SkyIsland: Aerial Docking Drone System

ECE 4011 Senior Design Project

SKYISLAND
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Executive Summary

SkyIsland is a drone system comprised of independent quadrotors with the ability to interlock and reconfigure into one collective drone structure. The reconfigured drone structure will have the ability to reverse the formation by breaking apart into its constituent drones. The system will reassemble itself based on the characteristics of the assigned task and the required features to execute it.

The flexibility of the system makes it versatile and adaptable in applications involving search and rescue in hazardous areas, cargo delivery, military recon, and difficult inspections in inaccessible areas. The ability for the drone swarm to reconfigure and reshape provides flexibility in unnavigable regions, such as narrow canyons, crowded traffic, and dense forests while minimizing air traffic in open areas.

When reassembling into a collective structure, electro-permanent magnets will be utilized as a holding force to maintain the connection between coupled drones. Distance sensors such as ultrasonic sensors and optical detectors as well as emitters will be employed to achieve mid-air, crash-free alignment between the drones prior to docking. The system will also be enhanced with a complex control system to guide the drones while in swarm mode and when docking mid-air. Drone swarm interactions will incorporate wireless communications utilizing a low-latency, in-order, and reliable transmission protocol. Docking and swarm interactions will be integrated into a centralized software platform coupled to a human machine interface (HMI) at a central ground station.

A wide variety of open-source software toolsets and drone platforms are readily available for the implementation of the SkyIsland system which aids in keeping the development costs relatively low. The project is estimated to cost $600.00 which will fund both the material costs of prototyping as well as acquiring any relevant software licensing.

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1. Introduction

The SkyIsland team will design a search and inspection drone system that features mid-air self-docking and undocking following commands from the ground. The team requests $600.00 to develop a prototype of this system.

1.1 <u>Objective</u>

The team will design and prototype a system of three specialized inspection drones that perform stabilized self-docking and undocking mid-air to achieve dynamic configuration, high payload capacity, and multifunctionality. The inputs from the user include movement directions (i.e. forward, backward, left and right), docking, and undocking commands and planned drone path. Individual drones operate semi-autonomously until a docking command is received. When a docking command is received, the set of three drones can aggregate together, perform mid-air docking, and operate in unity to perform a joint task. When an undocking command is received, the three drones separate, and are ready to perform individual tasks.

1.2 Motivation

Most of the commercially available drones operate individually with one functionality. There is no available product in the drone market that utilizes a drone system with docking and undocking in mid-air. Mid-air docking of drones is a relatively new topic in research area as well. One comparable product in research is Daniel Wilson's unmanned aerial vehicles with airborne docking, from the University of Sydney. However, this research is only for mid-air refueling of human-sized aircrafts. The researched product also requires specific shapes of the leader and follower drones: a cone-shaped, parachute-like drogue and nose [1]. The motivation of SkyIsland system is to introduce multipurpose and easy-to-assemble inspection drone system into the market. The team aspires to design a prototype that, when manufactured in large scale, will be cost-effective and has a wide range of applications. Currently, the primary customer base is comprised of communications, power, search & rescue, and military industries. With an inspection drone system of a smaller scale, the product could be extended to any business or individual who needs to search and inspect from the air.

1.3 Background

The closest commercial product to SkyIsland is the on-ground self-recharging inspection drone DRONEBOX from H3 Dynamics [1]. Mid-air docking, however, has been explored as a research topic for mid-air refueling of human-sized aircrafts [2].

There are four key components in this inspection drone system design: drone-to-drone communication, stability control, and software integration. There is plenty of research conducted in these distinct four areas.

Module to module communication has been explored and implemented in Seaswarm. Seaswarm is a project that Senseable City Lab at MIT developed to clean up oil spills in the ocean. Individual units in the system communicate through GPS and WiFi to position themselves according to the aggregation behavior [3].

Using electro-permanent magnet as a locking mechanism has been employed in M-blocks, a product developed by researchers at MIT. By activating and deactivating electro-permanent magnets in certain patterns, cubes interlock and reconfigure into a collective structure [4]. In addition, the interlocking of robotic modules employs position sensors to bring modules into proximity of each other, before activating electro-permanent magnets. *Won et al.* shows, signal strength is mathematically related to distance and angle between emitter and receiver of a pair of position sensors [5]. At a fixed distance, robotic modules can be aligned based on signal strength.

For stability control, the Euler-Newton equation applies to all models regardless of their geometries or number of rotors. The mathematical model is a set of equations that can determine the response of the motors to given reference commands and disturbances [6].

Open-source flight controller software solutions are available as well for software integration. The PX4 Professional Autopilot SDK and flight controller firmware allow full software extensibility and integration with swarm management systems such as UgCS [7]. Additionally, the PX4 SDK allows for the full customization of mounted sensory either through a PX4 compatible controller or from a PX4 Pro Controller distributed directly through the Dronecode Project which maintains the PX4 software suite.

2. Project Description and Goals

The main goal of this project is to design a drone system enabled with a docking mechanism that allows two or more drones to dock in mid-flight and operate as one unit. Docking will be achieved using switchable electro-permanent magnets. The magnetic interlock mechanism will be designed by the team and installed on an outer shell onto the drones comprising the system. The design of the interlock mechanism will include an isolated power source from the drone's main power source. The drone system will be comprised of a complex control system to manage flight stability, path planning and flight execution.

The final product would be excellent for search and inspection applications. The ability to dock more than two drones together allows the system to maximize efficiency in rotor operation for a larger drone structure. This modularity allows the optimal utilization of current resources to diversify the capabilities of user. It also offers much more flexibility and optimization. Assuming that the design is adaptable to any drone, the target price for a kit of three drones is $1600.

The final output for the project will feature the following:

- The ability to fly with great stability to accomplish an assigned task in three different modes:
    - Autonomously

        - Each of the drones comprising the system can fly as one individual unit
    - As one docked unit
        - Magnetic interlock is activated, the drones in the system are docked together and operate as a single unit
    - As a swarm
        - The drones comprising the system are on standby for a docking command from ground. They are not physically attached, but their behavior and flight control is influenced by the other drones in the swarm
- Midflight autonomous alignment and docking
    - Each of the drones comprising the system has active and passive sites on its outer shell. An active site on a drone locks with a passive site on another drone. These sites are defined as the following
        - Active Sites: locations where a controllable electro-permanent magnet is installed
        - Passive Sites: locations where a soft magnetic material is installed
    - Magnetic interlock maintains its holding force without actively consuming power during docked flight
    - Alignment is achieved by the utilization of the ultrasonic sensors, optical sensors and GPS
- Wireless communication and Network
    - The drones comprising the system are connected to a local area wireless network
    - Drone-to-drone communication is utilized significantly during alignment before docking
    - Drone-to-ground communication is maintained at all times

3. Technical Specifications

The specifications of the system are separated into two parts, hardware and software. Table 1 shows hardware specifications, and Table 2 shows software specifications. A position sensor will detect the range and directivity to determine available docking area. Alignment sensor sensitivity, orientation precision, and position precision ensures docking accuracy. The minimum electro-permanent magnetic force sets the physical limits for the added docking apparatus. Communication ranges determine the system coverage area. The stability correction rate sets threshold for operating conditions under outside influences such as wind. Communications latency and bit rate ensure timely exchange of information and the amount of command input determines user friendliness.

