Optimal Wiring of Hybrid VTOL Drone using Spanning-Tree-Based Architecture

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***Abstract*—This paper addresses the lack of framework in wiring complex UAVs, such as a Hybrid-VTOL UAV. The proposed framework is utilizing graph theory to optimize the wiring layout. The vehicle's electrical system is modeled as a weighted multigraph, seperated into distinct power and signal subgraphs. A custom cost function penalizes wire length, weight, and external routing in each path. By implementing Kruskal's Minimum Spanning Tree algorithm, an optimal, low-cost path is found, resulting in quantitative and safety improvements.**

***Keywords*—Graph, Minimum Spanning Tree, UAV, Wiring Diagram.**

I. Introduction

Unmanned aerial vehicles (UAVs) have been widely utilized in different fields, ranging from humanitarian rescue missions to modern warfare. UAVs come in different shapes, mainly differentiated by its way of flight: fixed-wing UAVs and VTOL (or rotary wing) UAVs. Fixed-wing UAVs are close enough to aeroplanes, it uses control surfaces to move in the cartesian axis, which makes it suitable for long distance flights with high altitude and high cruising speed. On the other hand, VTOL drones uses rotors for its vertical movement. VTOL drones solve the primary challenges of fixed-wing UAVs, VTOL drones do not need a long runway to takeoff and land, it uses its vertical rotors to do so. But since VTOL Drones use multiple rotors, it draws a lot of power from the battery, resulting in lesser flight times. With those two main problems in hand, a suitable solution is a Hybrid-VTOL drone, this type of drone uses both rotors and control surfaces for its movement in the cartesian axis, hence its hybrid name. It uses its rotors (usually four) for its vertical movement and uses one rotor plus control surfaces for its horizontal movement. This means a Hybrid-VTOL drone does not need to have a runway for a flight, making it suitable for harsh environments where it needs to takeoff and land vertically. On the other hand, Hybrid-VTOL drones are also great for long distance flights, since it uses a less power-drawing one rotor and control surfaces.

The primary challenge of a Hybrid VTOL drone is the complexity of its design. Since it uses both rotors and control surfaces, it presents a layer of complex systems that require optimal communication and operation, while maintaining a great placement for its components with factors such as weight, aerodynamic capability, and electromagnetic interference. One of the ways to optimally manage the integral factors mentioned above is through efficient wiring. An efficient wiring path could determine the amount of weight the wire adds to the vehicle, prevent poorly routed wires that disrupts airflow, and reduce the possibility of electronagnetic interference from nearby components.

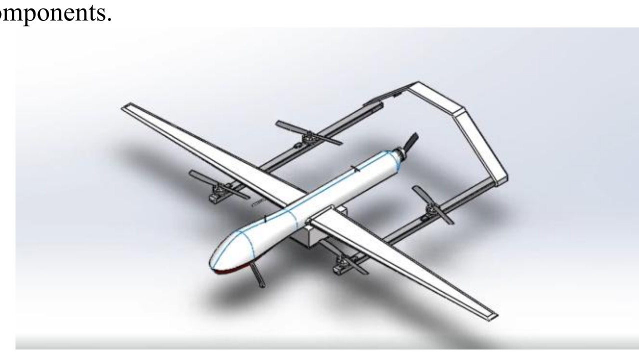

Fig. 1. Hybrid-VTOL Drone

Optimally wiring a drone also presents a new challenge. Since Hybrid-VTOL drones have abundant amount of components, there will be much more wires that are needed to connect one component to another. Usually, one component needs three cables, that is power, ground, and signal, but there are components that needs more than just three, such as components that need UART or RX/TX communication. This proposes a question, can graph theory, such as Minimum Spanning Tree (MST), be utilized in optimally wiring a Hybrid VTOL drone, where cables are abundant and path is a crucial factor?

