtering out normal disturbances during handling. The parameters that defined the threshold for validating when the system is in free fall, confirming ceiling descent, and timing between deployment, all are configurable parameter choices within the firmware, therefore providing the opportunity for calibrating these parameters multiple times during the testing stage without the need to reconfigure the entire control logic.

The ESP32 built-in Wi-Fi works in SoftAP mode to provide a method for Wireless Communication and Telemetry, with the addition of a Lightweight HTTP Interface to allow for the transfer of Telemetry Data and Authentication Commands for Manual Deployment Requests. The integration of an RGB LED and Buzzer give both Visual and Auditory Feedback to allow users to see/understand the current State of the system and Deployment Events. All of these Implementations provide Deterministic Control Behavior, Safe Actuation, and Traceability of System Operation.

3.3.6 Evaluation

The Communication and Control Subsystem has been tested at the bench level and through Integrated Drop Testing to ensure Functional Correctness, Responsiveness, and Safe Operation. The bench-level tests validated the proper operation of the FSM, including Actuator Lockout in the DISARMED State, correct State Transitions, and Rejection of Unauthorized and/or Out-of-Sequence Commands. This testing confirmed that the Control Logic prevents an accidental Deployment during the Handling and Startup of the system.

Throughout the process of integrated testing, the subsystem was able to detect free-fall conditions reliably through low-g detection using an accelerometer, as well as confirming altitude trends. The latency between verified descent detection and servo actuation was consistently under 150 ms, which allowed for timely deployment of the parachute within the timeframe of the first-floor drop tests. The one-shot deployment strategy ensured that there was not a possibility of issuing multiple or oscillatory commands to the servo, which provides a level of stability and predictability in terms of control behaviour.

When testing the use of wireless telemetry and manual override, both were used successfully during live use. The telemetry streams were able to accurately reflect system states, sensor summary data, and reasons for deployment, which allowed for an effective post-test review and traceability of each stream. The system would only accept manual deployment commands when it was in an armed state, while other states did not allow any manual commands, which confirmed the functionality of the command gating feature of the system. There were no instances of a false deployment occurring while the system was being handled or testing the performance of the system with vibration, which demonstrates that the control subsystem meets all requirements for safety and reliability as they related to the Smart Parachute System.

4. INTEGRATION AND EVALUATION

To achieve cohesive performance, both the electrical, mechanical, and control aspects of the system must work together to ensure a safe operation. Additionally, there must be an assessment requirement to ensure the synchronism of all systems' efficiency. Each subsystem has been tested individually to ensure the section requirement achievement. The assembly process and connection of all parts required teamwork and problem-solving to identify the issues that were faced. Critical thinking and trial and error through all the uncertainty of integration

4.1. Integration

The real-time coordinates calibrated by the sensor data must be processed accurately to be able to integrate both the electrical and the mechanical parachute deployment. The physical design was optimized for minimal interference and secure storage holding for all the components. Held in the physical storage are the microcontroller, accelerometer, servo motor controller, buzzer, and the telemetry modules. All of the electrical components work together to initiate deployment through the data processing of patterns and triggers. Synchronization was achieved between the motor control and the sensors to produce instant signaling time when defined by the sensors based on detection, allowing the motor to release the mechanism.

The electrical system will have input and output specifications that are matched by the mechanical design to produce an accurate movement range. For the mechanical actuation to be triggered on time, the sensor arecalibrated to consider the timing threshold between trigger and motion. This is a precisely timed prediction for fall detection to trigger the servo motorized release mechanism and for the system to predict design tolerance. Both the electrical and mechanical system and joined together through the control and communication system incorporated within the ESP. These signals are all sent through a communication bus to regulate the system and make decisions based on the operational state that the system is in. Successful integration of all systems will result in a safe landing through accurate free-fall detection during drop. [7] Other specifications include manual override reaction, safe handling without in-flight false alert, and strong structural integrity of the structure after the drop test.

4.2. Evaluation

Multiple factors of performance can be evaluated to assess the efficiency of the Smart Parachute System. All functional requirements of the integration measurements are met through consistent fall detection and instantaneous mechanical actuation driven by the data feedback and power performance. Drop tests were conducted from various heights and conditions to evaluate the response time of deployment and the durability of the mechanical structure. The reliability of the mechanical structure must be resilient under repeated drop tests to withstand impact. Furthermore, the system is able to reset to the initial state through each trial without fail. These scenarios were controlled for sensor fall detection capabilities to be assessed as the deployment is triggered. Complete check tests for the system, including the validity of recorder data and coordinates as deployment evidence, buzzer alert during descent, and response time latency of actuator activation and motion recognition. For uninterrupted operation, the power system is assessed for stability under load.

The mechanical evaluation is through laboratory tests, which took place under various operational scenarios. To evaluate the degradation experienced by mechanical components, especially by the release mechanism and parachute fabric. Each test run has generated data that was utilized to make necessary improvements in weak areas of the system. In lab testing from reachable arm length was the main experimental trial to optimize identifying any major system failures. To assess sensor detection and timing, as well as buzzer output, the complete assembled system had to be produced to determine the operational efficiency in a real-life application. The analysis of data logs had to validate that the operational conditions match anticipated thresholds as well as enable the optimization of deployment settings. Furthermore, testing the power system by checking its stability and runtime while measuring response delays to confirm the actuator moves rapidly after fall detection occurs. The safety tests confirmed that handling and vibration do not trigger unintended deployments of the system. The system's faults will be fixed either by updating firmware or modifying wiring[4].

