A Design-Agnostic Framework for the Salvage and Reverse-Engineering of Unmanned Aerial Vehicles (UAV)

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Abstract

This paper presents an Explorative Reverse Engineering (ERE) framework for the analysis and reverse-engineering of unmanned aerial vehicles (UAV). The framework is based on the life cycle theory and customized for the re-engineering of UAVs. It starts by identifying the UAVs' subsystems and key components, analyzing their functions, and exploring opportunities to replace the components with alternatives that serve similar functionalities. The procedure is tested for a black box aerial UAV with an unknown brand and performance. The components: airframe, propulsion system, avionics, sensors, communication systems, and payload modules are among the components that have been identified. Each part is carefully and accurately described, emphasizing its significance in the overall operation of the UAV. Different devices that can take the role of the identified components have been investigated. Using regression Machine Learning algorithm, two novel formula is established to calculate the thrust needed to take off and payload capacity. As the result of a successful implementation of the proposed farmwork, the identified elements have been used successfully to re-engineer a full-functioning real UAV.

Keywords: UAV, Reverse Engineering, Explorative Reverse Engineering (ERE), System Validation, Aerodynamics, SAA Systems, DAA Systems.

1. Introduction

Reverse Engineering (Re-Engineering) is the practice of recovering the design of an existing system by uncovering its building components, their functionalities, detailed technical data and specifications of the system (Chikofsky and Cross,1990; Rekoff,1985; Rozesara et al., 2023),[i] [ii]it is an innovative process (Junior, et.al., 2007)[iii] results in improving the current state of technology, forward engineering and innovation (Oecd, 2018).[iv] Re-engineering demands protentional engineering, technical and research skills, learning, and a lot of domain study, it is used as an input to the research and development activities (Zhang and Zhou,2016).[v]

Re-engineering is a common practice for improving Complex Product Systems (CoPS). These systems, unlike conventional product system models used in mass-production industries, require customized innovation approach (Rozesara et al., 2023)[vi], and different domains require their own life-cycle models. In this paper, we present a new Re-engineering model for UAV aimed at re-design, innovation and security purposes.

Unmanned Aerial Vehicles (UAVs) are vehicles that fly autonomously and from manufacturing point of view, they are considered CoPS (Walden, Roedler, and Forsberg, 2015).[vii] UAVs can be remotely managed by an operator, or they can use autonomous systems to fly along a predetermined path (Mohsan et al., 2023).[viii] Due to their adaptability and wide range of uses, UAVs—which come in a variety of sizes and configurations—have grown significantly in importance in both the military and civilian sectors. UAVs are categorized into different groups according to their size, autonomy, range, and intended use (White, 2016)[ix], (Yang and Pei, 2022)[x]. For example, based on size, micro-UAVs are frequently employed for urban surveillance and reconnaissance, mini UAVs are slightly larger and are used for operations like wildlife research and emergency assessment through specialized sensors, small UAVs are used frequently in mapping, aerial photography, filming, environmental monitoring, and have a higher cargo capacity, medium UAVs are appropriate for border monitoring, search and rescue operations, and scientific research due to its long endurance range, and large unmanned aerial vehicles (UAVs) are useful for carrying heavy loads over long distances and are used for remote aerial surveys, cargo transport, and military missions. When classified based on the airframe design, fixed-wing UAVs have wings that resemble those of an airplane and are great for effectively covering huge regions. While the great maneuverability of quadcopters, hexacopters, and octocopters, on the other hand, makes them appropriate for surveillance and inspections in limited spaces (White, 2016).

As aerial robots have demonstrated their effectiveness across various industries, the need to enhance UAV capabilities becomes increasingly critical. The development and advancement of UAVs have been significantly linked to national security leading to many restrictions in the transformation of their technology. On the other hand, the prevalence of regional and locally manufactured UAVs, especially quadcopters and other consumer-grade drones has presented new challenges. These drones have become affordable and popular among hobbyists, enthusiasts, and even malicious actors. Consequently, incidents involving UAVs have been linked to illegal border crossings, causing disruptions in airports and many other challenges. In some cases, drone attacks may lead to accidents when UAVs fall to the ground or disintegrate into parts raising concerns about their safety and security (Jeelani and Gheisari, 2021).[xi]

Recognizing the need for comprehensive solutions to the challenges, especially when the source and origin of the UAV is unknown, researchers, and industrial experts are seeking systematic methodologies to gain an understanding of UAVs functions, performance and manufacturing origins. A promising approach is the process of reverse-engineering (Toorajipour et al., 2021).[xii] Several factors could necessitate reverse engineering for UAVs. Gaining a competitive edge by comprehending the technology used by competitors is one of the main goals, which requires careful consideration of ethical and legal concerns. Companies can improve their unmanned vehicle models by analyzing and comprehending the frame designs of their rivals to pinpoint strengths and weaknesses. Fulfilling interoperability and compatibility is a key use of reverse engineering in the UAV industry.