This paper will further analyze the application of graph theory in wiring a Hybrid VTOL Drone, with the hypothesis that a drone can be wired optimally by diversing a tree into multiple layers of minimum spanning tree, such that each layer presents an optimal path and fulfills the efficiency of weight, aerodynamic capabilities, and electromagnetic interference.

II. THEORETICAL FOUNDATION

2.1 Graph

Graph is a set of vertices (also called nodes) and each of the related pairs of vertices are called an edge. Graphs can be used to represent discrete objects and their relations. Mathematically, graphs can be defined as $G = (V, E)$, V $\{v_1, v_2, \dots, v_n\}$ represents a set of vertices and E $\{e_1, e_2, \dots, e_n\}$ represents a set of edges. There are various types of graphs, such as:

1. Simple and Unsimple Graph (Multigraph)

Simple graphs are graphs that do not contain parallel edges and loops, whereas an unsimple graphs have either parallel edges, loops, or both.

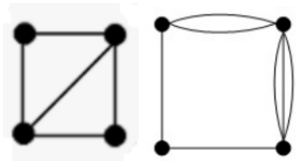

Fig 2. Simple Graph (left) and Unsimple Graph (right).
[Source: https://informatika.stei.itb.ac.id/~rinaldi.munir/Matdis/2024-2025/20-Graf-Bagian1-2024.pdf]

2. Directed and Undirected Graph

Directed graphs are graphs where each edges have a direction, whereas an undirected graph is the opposite.

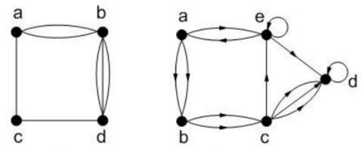

Fig. 3. Undirected Graph (Left) and Directed Graph (Right).
[Source: https://informatika.stei.itb.ac.id/~rinaldi.munir/Matdis/2024-2025/20-Graf-Bagian1-2024.pdf]

3. Weighted and Unweighted Graph

Weighted graphs are graphs where each edges have a weight, whereas an unweighted graph is the opposite.

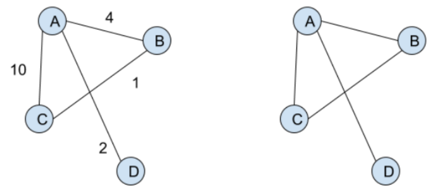

Fig. 4. Weighted Graph (Left) and Unweighted Graph (Right).
[Source: https://informatika.stei.itb.ac.id/~rinaldi.munir/Matdis/2024-2025/20-Graf-Bagian1-2024.pdf]

2.2 Tree

Trees are connected undirected graphs that do not contain circuits, meaning there are no closed loops formed by the edges. For a tree represented with $G = (V, E)$ and *n* amount of vertices, such tree has *n – 1* amount of edges. In the same way with graphs, there are also weighted trees, where each edge is assigned a numerical value.

A subgraph of a graph G that is obtained by only deleting its edges, so that the subgraph of G has the same vertex set as G is called a spanning subgraph (or a spanning tree). Practically, a spanning tree is a subgraph of G that is a tree and includes all the vertices of G.

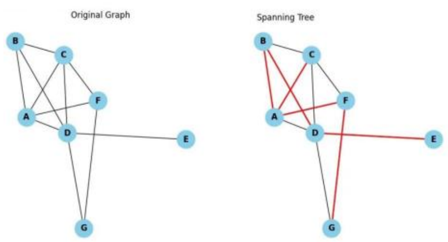

Fig. 5. Spanning Tree from a Graph

2.3 Minimum Spanning Tree

A weighted graph might have more than one spanning tree. Minimum Spanning Tree (MST) is a spanning tree that has the minimum amount of total weight. There are two practical algorithms to find MSTs: the Prim and the Kruskal Algorithm. To construct a minimum spanning tree using the Kruskal algorithm, there are four steps.

1. Create an ascending list of edges based on its weight,
2. Create an empty tree T,
3. Select an edge (u,v) that has the minimum weight that does not create a circuit at T. Add (u,v) to T,
4. Repeat 3rd step $n - 1$ times.