Table 1. Hardware Technical Specifications

Hardware Feature	**Specification**
Position Sensor Detection Range	> 10m
Position Sensor Directivity	> 40º
Alignment Sensor Sensitivity	< 1cm
Minimum Re-polarization Magnetic Field	> 50kA/m
Drone-to-Drone Communication Sensor Distance	> 20m
Drone-to-Ground Communication Sensor Distance	~100m
Power Supply	< 5V
Flight Duration	> 5 minutes

Table 2. Software Technical Specifications

Software Feature	**Specification**
Amount of Command Input	< 12
Bit Rate	125 kbs/s
Communication Latency	< 250ms
Orientation precision	±5º
Position Precision	±5cm
Stability Correction Rate	> 100Hz

4. Design Approach and Details

4.1 Design Approach

Based on the multi-UAV system *Yanmaz et al.* designed [8], the SkyIsland system will consist of four main design blocks and will be supplemented with a software interface. Path planning and task distribution occur in the *Coordination* block. The *Sensing* block is responsible for analyzing all the data of the environment gathered by the sensors implemented. The *Communications & Networking* block enables the circulation of information among devices in the. The *Swarm platform* contains drones, hardware and software for high-level and low-level controls and onboard processors, as well as the electromagnetic interlock mechanism which will allow drones to lock together in mid-air. The *Application* denotes the goal of the swarm system.

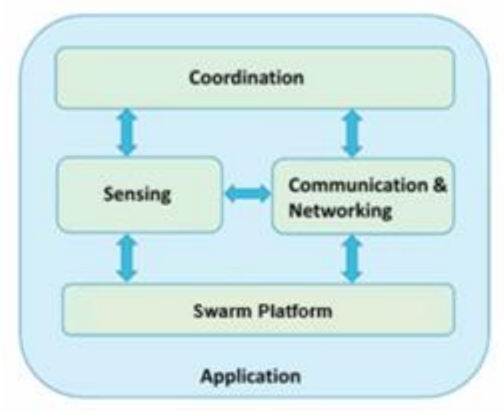


Figure 1. High level swarm design blocks [1].

4.1.1 System Overview

The system consists of three quadrotors with a custom outer shell attached to each drone. Drone-to-drone and drone-to-ground communication systems will be implemented to ensure data and command transmission in the system. Each drone has one active site comprised of electro-permanent magnets, and three passive sites made of soft magnetic material. Each drone carries power electronics to regulate the magnet polarity on its active site.

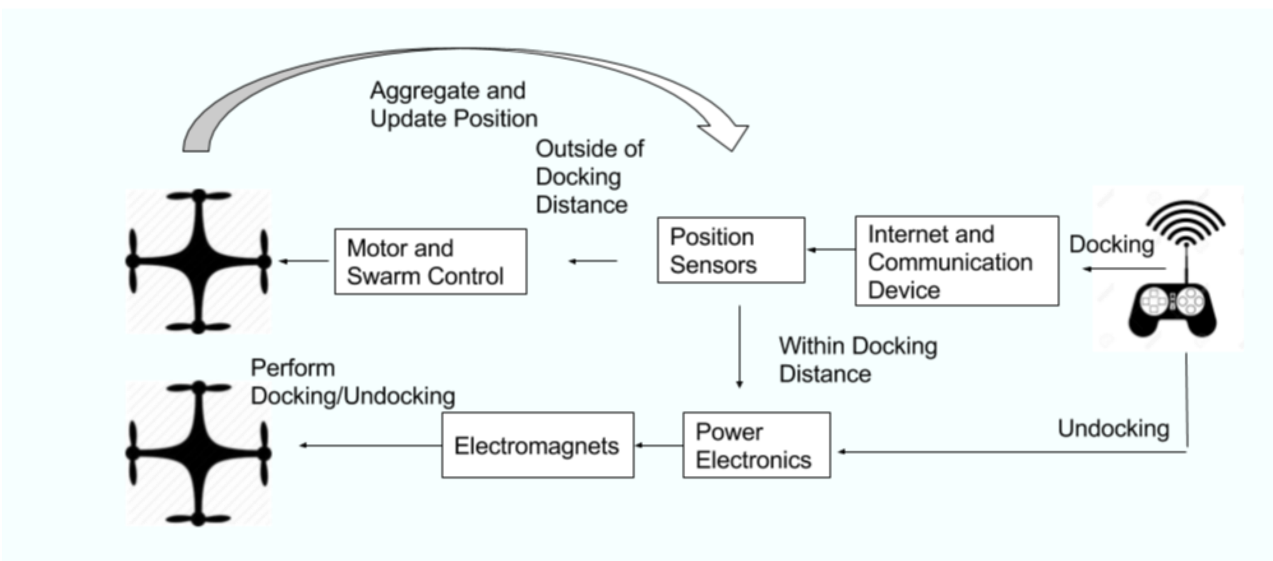


Figure 2. Comprehensive diagram of design block.

Figure 2 shows a comprehensive block diagram of the SkyIsland system. The ground station (i.e. remote controller), sends out a projected path to drones, a command to invoke the “Swarm” mode and a command to initiate docking process or alternatively undocking process via drone-to-ground communication. When a docking command is transmitted, the “Docking” state in the probabilistic finite state machine in swarm mode will be invoked, a magnet on the active site of one of the drones is repolarized exerting a force of attraction on the soft magnetic material on a passive site of another drone and the drones lock together. When an undocking command is transmitted, the polarity of the magnet on the active site of the drone is reversed, the magnet no longer attracts the soft magnetic material on the passive site of the other drone, and the two drones are not locked anymore.