In the UAV industry, engineers can create interoperable systems by using reverse engineering to analyze the protocols for communication and data exchange processes between various unmanned aerial vehicle parts. Furthermore, an essential part of reverse engineering for UAVs is security analysis–and to evaluate the security safeguards built into the vehicle's software and hardware components by locating potential vulnerabilities that must be fixed to prevent malicious exploitation. Unmanned aerial vehicles contain complex electronic systems, and suppliers may not always supply third-party repair services with comprehensive technical information. Reverse engineering enables these services to carefully understand the UAVs internal framework and functionalities, allowing them to carry out efficient maintenance and repairs. Reverse engineering is also used by UAV enthusiasts and engineers to customize and alter existing UAV designs. Developers can customize both the electronic components and software configurations of UAVs by reverse engineering them. They can then make compatible accessories and improve the robot's overall capabilities (Bappy et al., 2015).[xiii]

In this study, a new framework based on life cycle theory is introduced for re-engineering UAVs. The remainder of the paper is organized as follows: Section 2 reviews related works, followed by the development of the framework in Section 3. In Section 4, the framework is applied to a black box UAV, and Section 5 discusses the test results. Finally, conclusions are drawn in the last section.

2 Related Works

While UAVs are representatives of Industrial Revolution IR4 and IR5, the concept of reverse-engineering has roots that trace back to IR1. This section reviews key studies in the literature on UAV re-engineering, highlighting important contributions that have shaped the field.

One of the re-engineering methodologies has been conducted using laser scanner measurement (Burston et al., 2014).[xiv] The development of a virtual model or mockup of an Unmanned Aircraft (UA) is a key component of the reverse engineering methodology described in this study. A CAD (computer-aided design) program is employed to reassemble the UA model after taking measurements from a 3D scanner. The 6-DoF design is then created by figuring out the UA's mass properties from the CAD mockup. Parallel to this process, point measures generated from the airframe are used to calculate the aerodynamic factors and derivatives. Another research study investigated the simulation of a drone's realization after swapping out the laminate of the rotors' supporting structure with a sandwich design made of a polystyrene core and a skin made of carbon fiber and epoxy resin. The typical laminate is contrasted with this sandwich architecture in terms of both weight and mechanical strength. The authors noted that polystyrene has been investigated in the past as a sandwich core material, either by itself or when doped with additional substances such as carbon nanotubes. Plastic materials are used to construct the drone's body for the electrical control housing. In their work, the researchers designed the UAV through reverse engineering (Raffaele et al., 2020).[xv]

A reverse-engineered firmware has been introduced by a study that focused on quadcopter firmware aiming to improve control design and implementation. This is done by using the dispatch process, which combines the control theory with program analysis utilizing symbolic code execution and data circulation analysis to first decompile binary instructions and then recover controller functions and fundamental controller variables (Kim et al., 2022).[xvi] There have been other efforts introducing the decoding process of DJI robots to overcome the bugs that lead to intercepting no-fly-zone areas without interruption by DJI firmware. A decoder has been designed and used for DJI's tracking protocol DroneID using COTS hardware (Schilleri et al., 2023).[xvii]

This survey showed some successful re-engineering attempts to UAV, but as you have seen that there are significant gaps remain in addressing various aspects of UAV functionality and performance during the process of reverse -engineering. This study focuses on considering these issues through a life cycle theory approach to UAV reverse engineering. The study implements the new framework for deconstructing existing UAV systems, analyzing their performance, and identifying the building blocks and components.

3. Methodology

3.1 The Framework Design

The proposed framework is based on a life cycle that must be followed sequentially. It consists of seven phases, as illustrated in the block diagram shown in Figure 1.