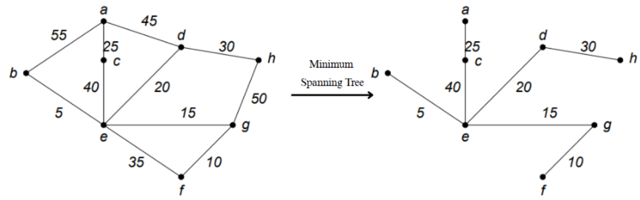

Fig. 6. Minimum Spanning Tree from A Graph

2.4 VTOL Components and Placements

A VTOL vehicle requires at least ten types of components to function safely[4].

1. Flight Controller

The flight controller (FC) functions as the motherboard of the entire system. an FC takes input from various sensors and commands other component, such as the electronic speed controller (ESC), to manage the vehicle's flight path. Due to it connecting to almost all components in the vehicle, it is placed in the middle of the airframe.

2. Battery

The battery provides power to run all the electronic components. Due to its heavy weight, it is usually placed in the middle or close to the center of gravity (CG).

3. Power Distribution Board (PDB)

PDB takes the high current power from the main battery and distributes it to various components that require power, most notably the motors via the electronic speed controller (ESC). It is placed near the battery to ensure safe connections.

4. Universal Battery Eleminator Circuit (UBEC)

The UBEC serves to step down the high voltage from the main battery to a lower, consistent voltage (typically 5V). UBEC is imporant to maintain safe power supply for the FC, GPS, etc. It is also important to place the UBEC near the battery.

5. Motor

The motors are responsible for generating the vertical thrust and the horizontal thrust of the vehicle. Motors are placed farthest from every components, usually creating an X-Frame at the corners of the vehicle. It is important to place the motors in a location that lets it give balanced thrust for a lift.

6. Electronic Speed Controller (ESC)

The ESC acts as a "bridge" between the FC and the motors. It receives signals from the FC and precisely controles the speed of the motors through Pulse Width Modulation (PWM). It is placed near each motors.

7. GPS

The GPS module provides the FC with positioning datas, i.e. attitude and altitude. The GPS receives the data from the satellite, hence it needs to be placed outside of the vehicle.

8. Telemetry

Telemetry systems enable the communication between the vehicle and the ground control station (e.g. Ardupilot Mission Planner). It is located outside the vehicle, very far from the GPS to prevent electromagnetic interference.

9. Servo

Servos are small motors that can rotate to a precise position. In VTOL vehicles, it is used to tilt the control surfaces to change the aircraft's altitude. It is placed exactly where the aircraft's control surfaces are located.

10. Airspeed Sensor

This sensor measures the speed of the aircraft relative to the surrounding air. The measurement is used to stabilize flight and to ensure safe transition from VTOL to horizontal fixed-wing flight.

2.5 Component Communications and Wire Gauge

Each components in a VTOL drone has different ways of communication. Each type of communication represents the type of data that is being transmitted and received. For each type of communication, the type of wire used is also different. American Wire Gauge (AWG) is the standardized way to classify a particular wire. AWG determines the diameter, electrical resistance, and ampacity of a wire. The higher the AWG number, the thinner the wire, vice versa. Here are the types of communication relevant in a Hybrid-VTOL drone with the wire gauges used.

1. *UART (Universal Asynchronous Receiver-Transmitter)* [5]

   UART is a hardware protocol for asynchronous serial communication. Within a drone, UART is a fundamental protocol for exchanging continuous streams of data between the FC and complex peripherals. Typically, UART connection is established with two cables for transmit (TX) and receive (RX) with a 26-30 AWG wire.

2. *I^2C (Inter-Integrated Circuit)*

   I^2C is a synchronous, multi-point serial communication. It allows a single "master" device to communicate with one or more "slave" devices over two-wire, one for SDA and one for SCL. Typically, I^2C uses 28-30 AWG wire.