4.1.2 Coordination

Path planning with obstacle avoidance will be established on the ground station and then will be transmitted to the target drone via drone-to-ground communication. There are two envisioned path planning models; one for drones behaving independently from each other (no swarm behavior) and one for the docked drone structure. In the case of independent drones, path planning model with obstacle avoidance will be transmitted to each drone separately. When all the drones are docked mid-air, the ground station will re-assess the path for the structure to follow and convey it to the head drone. On the head drone, the implemented control systems will enable rotors on docked drones to rotate accordingly.

In case drones stray off the projected path due to an unexpected obstacle, drones will reposition themselves to their last location on the path prior to the obstacle.

To maintain spatial organization in the swarm, aggregation behavior will be used. A probabilistic finite state machine (PFSM) with two main states, “Go” and “Wait” will be implemented to ensure relative positioning and spatial organization in the swarm. The “Go” state will have two sub-states; “Approach”, to move closer to other drones in the swarm, and “Pull Back”, to move further away from other drones. When the proximity conditions for docking are met, the “Wait” state will be invoked, and during this state, the docking procedure will be initiated after a small amount of waiting to dock in a specific pattern provided by the ground station. The transition between states will be based on data disseminated via drone-to-drone communication and drone-to-ground communication and will have a stochastic component to account for random aggregation dynamic [9]. PFSM will be initiated only if the drones are in “Swarm” mode, which will be activated by the ground station.

4.1.3 Sensing

This project utilizes Infrared sensor and Infrared LED for drone alignment. Figure 2 shows the working mechanism. The relationship between signal strength (S), distance (L), and angle (θ) between IR emitter and receiver is shown in [5, eq. (1)], where the gain (a) and offset (β) are specific to the IR emitter and receiver.

$$S(L,\theta) = a \cdot \frac{cos(\theta)}{L_2} + \beta \ (1)$$

$$\theta = \theta_e + \theta_r \ (2)$$

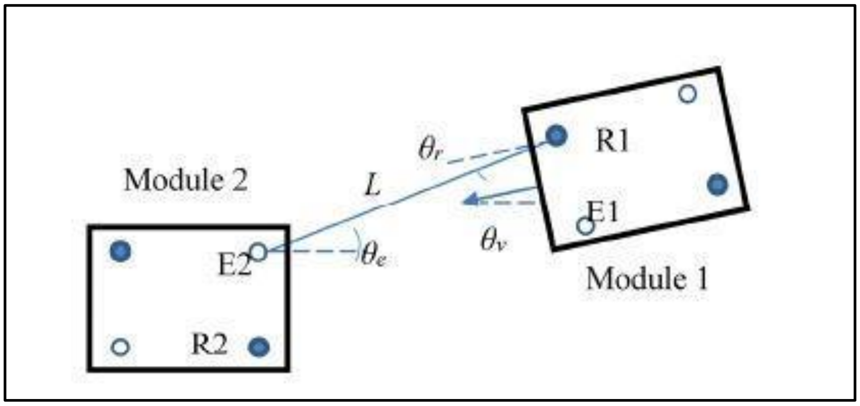
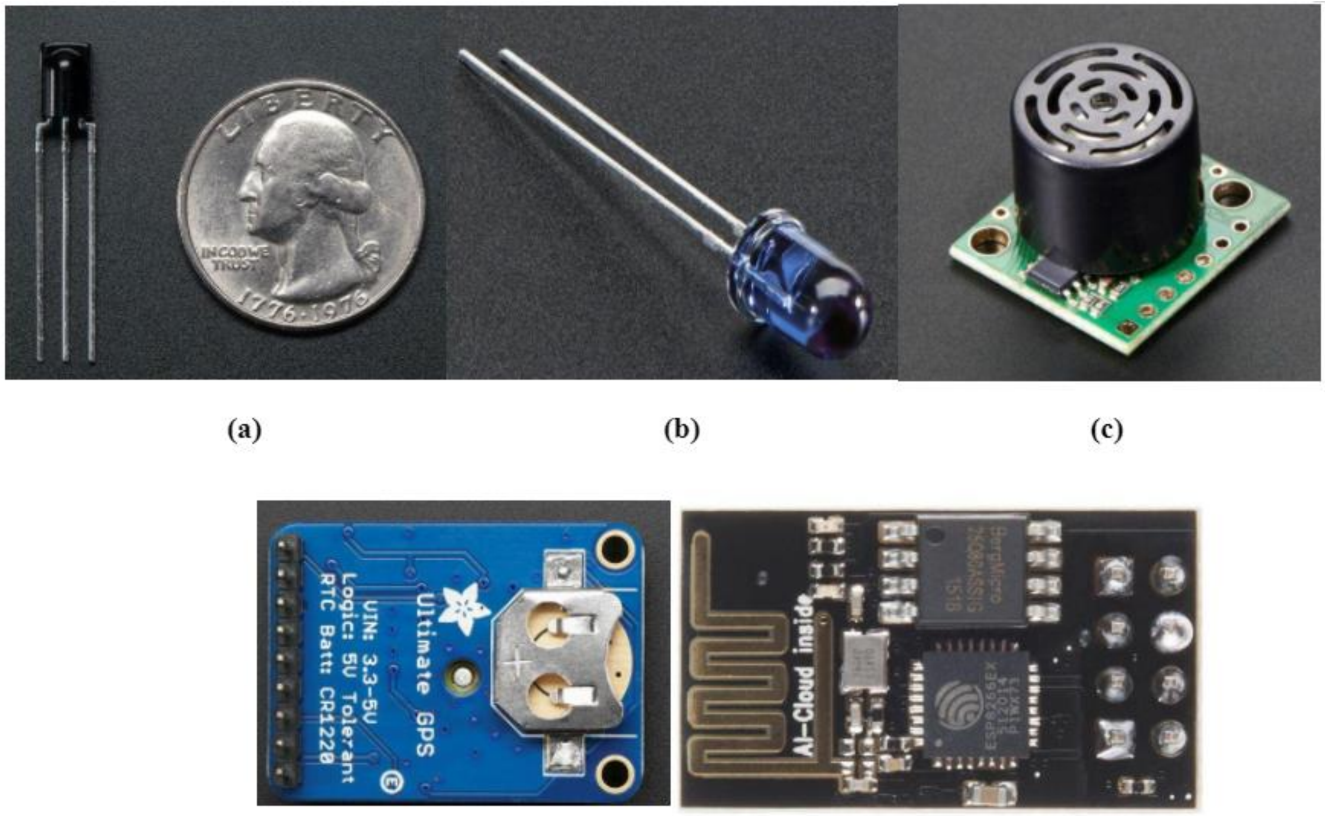


Figure 3. Schematic of two robotics modules, distances between IR sensors, and emitter and receiver angles. R1 and R2 represent receivers and E1 and E2 represent emitters [5].