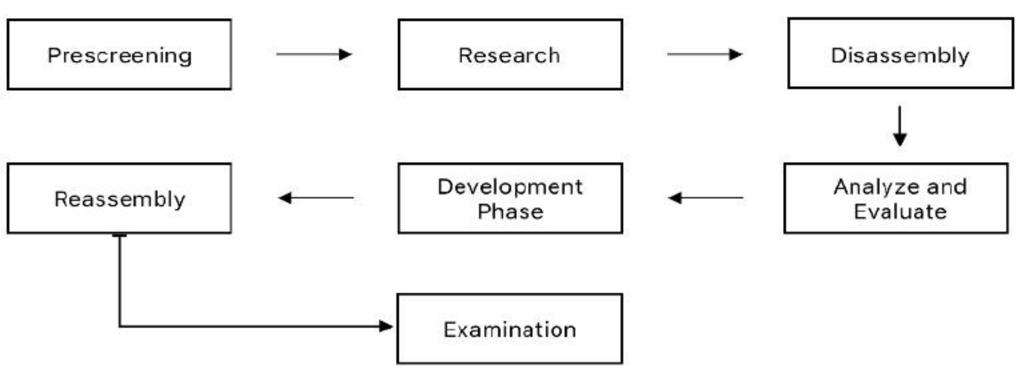


Figure 1 Reverse Engineering Life Cycle

3.1 Preprocessing Phase

In the prescreening phase, we identify the overall object, in such a case, the firmware of the UAV must be identified, and the components attached must be allocated to be re-engineered later.

3.2 The Research Phase

In the research phase, the re-engineering team identify the application of each component and collect data about its physical shape and specifications including hardware dimensions, weight, compatibility with other hardware devices, main function, manufacturing process and resource, and its software specifications.

3.3 Dissembling Phase

The disassembly phase is an important stage in the re-engineering process. When dealing with physical objects, this may entail disassembling each component to view its mechanism at work. The process of dissembling in the industry is well known for engineers. They will typically endeavor to mark and store each component in the correct sequence. In this phase, wire diagrams are studied carefully, as it represents the compatibility of each component with each other. Reverse engineering in software entails downloading the source code.

3.4 Analysis and Evaluation

This phase includes a thorough analysis of every element. There can be a bit of guesswork involved depending on the availability of the product itself or the knowledge gathered in phase two and three. The analysis and evaluation phase plays a significant role in developing the products under examination. Each part or component has to be checked after being disassembled. This is an excellent moment to mention any design, software, or hardware changes you could recommend as well as any mistakes or problems you find. At this time, every piece of information should be fully documented for the future.

3.5 Development Phase

been identified, it is crucial to take into consideration an implementation of development process on the fallen UAV to strengthen the overall performance of the product, this is carried out in the development phase. The development could be applied to the communication and ground station power and payload systems.

3.6 Reassembling Phase

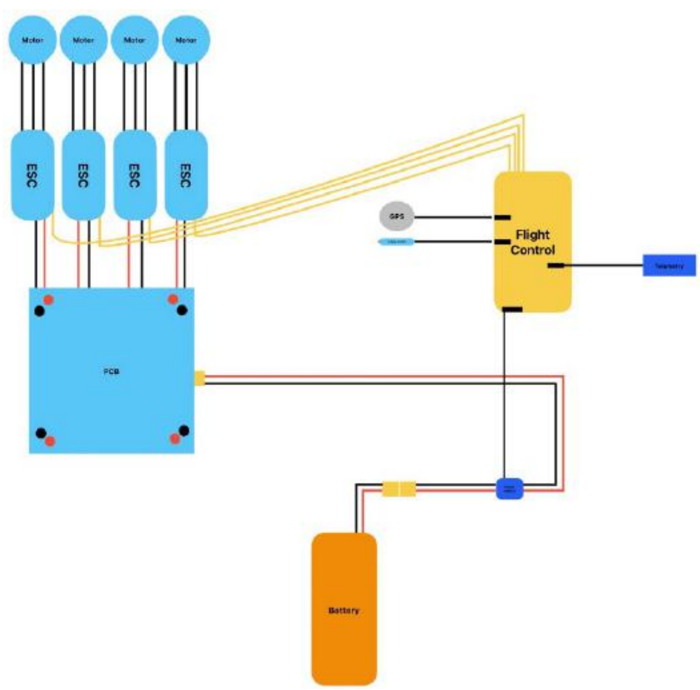
In the reassembling phase, engineers now put all the components back together in the reverse order. making sure that each component contributes to the outcome. The reassembled item ought to deliver the desired outcomes and must take the process to the testing phase safely. Accurately reassembling the product verifies that no parts or procedures were overlooked.

3.7 Testing Phase

Testing is the final phase of the re-engineering life cycle. In the testing phase, the overall product must bring results either identical to the functionality of the examined product or a developed version of it.