3. *PWM (Pulse Width Modulation)*

   PWM is a communication tehcnique where the command value is encoded in the duty cycle of a fixed-frequency electrical pulse. A component will send a digital signal (on/off) with a frequency that is used to control analog-like behavior in actuators. Typically, PWM connection is estaablished through a 22-26 AWG wire.

III. PROBLEM DEFINITION AND SOLUTION

3.1. Vehicle Design

The vehicle we will be using in this paper is a Hybrid-VTOL drone. A type of drone that uses both rotary wings and control surfaces. We will use five rotary wings in this vehicle, four of them will be used for vertical takeoff and landing, one of them will be used for horizontal thrust. We will also use five tilt servos for the control surfaces.

The 3D design shown in figure X shows the component and its placements in the vehicle. The placement of the components have two things as considerations. Firstly, the placement of each component based on its weight and CG calculation. Secondly, its ability to create electromagnetic interference with each other, such as the GPS with the telemetry.

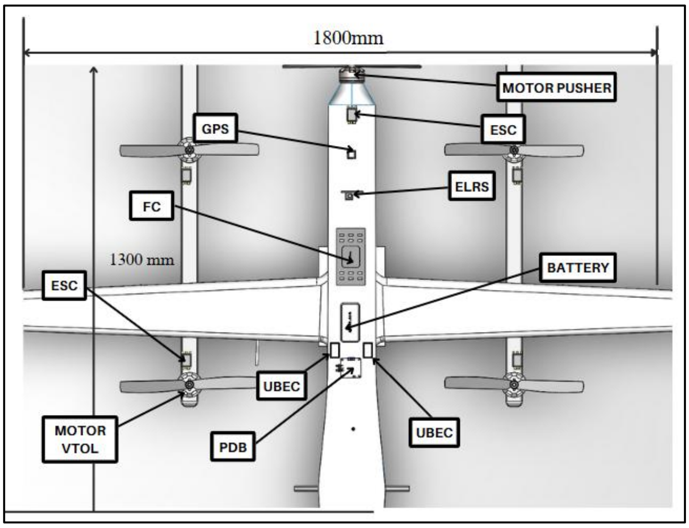

Fig. 7. Top View Design

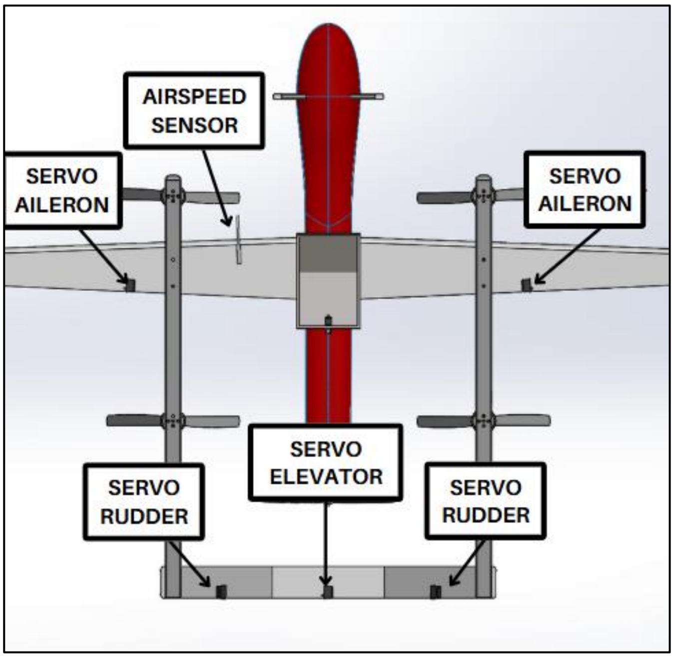

Fig. 8. Bottom View Design

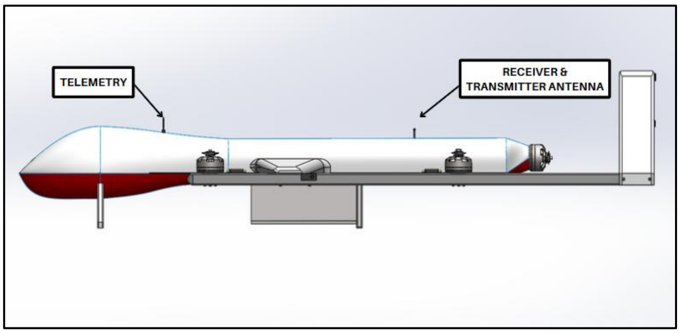

Fig. 9. Side View Design

3.2. Vehicle components

No	Component	Con. Destination	Wire Gauge (AWG)
1	FC	PDB	22
2	ESC	PDB and VTOL Motors	12
3	Battery	PDB	10
4	VTOL Motors	ESC	14
5	Tilt Servo	FC	22
6	PDB	Battery	10
7	UBEC	Battery and FC	16

Table 1. Components and its Power Connections

No	Component	Con. Destination	Com. Protocol	Wire Gauge
1	FC	ESC	PWM	26-28
2	FC	GPS	UART	28-30
3	FC	GPS (Compass)	I^2C	28-30
4	FC	Telemetry	UART	26-28
5	FC	Airspeed Sensor	I^2C	28-30