Signal strength decreases quadratically with distance, and it is the strongest when the emitter and receiver line up. The IR receiver model is TSOP38238 and requires a 5V input, with its wavelength sensitivity ranging from 800nm to 1100nm with peak response at 940nm. The frequency range of the sensor is 35KHz to 41KHz with peak detection at 38KHz. The typical transmission distance is 45 meters, and typical directivity is 45° [10]. The IR LED model is IR333-A. Its peak wavelength is at 940nm, with a 20° beam width [11].

The Ultrasonic sensor LV-EZ1 Maxbotix Ultrasonic Rangefinder will be implemented for drone alignment. Its required input power ranges from 2.5V to 5.5V. The sensor can detect objects at a distance ranging from 0 to 6.54 meters, and provide sonar range information from ranging 0.1524 to 6.54 meters with a 0.0254-meter resolution [12]. This project will use Ultimate GPS Version 3 for positioning. The power supply for this GPS is 5V, sensitivity is -165 dBm, and update frequency is 10 Hz [13]. Figure 4 depicts the sensing components.



(a) (b) (c)

(d) (e)

Figure 4. Sensor modules proposed for use in SkyIsland. (a) IR receiver TSOP38238 [10] (b) IR LED IR333-A [11] (c) ultrasonic sensor LV-EZ1 Maxbotix Ultrasonic Rangefinder [12] (d) GPS module [13] and (e) WiFi module [16].

3.1.1 Communication and Networking

3.1.1.1 Drone-to-Drone Communication

Decentralized drone-to-drone communications could be achieved via Bluetooth, wireless LAN or infrared [14]. Since infrared is directional, it will prove inefficient when drones are within line of sight of each other. Bluetooth is a more preferably method of drone-to-drone communication especially in areas with scarce WiFi hotspots etc. and its low power consumption constricts the power source of the drones significantly less for long-term use. On the other hand, wireless LAN has a range of approximately 300 feet outdoors in comparison to a range of approximately 95 feet Bluetooth has and a significantly higher bit rate of 600Mbps, which makes it more suitable for drone-to-drone communications in larger areas, where drones might be farther away from each other [15]. Based on the disadvantages of Bluetooth, a wireless LAN will be utilized for drone-to-drone communication. Depending on our communication choice, a WiFi module will be used to connect the drones to the Internet via an IEEE 802.11b wireless network.

Each drone in the swarm will be assigned a unique ID to distinguish communication routes. To simplify the drone-to-drone communication, transmission data will include only ID, position of the transmitting drone and maybe a simple command or status phrase. Conveyed data will be used by each drone for spatial positioning and path planning purposes in the swarm.

For drone-to-drone communication, the ESP8266 WiFi module will be utilized. Wake up and transmit packets exchange within 2ms. Standby power consumption is less than 1.0mW and TCP/IP is integrated into the protocol stack [16].

4.1.3.1 Drone-to-Ground Communication

Drone-to-ground communications will require a different RF system to ensure reliable and high-bandwidth information exchange. One system in consideration is the proprietary DJI Lightbridge technology which employs a custom 2.4 GHz radio to give a maximum transmission distance of 3 km of HD video and telemetry transmission given no obstructions and interference [17]. Furthermore, the swarm can be designed to work in conjunction to transmit from drone to drone to ground station to further increase the transmission distance of the entire system where the drone with the best signal strength will handle telemetry transmission of the entire swarm to the ground station.

4.1.4 Swarm Platform

4.1.4.1 Drone Choice and Shell

For the SkyIsland prototype, three modified Crazepony MINI drones will comprise the three-drone kit. Crazepony MINI, as shown in Figure 5, is an open-source and ultra-compact quadcopter development kit with a publicly developed and maintained Git repository. The drone comes with its own RC controller as well as Bluetooth 4.0 LE connectivity for wireless connections with smartphones and tablets. Each unit only costs $90 [18]. The drones are ready to fly out of the box without prerequisite assembly or configuration. Alternative choices such as the DJI F450 Naza-M Kit and the LHI 220 Quadcopter Kit were ruled out due to their high per unit pricing (>$200) for a complete and flight ready aircraft, and lack of RF transmitters/receivers which alone would cost over $60 per pair to support SkyIsland's advanced functionalities.

Figure 5. a Crazepony MINI drone unit.

The physical design of this project heavily relies on the shell that the drones must have to be able to dock. This shell must host the magnets, sensors and electronics needed for the docking. The use of this shell resembles the use of a collision shield. The shell is added to a specific compatible drone to allow mid-air docking, and can be later removed. The criteria that most influence the design are the total weight, mechanical strength and mechanical docking aids.

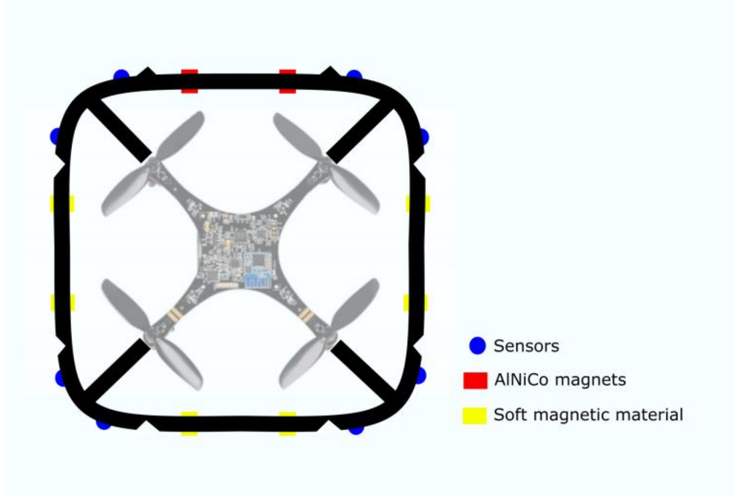


Figure 6. Proposed design of the shell.

4.1.4.2 Magnetic Interlock Mechanism

The interlock mechanism is an electromechanical system employed in the docking process of the SkyIsland's drones. The interlock mechanism uses the holding force of an electro-permanent magnet system. An electro-permanent magnet is a magnet that can be repolarized with a strong current impulse.

To build the magnetic drone interlock, two AlNiCo magnet rods will be held next to one another inside of a housing. The housing will be made of a soft magnetic material such as iron and will simply comprise of two plates sandwiching the AlNiCo magnets as shown in Figure 7. One of the magnets has a coil of copper wire wrapped around it forming a solenoid. This magnet structure forms the active site on a drone. A short pulse of current is passed through the coil creating a magnetic field that can repolarizes the AlNiCo magnet enclosed by the coil.