4. The Explorative Reverse Engineering Method for UAV

The methodology of reverse engineering proposed in this study is customized to an Explorative Reverse Engineering (EME) that focused on upgrading a fallen quadcopter firmware to a more functional one of the same firmware. The block diagram illustrating the components of a typical quadcopter is shown in figure. 2. The proposed EME-UAV framework is detailed in the block diagram of figure 3. The steps must be followed in sequence to ensure a clean reverse engineering process with significant consequences.



Initially, and before handling the quadcopter, we should make sure the area is secure and safe. Most importantly, the power source must be disconnected to prevent any unintentional activation. In the second step, we must take detailed photographs and record the location and condition of the quadcopter at the crash site. This includes paying attention to any visible damage on the frame, propellers, and electronic components. In the third step, the quadcopter's frame, arms, propellers, and landing gear must all be examined. Each component must be checked for evidence of impact, stress, or wear. In the fourth and fifth step, disassemble the quadcopter with care, noting where each part is located and how it is facing. Examine each piece of hardware separately, paying particular attention to the battery, gyroscope, accelerometer, and barometer sensors, as well as the flight controller, motors, ESCs, and camera (if used). During the disassembly process, a check for any physical flaws or abnormalities is necessary.

In the *Fig 2 The block diagram of a typical quadcopter* tions of the electronic components, if it is possible, draw circuit diagrams. Pay close attention to the connections between the motors and sensors and the flight controller. In the seventh step, we must Identify any potential thrust or balance issues by analyzing the motors and propellers to comprehend their specifications (such as the Kv rating for the motors and propeller pitch). While in the software and firmware analysis phase, it is necessary to go through the firmware and flight

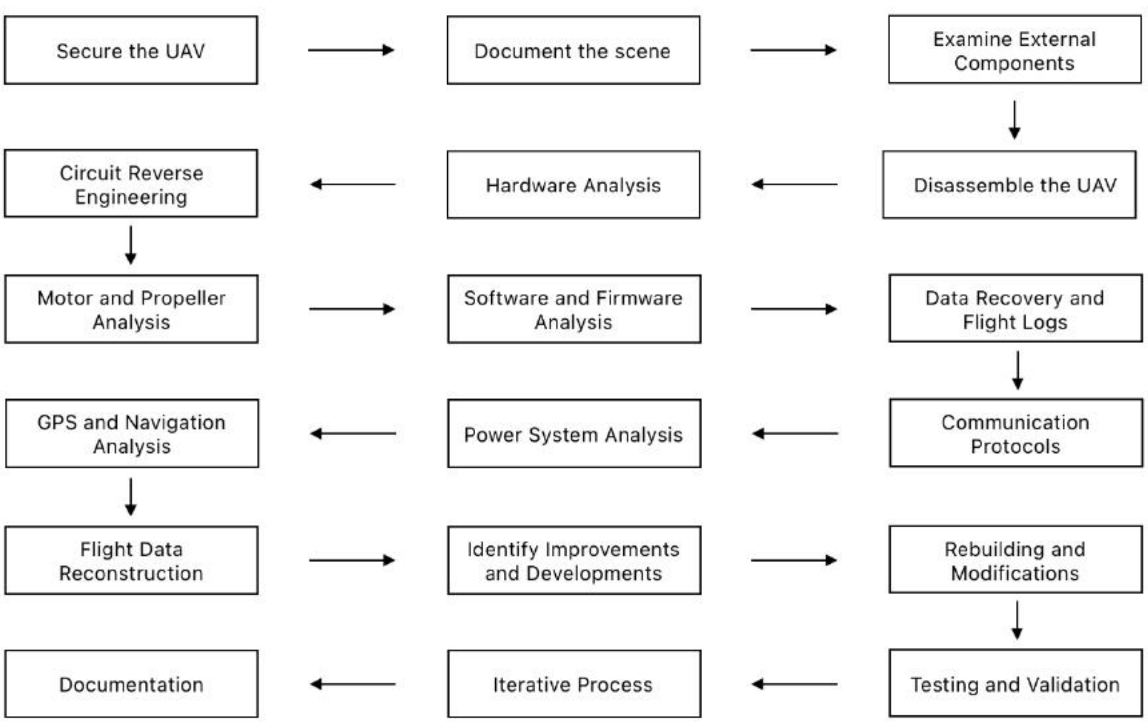


Figure 3 The Proposed Explorative Reverse Engineering Method for UAV

controller software for the quadcopter. We can develop a flight management system with a more advanced feature board by analyzing controlling algorithms, PID variables, and any stabilization or autopilot features.