6	FC	ELRS	PWM	26-28

Table 2. Components and its Signal Connections

3.3. Problem Definition

The process of wiring a Hybrid-VTOL drone is complicated. For an amateur, the process itself is ambiguous with little to no set framework on how to efficiently path the wires in the airframe, especially for the tight spaces connecting the FC to the VTOL motors.

One might instinctively start from the FC, since it is the center of all connections, as how one would wire a computer, and then finish with the wires for power. The problem is, by doing that, the bigger wires (i.e., the power wires) could be stacked on top of the smaller wires (i.e., the signal wires). This could cause problems during flight, such as vibrations, loosened signal wires, and soldered wires to expose, ultimately leading to a short circuit.

The author of this paper proposes a framework one could use to wire a drone. Usually, one would only create a wiring diagram that shows the connection from one component to another, shown in figure X.

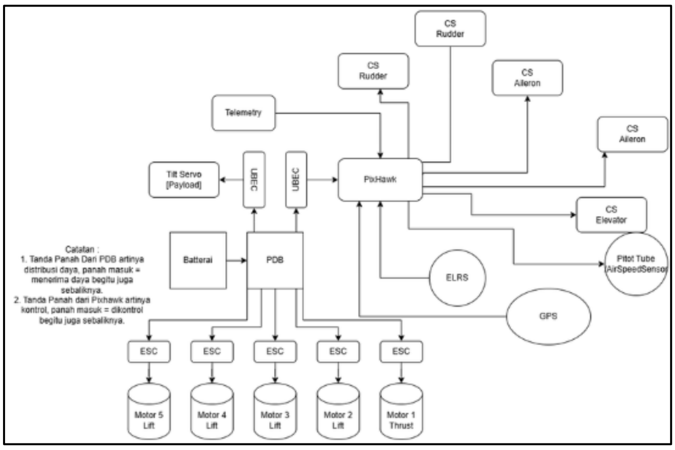

Fig. 10. Basic Wiring Diagram

The problem with the diagram in Fig. 10 is that unless the person in charge of wiring is experienced, they would not know where to start the wiring process, which wire is prioritized, which one is on top of one another. The proposed framework is to create the wiring diagram using a graph representation.

3.4. Component to Graph Representation

Based on the connections in Table 1 and Table 2, we can calculate the cost of each edge using a custom cost formula below.

$$K = (L \times W_u) * P_f$$

K : Edge weight,
L :Wire length (m),
W_u : Wire weight (g),
P_f : Route penalty (constant),
- Internally Routed, $P_f = 1$,
- Externally Routed, $Pf = 5$.