Once repolarized, the magnet maintains its altered magnetic field properties without the need for a power source. When the coiled magnet is polarized in the same way as the uncoiled magnet, magnetic flux from both magnets adds together and flows through the soft magnets of the housing and through air around the magnets. However, when a plate of soft magnet is present in the vicinity as shown in the "ON" state of Figure 7, the magnetic flux will flow through the closed soft magnet structure and a magnetic lock is achieved. This third soft magnet plate is what forms the passive site on a drone. When magnetic interlock is achieved two drones are said to be docked. However, when the two AlNiCo magnets are polarized differently, the magnetic flux is contained within the two magnets and the soft magnet on the passive site of another drone will not be attracted. In that case, a magnetic lock is not achieved and the two drones are said to have undocked.

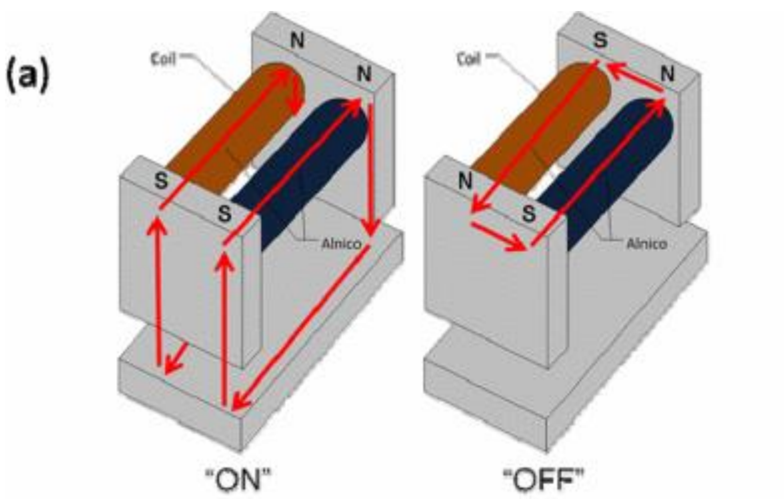


Figure 7. Electro-permanent magnet housing showing the two states of the system obtained by different magnetic flux flows [19].

A major part of the magnetic interlock mechanism is designing a circuit that controls the direction of current flow in the coil surrounding one of the AlNiCo magnets which allows the repolarization of the magnet. One way to control the current direction is by the use of 4 n-MOSFETs to direct the current in two directions through the same coil as shown in Figure 8. Transistors Q1 and Q3 are controlled with the same pin on the microcontroller while transistors Q2 and Q4 are controlled with another pin on the microcontroller. To repolarize the coiled AlNiCo magnet, the generated magnetic field must be greater than the intrinsic coercivity of the magnet. The intrinsic coercivity for a 1" cylindrical A5 AlNiCo magnet manufactured by Littlefuse is reported to be 640 Oe [20]. The current required to overcome the intrinsic coercivity is listed in Table D1 in Appendix D for different wire gauges along with the resistance for the required length of wire. The In addition, the power dissipated by the coil wire is also calculated. The equations used to create the table along with relevant constants are also listed in Appendix D. The table will be used during wire gauge testing and optimization depending on the available copper wires and maximum current tolerated by the overall system. If the voltage drop needed to create the repolarization field is unattainable, a DC-DC converter will be used to step up or step down the voltage to required level.

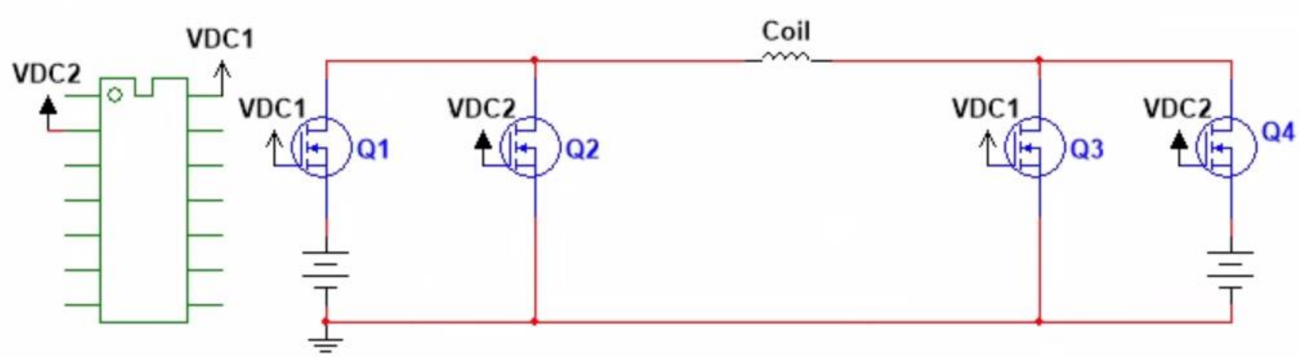


Figure 8. Proposed circuit to control the direction of flow of the repolarization current impulse in the magnet coil.

4.1.4.3 Control

The control system of this project is based on a 12-dimension state-space model. The goal is to control drone position with three Cartesian coordinates (x, y, z), orientation with three angular coordinates (α, β, γ), and all their derivatives. These variables are arranged in a vector called "state", the change in state is calculated with current state and actuator inputs as in (3). Matrix A and matrix B are the coefficients for current state and actuator inputs.

$$\begin{pmatrix} \dot{\vec{x}} \\ \dot{\vec{\alpha}} \\ \ddot{\vec{x}} \\ \ddot{\vec{\alpha}} \end{pmatrix} = A \begin{pmatrix} \vec{x} \\ \vec{\alpha} \\ \dot{\vec{x}} \\ \dot{\vec{\alpha}} \end{pmatrix} + B \begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{pmatrix} \tag{3}$$

Matrices A and B are calculated according to physical model of the system and Euler-Newton equations [21]. Matrices B in generic dynamic system is modeled by (4). There are three axes, denoted by α, β, and γ. Force (F) and momentum around each axis ($M_\alpha, M_\beta, M_\gamma$) are the products of B and actuator inputs. The four by four matrix in (4) is B, composed of force coefficient (k_F), torque coefficient (k_m), and distance between the nth motor and the axis (L). These physical properties are unique to the drone model. In (5), additional physical properties and results from (4) are incorporated to derive matrix A. Inertia matrix around the center of rotation is represented as Icr, mass is denoted as m, identity matrix is I, and n is the number of motors for each drone. In this project, each drone has four motors.