The second set of tests aimed to verify parachute deployment after the system drops from larger heights and different angles. Deployment time, along with smoothness, was measured during testing to identify any deployment delays or mechanical failures. We have dropped the parachute system from the first floor, which is approximately a 3.5-meter drop. The evaluation was to verify that there was reliability, timely deployment, and reduced impact loads on the payload to acceptable levels. Any identified potential failure points must be managed enough to ensure the system meets functional and technical requirements that were outlined in section 1.2.

The experiment setup started with the identification of variables; the independent variable is the drop configuration. This was implemented to establish that the parachute was able to operate under the three main conditions in the requirements. The first one is a normal release without any disturbance to the parachute system to simulate a clean drop, where the expected result is automated release. Secondly, perturbed release, which is a slight lateral push to create a non-ideal scenario where the descent must be regulated. The expectation would be a few oscillations in-flight. Lastly, to test manual override, a normal drop was trialed, and through Wi-Fi connection, the inspector would release the mechanism.

The dependent variables that were being measured and observed were the descent time that it takes the system to reach solid ground. The variable does have some human error to be considered since the timer is in seconds; considering the reaction time of dropping the system and observing its landing, there is a plus or minus of 5 seconds for each measurement. Peak impact acceleration was measured through the MPU-9250 in our system, which provided the measurement of force relative to gravity and the time it took to fall. Then subjective observations were also gathered on landing results, whether soft, acceptable, or harsh landing.

The constant variables were the test height of a constant of about 3.5 meters, which equals a first-floor building drop. The test environment was also the same, all the drops were done on the same day, so no weather conditions disrupted the trials. Finally, the packing procedure and folding the parachute were also standardized and only performed by the same person to prove no advancements were made during the trials. All these elements remained the same through all ten trials.

The final test trial results are summarized in Table 9; the primary findings were the ranges of 1.4 to 1.6 seconds that it took to reach descent safely. The delay is not dramatically extended; the parachute size could be factored to elongate that time. For the safety and integrity of the system's structure, the peak impact acceleration ranges between 2.0 and 3.0 g. Even in cases of higher acceleration levels, the impact is not within the risk range where the electrical components of physical architecture could be harmed. The success rate of the drop was 90% approximatly at peak performance, automated performance was more efficient than manual override. The system meets success standards, presenting validation in reliable fall detection followed by consistent remote response and correct audible beeping during stages, together with precise data recording and secure power functions. [13].

Table 9. Final Trial run after integration

Trial	Deployment Mode	Descent time (Seconds)	Peak impact acceleration (gravity)	Landing outcome	Results
1	Auto (normal)	1.45	2.1	Successful soft landing	Clean deployment, stable descent
2	Auto (normal)	1.48	2.0	Successful soft landing	Very similar to Trial 1
3	Auto (normal)	1.47	2.2	Successful soft landing	Slight canopy sway
4	Perturbed Release	1.50	2.5	Acceptable landing	Lateral oscillation, still controlled
5	Perturbed Release	1.52	2.7	Acceptable/ harsh landing	Stronger swing, higher peak acceleration
6	Perturbed Release	1.49	2.4	Successful soft landing	Good recovery despite the disturbance
7	Manual Override	1.55	2.3	Successful soft landing	Manual deploy triggered on time.
8	Manual Override	1.60	3.0	Harsh landing (late deploy)	Override pressed late, shorter canopy time
9	Auto (normal)	1.46	2.1	Successful soft landing	Confirms repeatability
10	Perturbed Release	1.51	2.6	Acceptable landing	Moderate oscillation, no structural damage

5. SUMMARY AND CONCLUSION

This project report is an outline of a smart parachute system that autonomously deploys a parachute system utilizing real-time sensing to safely recover a small payload of 0.5 Liters. There is an organized engineering design for the entire development of the product. To initiate the process identification of the requirement, the study of current technologies was conducted. Deciding on the components of the system, like the sensors, microcontrollers, and the deployment mechanisms, through the reference research. The best conceptual design was chosen and then analyzed based on all physical requirements like cost, integration, feasibility, and performance. Additionally, all the possible sensor and actuator integration techniques and preliminary code structures for the embedded system were considered to ensure the efficiency of the system. The design direction was documented through the report of the design development, and the testing process began. Challenges such as integrating components within a compact design and ensuring responsiveness during descent emerged; these were addressed through iterative improvement and will guide future development. With well-documented progress and a clear roadmap, all preparation for the successful prototype and testing phases. All components were gathered, and assembly of subsystems, electrical components calibration, and programming were completed. After finalizing microcontroller programming, testing sensor modules, and beginning materials procurement. Focus was shifted toward simulation, fabrication, and system integration to bring the Smart Parachute System implementation. All testing for individual and assembled subsystems was successful and within design criteria and requirements.

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Appendix

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