This custom edge cost equation translates physical properties into a quantifiable cost, mainly the route penalty constant that ensures an external wiring routes are avoided do to their negative impact on aerodymanics and physical safety. We also want the length of a wire to be as short as possible[4].

For the graph shown below, the calculations are included in a Microsoft Excel Sheets in the Appendix section.

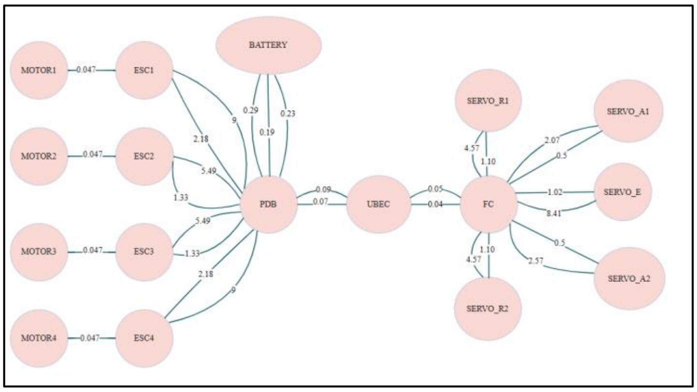

Fig. 11. Power Connection Graph

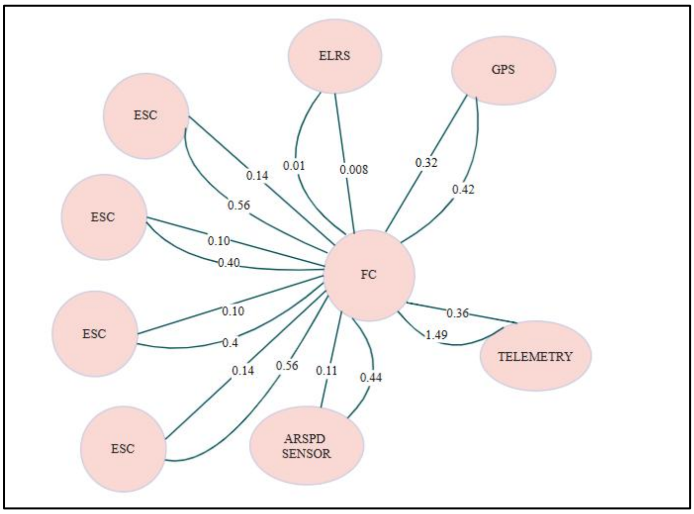

Fig. 12. Signal Connection Graph

The graph in Fig. 11 and Fig. 12 represents the possibilities of every component's wire path could take to connect to another component. Each nodes represent the components and the edges represent all the possible, yet still logical path of wiring it could take, otherwise each nodes will have infinite degrees. The weight of the graph is calculated using the equation below.

3.5. Minimum Spanning Tree Utilization

Given each weighted graph in Fig. 11 and Fig. 12, we can find the most optimal path of each graph by implementing Kruskal's MST algorithm.