$$\begin{pmatrix} F \\ M_\alpha \\ M_\beta \\ M_\gamma \end{pmatrix} = \begin{pmatrix} k_F & k_F & \dots & k_F \\ L_{1,\alpha} \cdot k_F & L_{2,\alpha} \cdot k_F & \dots & L_{n,\alpha} \cdot k_F \\ L_{1,\beta} \cdot k_F & L_{2,\beta} \cdot k_F & \dots & L_{n,\beta} \cdot k_F \\ L_{1,\gamma} \cdot k_m & L_{2,\gamma} \cdot k_m & \dots & L_{n,\gamma} \cdot k_m \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{pmatrix} \tag{4}$$

$$\begin{pmatrix} \ddot{\vec{x}} \\ \ddot{\vec{\alpha}} \end{pmatrix} = \begin{pmatrix} mI_3 & 0 \\ 0 & I_{cr} \end{pmatrix}^{-1} \left(\begin{pmatrix} \vec{F} \\ \vec{M} \end{pmatrix} + \begin{pmatrix} \vec{F}_{mag} \\ \vec{M}_{mag} \end{pmatrix} - \begin{pmatrix} 0 \\ \dot{\vec{\alpha}} \times I_{cr} \dot{\vec{\alpha}} \end{pmatrix} \right) \quad (5)$$

The complete control system is shown in Figure 9. Inputs to the system are position and yaw reference values (r_x, r_y, r_z, r_γ), and the references come from a desired location. Outer controller takes in position reference values, and reads in the drone's current positions and speed. The outputs of outer controller are reference values for roll, pitch, and vertical velocity ($r\alpha$, $r\beta$, $\dot{r_z}$). The inner controller takes those values and the yaw reference, and calculates the input (u) to each motor. With A, B, and actuator inputs, a complete control cycle is established.

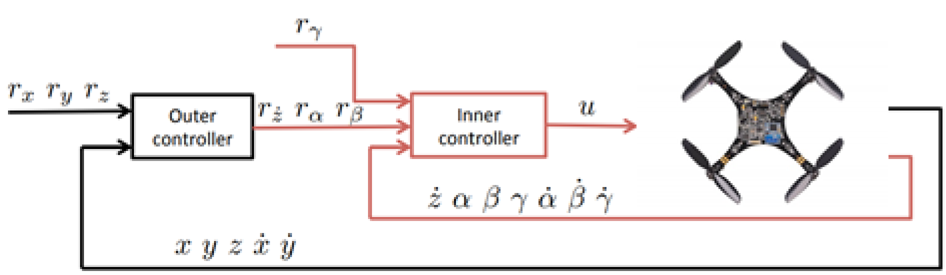


Figure 9. Cascaded controller diagram.

4.1.4.4 Human Machine Interface

The human machine interface (HMI) of the SkyIsland system will utilize a simple RC controller with a basic LCD display showing essential telemetry coupled with the smartphone or tablet device to display the first-person-view (FPV) feed and other more advanced features. Using a touch display readily available in a smartphone or tablet will allow for maximum flexibility and update serviceability in the graphical user interface (GUI) while the analog joysticks on the RC controller coupled with the smartphone or tablet device will provide the system operator with the proper ergonomics and fine-tune control for manual and semi-autonomous flight. Figured below is one such example of proposed HMI built by DJI.

Figure 10. DJI Mavic Pro remote controller coupled with an iPhone providing the drone FPV feed and advanced functionality.

4.2 <u>Codes and Standards</u>

1. The Inter-integrated Circuit (I^2C) Protocol will be employed to allow multiple digital integrated circuits/chips to communicate with one or more master chips.
2. Bluetooth protocol will be used for short-range, low-power, low-cost, wireless transmissions between electronic devices.
3. GPS protocol will be adopted for relative positioning.
4. TCP/IP, UDP and DJI Lightbridge protocols will be used for communication purposes.
5. UAS NOTAM FDC7/7282 defines a restricted airspace for flight, and is utilized to determine drones of choice.
6. IEEE 802.11b will be used to provide Internet access to each drone and enable drones to disseminate information among themselves.

4.3 Constraints, Alternatives, and Tradeoffs

Options for drone-to-drone communication are WiFi and Bluetooth networks. A WiFi network provides a greater range of 300 feet outdoors in comparison to a Bluetooth range of approximately 95 feet indoors. In addition, WiFi has a greater bit-rate than Bluetooth. A Bluetooth system is best suitable for close-range applications and has lower power consumption compared to WiFi. A disadvantage of Bluetooth over WiFi is that Bluetooth is more susceptible to interference, causing it to be less efficient outdoors.

Drone-to-ground communications require expensive and high powered RF systems for the aircrafts to maintain connectivity in ranges above 1 km. For the prototyping and demonstration phase of the project, a cheap short-range solution will be adopted with the Crazepony MINI's Bluetooth LE serial interface and 2.4 GHz low-power radio working in conjunction for basic flight controls and flight telemetry collection. These two solutions are low-cost and are already integrated with the Crazepony MINI as shipped from the manufacturer, but could only support an operating range of up to 100 meters.

The choice for magnetic interlock was driven by how power consumption could be minimized. Electromagnets are widely used and are readily available but they require constant current supply during operation. An electro-permanent magnet, however, only requires a high current impulse to flip its polarity and then it maintains its new state which is more effective in terms of power consumption.

5. Schedule, Tasks and Milestones

Appendix A, lists all tasks and major milestones, team member(s) assigned to each specific task, and risk levels of these tasks. Appendix B contains a comprehensive Gantt chart presenting the timeline of the project. In Appendix C, a comprehensive PERT chart is presented to outline the critical paths and risks associated with each task.

6. Project Demonstration

A demonstration of full project functionality will include swarm flight, docking procedures, a docked flight and undocking procedures, all in one exercise. To demonstrate the search and rescue abilities of the system, a small object will be located and retrieved during the exercise.

Prior to final project demonstration, two tests are required, an on-ground docking test to prove the design and implementation of the docking mechanism, electronics and sensors along with a simulated flight on MATLAB to validate the software and the control system.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

There are currently no competing products in the market today which would mirror the aerial docking capabilities of the SkyIsland platform. However, there are two rising commercial autonomous drone platforms which can compete against the swarm capabilities of SkyIsland. However, these competitors lack the flexibility, modularity, and on-mission reconfigurability that SkyIsland provides [22, 23]. Current competing systems only provide swarm/fleet management and autonomous docking with a charging dock at the ground station [22, 23]. For search and rescue as well as aerial reconnaissance applications, SkyIsland offers unparalleled flexibility for operators to execute flight missions as efficiently as possible.