The Data Recovery and Flight Logs phase will provide the opportunity to attempt to retrieve flight logs or data from the GPS and flight controller. The behavior of the quadcopter prior to the crash can be learned from flight logs. while in the Communication Protocols phase, we examine the telemetry, remote control, and other communication elements on the quadcopter's communication protocols to estimate the range of the quadcopter. In the power system analysis phase, we investigate the energy source, power regulators, as well as ESCs in the quadcopter's distribution of power system. We try to solve any problems that may have caused a power outage or other anomalies. While in the GPS and navigation analysis phase, we must examine the GPS and compass systems on the quadcopter. If the quadcopter is capable of autonomous flight, this step is essential. In the flight data reconstruction field, the path of flight and behavior of the quadcopter prior to the crash must be reconstructed using the data that was gathered. We may be able to determine potential incident causes with the aid of this analysis. Later on, we determine areas where the quadcopter could be enhanced or improved according to the reverse engineering analysis. This could entail choosing superior components, improving algorithms, or including new features. After that, Redevelop the unmanned aircraft with the desired advancements using the knowledge obtained from the evaluation and the recognized improvements. This might entail upgrading hardware, swapping out faulty parts, and updating the flight controller to ensure more parameters are used and other added hardware is compatible with the new system. To confirm that the improvements and advancements function as planned, thoroughly test the refurbished quadcopter in controlled conditions. To assess its stability, reactivity, and general performance, conduct flight tests. Lastly, it is advised to record each stage of the reversing, reconstruction, and development process. This includes the discoveries, the approaches utilized, the alterations that have been done, and the outcomes gained. For reference as well as information exchange, this material will be essential.

5. Experimental Validation

In this section, we will apply the proposed framework to a damaged quadcopter in the laboratory. In the performance evaluation, we will focus on the payload capacity as it is important to measure the thrust generated by the quadcopter to estimate the total capacity of the payload to seek developments. To measure the thrust generated by each motor accurately using the intended used propellers, we have used a Thrust Meter and is shown in fig 4.

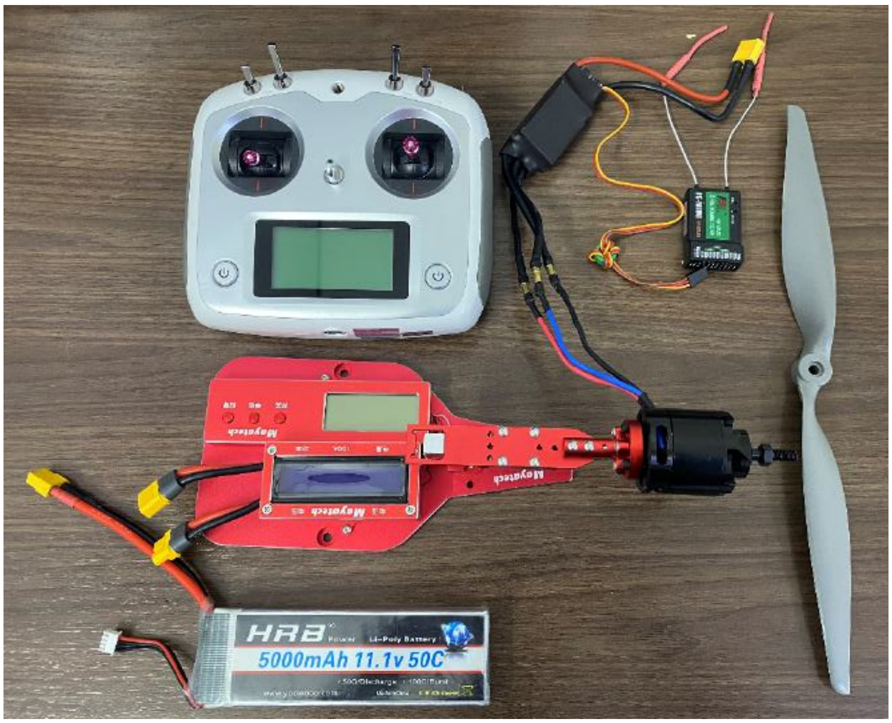


Figure 4 Motor Thrust Meter

To estimate the UAV's payload capacity, we should weight the drone and measure the thrust generated by the motors using a thrust meter. The quadcopter to takeoff, it needs a thrust that is at least double its weight and any extra thrust generated by the motors will be considered as a payload capacity. The quadcopter's thrust has been measured in different situations with different payloads. These measurements have been recorded and used to build a dataset. Using Machine Learning (ML) Regression algorithm and the dataset, a new novel model has been established which is shown in equation 1.

$$Ft = Mg * 2 * K \qquad (1)$$

Where Ft and N represent thrust needed to takeoff in N and quadcopter weight in g respectively, and K the safety measure. K is set to 1.2 as %20 of the total thrust needed must be extracted from the thrust generated from the motors to ensure a safe takeoff.