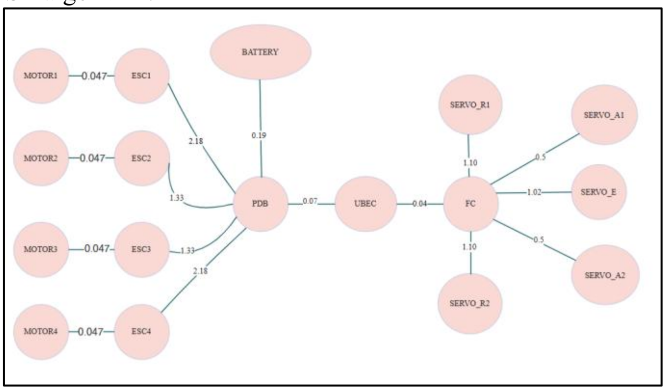

Fig. 12. MST of Power Connection Graph

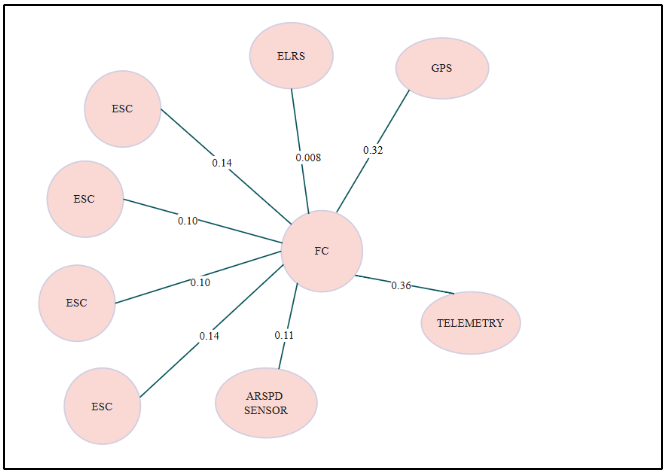

Fig. 13. MST of Signal Graph

3.6. Airframe Integration

Fig.12 and Fig.13 shows the most optimal path for each power and signal subgraphs, but it doesn't necessarily show how it could be implemented in our physical design. With the design in Fig.7, Fig. 8, and Fig. 9 as our reference, we can create a wiring diagram based on the results of MST and is applicative in our physical design.