7.2 Cost Analysis

The team consists of five engineers working at an hourly rate of $45.00 part-time. Assuming a 6 hour weekly individual workload, the weekly personnel operating cost for the project comes out to be $1350.00 spanning over a period of 12 weeks for a total personnel cost of $16200.00 to develop the product. The drones can be reasonably acquired for $200.00 per unit, upgrading from the $90.00 unit cost of the prototype drones. The improved drones should comprise of a more power RF transmission and receiver system as well as an upgraded FPV gimbal camera system. The SkyIsland system will be sold in kits of three individual drones which would put the material costs at $600.00 per kit. The cost of software development for the system is folded into the personnel cost as open-source toolsets will be utilized. In order to achieve reasonable market penetration, the SkyIsland kit will be priced at $1600.00 at launch. A total of 16 units of the kit will need to be sold in order recuperate the costs of R&D and materials.

Table 3. Project labor breakdown and associated costs

Labor Type	**Salary (USD/Hr)**	**Weekly Hours**	**Total Cost (USD)**
Individual Work	$45 / Hour	4 Hours	$180.00
Group Work	$45 / Hour	2 Hours	$90.00
Total Work / Member	$45 / Hour	6 Hours	$270.00
Total Project Labor	$225 / Hour	6 Hours	$1350.00

Table 4 Individual SkyIsland kit component costs

Part Description	Quantity	Unit Price (USD)	Total Cost (USD)
Crazepony MINI	3	$90.00	$270.00
IR receiver TSOP38238	3	$1.95	$5.85
IR LED IR333-A	3	$0.40	$1.20
Wifi Module ESP8266	3	$6.95	$20.85
Ultimate GPS Version 3	3	$39.95	$119.85
AlNiCo Magnets	12	$2.63	$31.56
Drone RF System Upgrades	3	$50.23	$150.69

Table 5. Projected total development costs.

Project Component	Cost (USD)
Labor	$16200.00
Prototype Materials & Parts	$600.00
Total	**$16800.00**

8. Current Status

Individual research (on drone, sensor parts, magnets, and power electronics) and project proposal have been 100% completed and on time. The next step on the timeline is to make a presentation on our project proposal to our faculty advisor Dr. Hasler and order parts. The team already contacted Dr. Hasler to set up a date and time for proposal presentation.

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Appendix A: Task Distribution

Task Name	Task Lead[1]	Risk Level
Planning, Documentation and Presentations	All	Low
Research on drones	All	Low
Research on sensor parts	All	Low
Research on magnets	All	Low
Project Proposal	All	Low
Proposal Presentation (for parts)	All	Low
Ordering parts	All	Low
Final Project Presentation	All	Low
Final Project Demonstration	All	Medium
Final Project Report	All	Low
Docking Mechanism Design	All	Medium
Building magnet interlock	LA	Low
Power electronics and circuit design	LA	Medium
Sensor-based alignment design	JL, AIV	Medium
Ground Testing	All	Medium
Prototyping	AIV, AE, JL,LA	Low
Shell Assembly	AIV	Low
Sensor Implementation	JL, AIV, AE	Low
Power electronics implementation	LA	Medium
Control Design and Implementation	AIV, AE, JL,LZ	Medium
Stability Control	AIV	Medium
Drone-to-Drone Communication	AE, LZ	Low
Swarm Control	AE	Low
Path Planning	AIV, AE	Medium
Docking Control	AIV, JL	High
Simulation Testing before implementation	All	Medium
Software Integration	LZ, AIV, AE	Low
Communication Protocol	LZ, AE	Low
Human Machine Interface (HMI)	LZ	Low
Controls	LZ, AIV, AE	Low
Testing and Optimization	All	High
Indoor Testing	All	Medium
Field Testing	All	High