In order to calculate the payload capacity, equation **2** is applied. We have developed this special equation that has been tested up on experiments to measure the payload capacity.

$$Pc = Fm * 4 - Ft \qquad (2)$$

Where Pc represents payload capacity, Fm represents thrust generated by the motor.

In order to calculate the payload capacity for the sample we have, we have calculated the thrust of the motor, which is 0.9kg for each motor. However, the drone weight is 1.4kg, using the equations 1 and 2, we will result in a payload of 240g. To develop the payload capacity, we have replaced the motors with motors that have 1.2kg of thrust generated for each. As a result, we will have a payload capacity of 480g, considering that the weight of the drone changes to 1.8 kg. This calculation has been done taking into consideration both quadcopters use a propeller with a 4.5 pitch angle.

The proposed EME-UAV framework when it is applied to the quadcopter under test revealed the specifications of the damaged unknow quadcopter as shown in Table 1.

As we have mentioned before, the two objectives of reverse engineering a UAV are to identify its origin and to build a new version with improved capabilities after analyzing the strengths and weaknesses of the damaged UAV. The main goal is now to increase such specifications to result in a more functional quadcopter with more capabilities. The original flight controller used in the sample is the “Ardupilot Mega 2.5”, shown in figure 5. Due to its improved hardware capabilities, greater processing power, and improved sensor compatibility, Pixhawk 2.4.8 shown in figure 6 is superior to ArduPilot Mega 2.5 for use with quadcopters and offers more accurate and dependable flight control. Therefore, the Ardupilot mega will be the first choice.

Table 1 Quadcopter Sample Specifications using the proposed ERE framework

Parameter	Calculate Value Using ERE
Generated Thrust	35.3N
Payload Capacity	240g
Range Without Amplifier Applied or Noise	1km
Flight Controller	ArduPilot Mega 2.5
Electric Speed Controller (ESC)	30Amp
Battery	3000mAh 3S 25C (low charge/discharge rate)
Total weight	1.4kg
Receiver	Futaba R304SB
Control Frequency	2.4 Ghz
Frequency of Control Signals	900MHz
Estimated cost (2023)	$450

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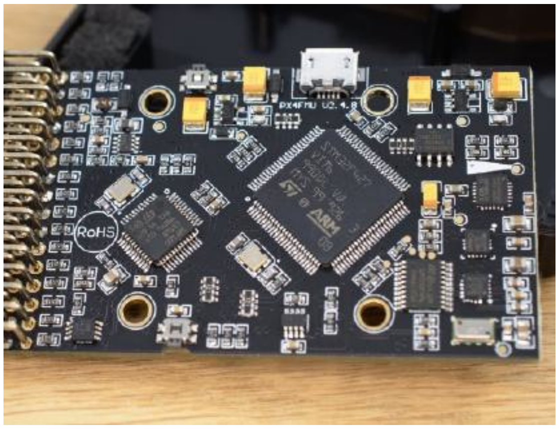

Figure 6 Pixhawk 2.4.8 Flight Controller

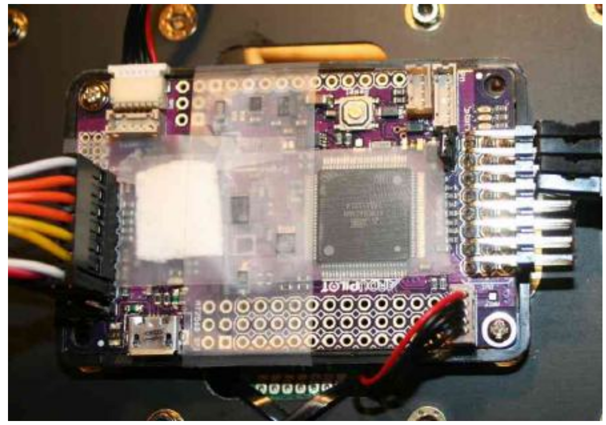

Figure 5 Ardupilot Mega 2.5 Flight Controller

A quadcopter can benefit greatly from switching from ArduPilot Mega 2.5 to Pixhawk 2.4.8 as the flying controller. Faster data processing and the use of sophisticated flight control algorithms are made possible by the Pixhawk 2.4.8's increased processing power, memory, and storage capacity. By leveraging more modern IMUs for more accurate flight data, its improved sensor compatibility raises stability, precision, and dependability. The Pixhawk 2.4.8 improves the quadcopter's adaptability, security, and navigational skills by adding more flight modes, adding security measures, and improving GPS performance. Configuration, calibration, and updates are easier to access because to its modular design and community support for peripheral integration.