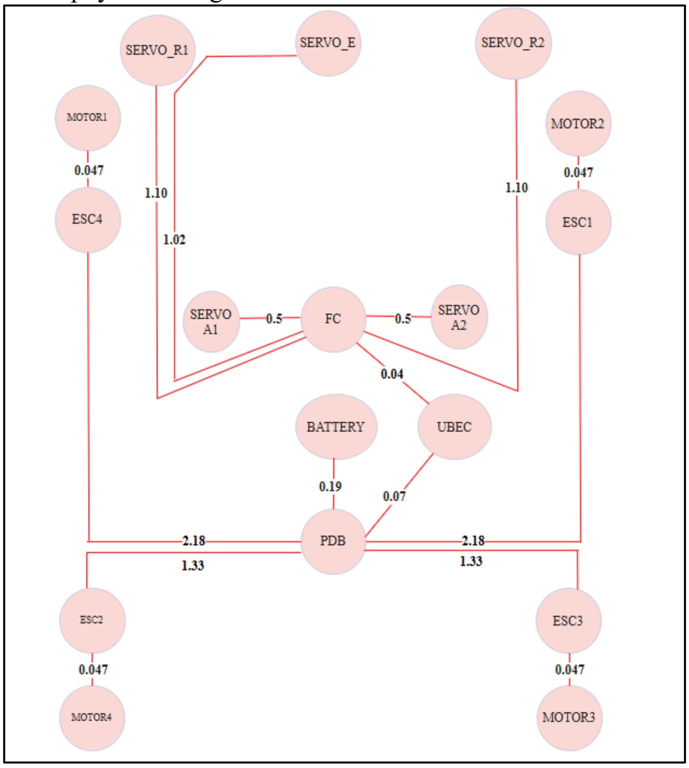

Fig. 14. Power Wiring Diagram

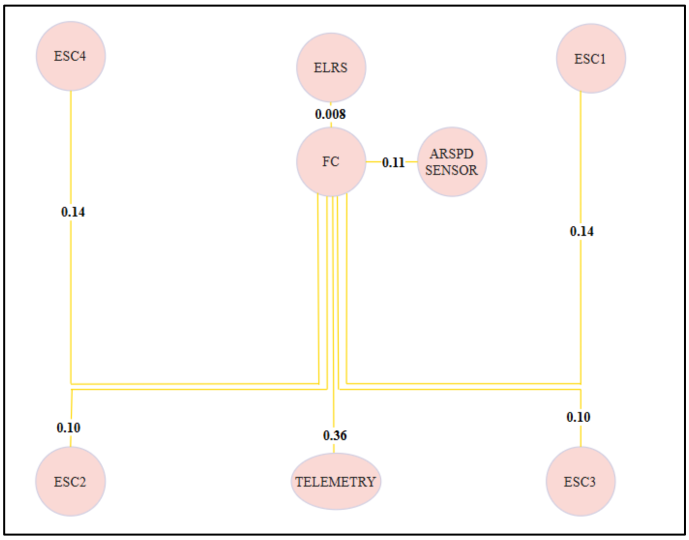

Fig. 15. Signal Wiring Diagram

IV. RESULTS

After implementing Kruskal's algorithm to find the MST of the wiring graph shown in Fig. 11 and Fig. 12, we can see that we have two graphs in hand, the power subgraph (Fig. 14) and the signal subgraph (Fig.15). The two subgraphs represent the most efficient wiring configuration according to our defined cost function. The next step is to combine both wiring diagrams through a layered approach. The heavier and more rigid power cables should be installed first as the bottom layer to create a stable base that prevents heavier cables inducing stress or vibration to the smaller and vulnerable signal cables. The signal cables are wired on top of the power cables.

The cost function, $K = (L \times W_u) \times Pf$, ensures that cable paths are all routed internally within the airframe ($P_f = 1$). This method prevents unwanted aerodynamic drag and other risks that comes from externally routing the wires.

For comparison, the total length and weight of our combined graph is 9.2 meters and 32.93 grams respectively. Say we take a random path for each components, our optimized graph achieves 7.2% reduction in total wire weight and 0.3% reduction in total length.

This method of creating a wiring diagram and plan isn't only limited to weight and length. Planning a highly organized and structured wiring path using MST minimizes possibility of intersections between cables, damage from vibrations, and most importantly possibility of short circuits. Internally routing the vehicle's wiring path ensures the vehicle's aerodynamic capabilities are not compromised by exposed wire.

As a whole, creating a more clear wiring diagram through graph theory gives more room for improvements in manufacturing. It allows precise calculations for the airframe's requirements, such as the necessary diameters for tight spaces within the PDB and ESC power connection.

V. Conclusion and Recommendation

This methodology presents a new framework in modeling a drone's electrical system using a weighted multigraph. By applying a cost function for each edge, $K = (L \times W_u) \times Pf$, we assigned a quantitative penalty to each path based on its length, weight, and route. Using the Kruskal's minimum spanning tree algorithm, we can find the most optimal wiring path, resulting in lesser length, weight, and safer routing choice.

Although theoretically this methodology might be optimal, there needs to be more physical testing on whether this method is possible or not. There are some assumptions that are made in this paper, such as the dimensions and the penalty of each variable in the cost function. Whereas in practice, the penalty might be smaller or larger depending on the situation and the design of the vehicle. The 2D design of the wiring graph result might also not be as representative in real life.

Therefore, the author of this paper recommends testing in physical builds in order to allow for precise measurements. Also, integrating designs with 3D softwares and simulation softwares is highly recommended to further improve the calculations from this paper.

VI. Appendix

The table for the calculation made for this paper is located at the this link.
[Calculation Sheets](https://docs.google.com/spreadsheets/d/1Tuj_b9SjJzbuuPboLH6wYObeJtOlVdnRKXMpYgINU9I/edit?usp=sharing)
https://docs.google.com/spreadsheets/d/1Tuj_b9SjJzbuuPboLH6wYObeJtOlVdnRKXMpYgINU9I/edit?usp=sharing
The video presentation is located in this link.
[Presentation Video](https://youtu.be/VWQ3eHzQ8-o)
https://youtu.be/VWQ3eHzQ8-o

VII. Acknowledgment

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Pernyataan

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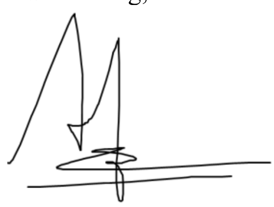
Sumedang, 20 Juni 2025



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