1

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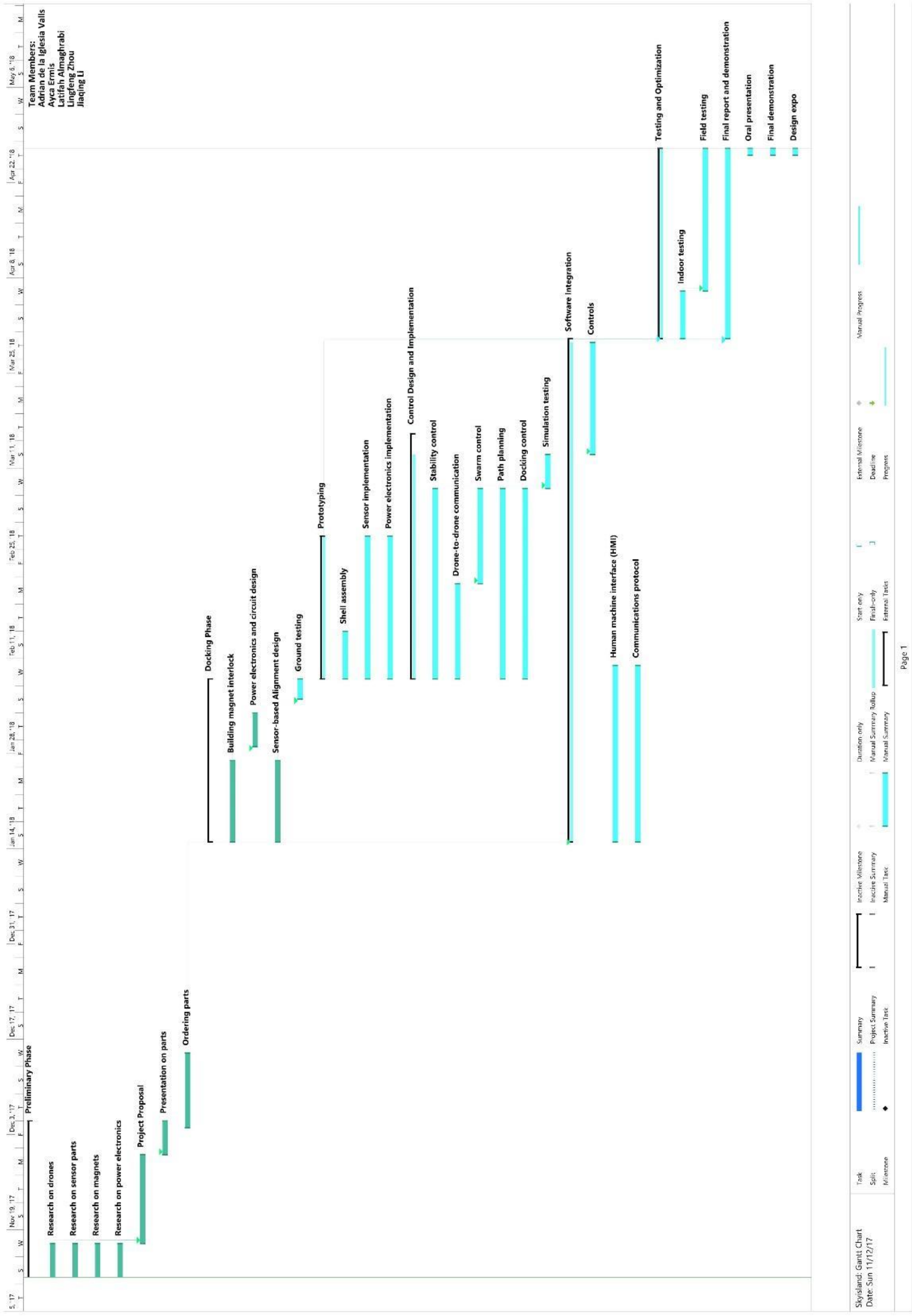
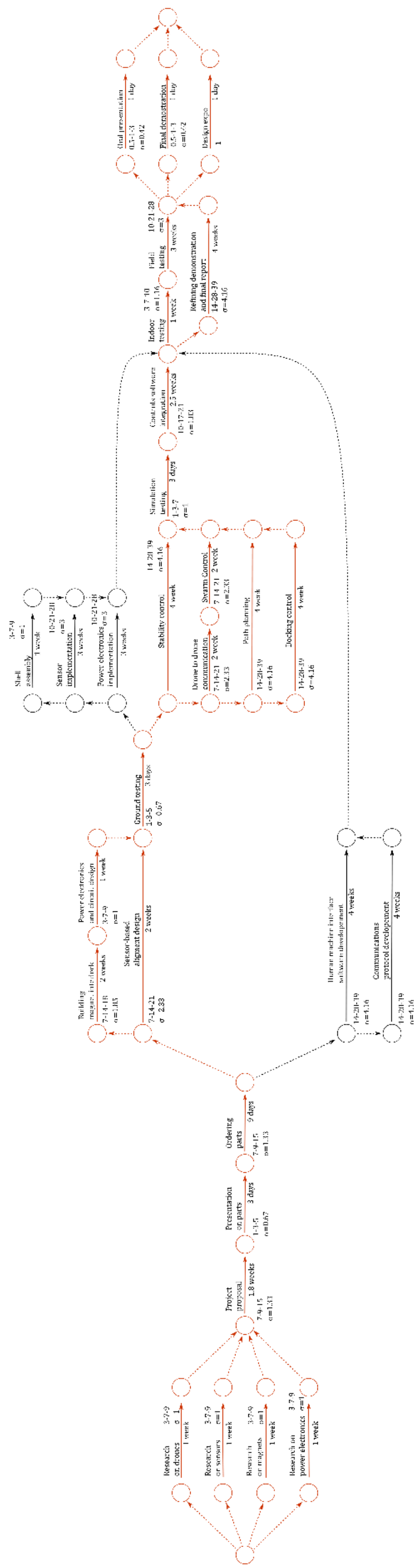
Appendix B: Comprehensive Gantt Chart



Appendix C: Comprehensive PERT Chart



Appendix D: Coil Calculations

Given:

1- Intrinsic Coercivity of AlNiCo = H_{ci}= 152788A/m

2- AlNiCo Cylindrical Magnet Geometry Dimensions:

   a. Height =h= 25.4mm

   b. Diameter = D1 = 4.7625mm

3- Diameter of different Gauges of wire = d_{wire}

Calculations Specifications:

- The current generated magnetic field must be at least three times the intrinsic coercivity to account for fringing field at the top and bottom of the coil

The following Equations were used to calculate the current required to overcome the intrinsic coercivity of AlNiCo:

$$D_{coil} = d_{wire} + D_1 \text{ (D-1)}$$

$$N \cdot I = \frac{H_{ci} \cdot (D_{coil} - D_1)}{\ln\left(\frac{D_{coil} + \sqrt{D_{coil}^2 + h^2}}{D_1 + \sqrt{D_1^2 + h^2}}\right)} \text{ (D-2)}$$

$$I = \frac{h \cdot (D_{coil} - D_1)}{2 * d_{wire}} \text{ (D-3)}$$

- N: the number of turns
- I: repolarization current

Table D-1 shows the current and power dissipation for AWG ranging from 20 to 39. The rows in red are discarded because the heat might melt the wire.

Table D1. Current required for repolarization of 25.4mm long AlNiCo cylindrical magnet a coil different wire gauges and the power dissipated by the coil for the calculated current

d_{wire} (mm)	R (mΩ/m)	I_{Fusing}, 32ms pulse (A)	D_{coil} (mm)	N I (turns A)	N (turns)	I (A)	L_{wire} (mm)	R (Ω)	P_{wire} (W)
0.8128	33.31	882	6.388	3974	31.25	127.2	1095	0.0365	589.6
0.7238	42	700	6.210	3971	35.09	113.2	1210	0.0508	650.5
0.6446	52.96	551	6.052	3968	39.41	100.7	1339	0.0709	719.0
0.5740	66.79	440	5.911	3966	44.25	89.62	1484	0.0991	796.0
0.5112	84.22	348	5.785	3964	49.69	79.77	1646	0.1387	882.4
0.4552	106.2	276	5.673	3962	55.80	71.01	1829	0.1943	979.5
0.4054	133.9	218	5.573	3960	62.66	63.21	2035	0.2724	1088
0.3610	168.9	174	5.485	3959	70.36	56.27	2265	0.3826	1211
0.3215	212.9	137	5.405	3958	79.01	50.09	2524	0.5373	1348
0.2863	268.5	110	5.335	3957	88.72	44.60	2814	0.7557	1503
0.2549	338.9	86	5.272	3956	99.63	39.71	3141	1.064	1678
0.2270	426.9	69	5.217	3955	111.9	35.35	3507	1.497	1871
0.2022	538.3	54	5.167	3954	125.6	31.48	3919	2.110	2090
0.1800	678.8	43	5.123	3954	141.1	28.03	4381	2.974	2336
0.1603	856	34	5.083	3953	158.4	24.95	4900	4.194	2612
0.1428	1076	27	5.048	3953	177.9	22.22	5483	5.899	2912
0.1272	1361	22	5.017	3952	199.8	19.78	6137	8.353	3269
0.1132	1716	17	4.989	3952	224.3	17.62	6872	11.79	3660
0.1008	2164	14	4.964	3951	251.9	15.69	7697	16.66	4099
0.0898	2729	11	4.942	3951	282.9	13.97	8624	23.53	4592