In the sample quadcopter, a development in the circuit of the quadcopter will take place and a rangefinder will be added to avoid obstacles as most of the quadcopters that result in falling is due to the lack of rangefinders. Therefore, the reverse-engineered sample will include a GY-US42 rangefinder. This addition will provide the UAV the ability to deal with terrain changes during the autonomous missions and will notify the drone of any changes in the terrain readings even if the software has set a limit to the altitude of the unmanned vehicle mission. The wiring diagram is shown in figure 7. The GY-US42 ultrasonic rangefinder is used in quadcopters to determine altitude and distance. It uses the time-of-flight concept to determine distance by sending out ultrasonic waves and timing how long it takes for the waves to return after hitting an object. It plays a significant role in altitude measurement for stable flight control, the deployment of terrain-following capabilities, and obstacle avoidance, which accounts for its effectiveness in quadcopters.

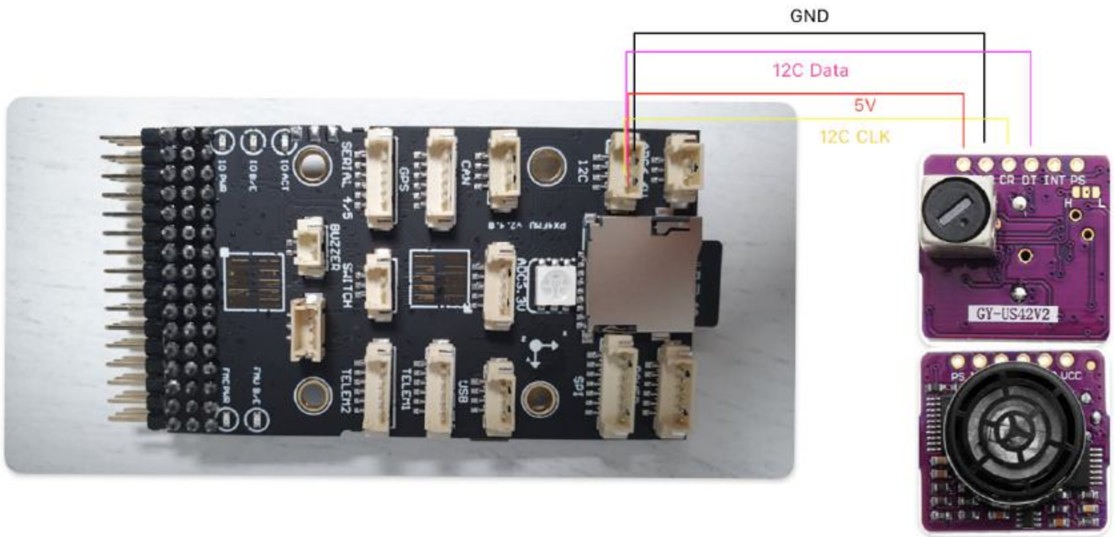

Figure 7 GY-US42 Wiring with Pixhawk 2.4.8

The sensor assists with obstacle detection and trajectory adjustment to avoid collisions by continually monitoring distances to nearby objects. Additionally, it is energy-efficient that extends flying periods.

6. Performance Evaluation

In the software and firmware analysis phase, we must check the flight controller supported software. In our sample, the quadcopter had an Ardupilot Mega 2.5 flight controller and it supports both Mission Planner and QGroundControl software. Therefore, the data recovery and logs will be extracted from the flight controller through the software supported by the flight controller used. This is done by unlocking the flight controller log files to re-generate the waypoints and missions that were previously used. The extracted data will be the parameters list, autonomous mission flight path, GPS coordinates and the flight performance log data. In the sample provided, after a long investigation and analysis, we have detected the reason that led the quadcopter crash. The crash has occurred due to a sharp decrease in the rotation movement of the pitch angle. This means the quadcopter faced terrain changes in its flight path that led it to crash. The change in the rotation movement has been extracted from Ardupilot Log Viewer website, which is online viewer for UAV log files. The change in the rotation movements is shown in figure 8.

In this part, we will explore the fundamental improvements performed to the quadcopter, including crucial changes to the motors, circuit design, and addition of an innovative obstacle avoidance mechanism.

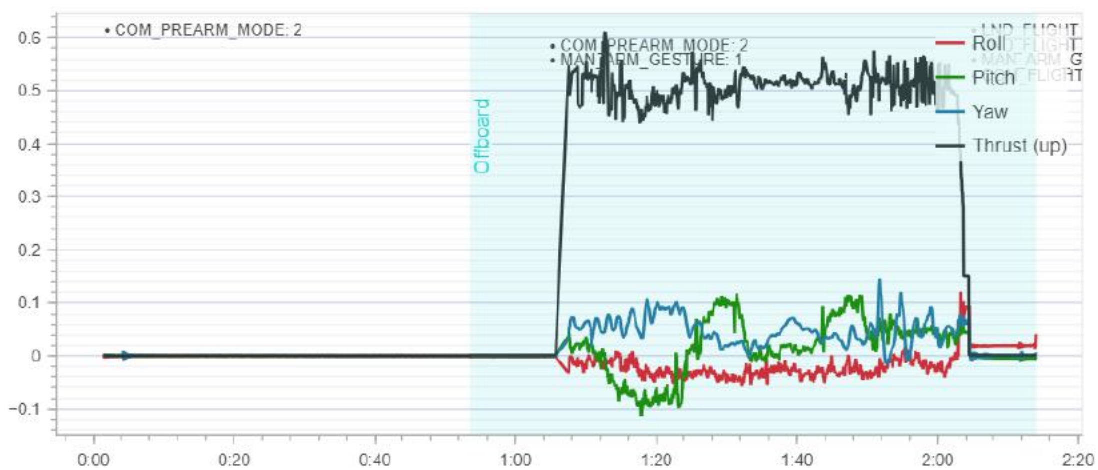

Figure 8 Pitch Rate Movement

Table 2 Enhanced Quadcopter Parameters Using the Proposed Reverse engineering Framework

Parameters	**Sample UAV**	**Reversed Engineered UAV**
Thrust Gain	35.3N	47N
Payload Capacity	240g	480g
Flight Controller	ArduPilot Mega 2.5	Pixhawk 2.4.8
Weight	1.4kg	1.8kg

Propeller Pitch	4.5	4.5
Software	Mission Planner	QGroundControl
Battery Capacity	3000mAh 3S 25C (low charge/discharge rate)	5000mAh 4S 50C (high discharge/charge rate)
Estimated Cost	$450	$600
Receiver	Futaba R304SB	FS-IA10B
Control Frequency	2.4Ghz	2.4Ghz
Electric Speed Controller (ESC)	30mAh	40mAh
Motor	DJI 2212/920Kv	Emax MT2216 810kv
Frame Wheelbase	S500, 500mm	S500, 500mm
Propeller Material	Plastic	Carbon Fiber
Rangefinder	N/A	GY-US42
Transmitter Range	1km – 1.5km	1.5km – 2km
Telemetry	3DR Radio v2	3DR Radio v2

The reversed-engineered UAV has more advanced capabilities in thrust gain, payload capacity, flight control, battery capacity, obstacle avoidance system, and transmitter range. Our proposed EME-UAV framework offers a new avenue for developers to enhance the quadcopter performance using an existence one even where it is in a black box state without data and specifications.

7. Conclusion

In this study a new framework for reverse engineering in the UAVs industry has been established. The framework which was based in life cycle theory included 18 sequential phases, ensuring a systematic reverse engineering process. The framework was applied to a real quadcopter. The key components, the airframe, propulsion system, avionics, sensors, communication systems, and payload modules were identified, and missing components were detected using the proposed framework. Different testing scenarios were carried out to build a dataset. A Machine Learning regression algorithm has been used to develop two prediction equations for thrust and payload capacity. The results were highly comparable between the actual values of the components and performance and the calculated specifications of the quadcopter under test. These findings were used to improve the quadcopter performance, leading to main changes in the circuit diagram. The flight controller was replaced, and a rangefinder was added based on insights from data flash logs. The framework was successful to determine the causes of the non-functionalities of the quadcopter components. The final product, the upgraded quadcopter, showed substantial improvements in the payload, thrust gain, obstacle avoidance, and flight controller, resulting in a significantly enhanced performance.

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