A Modular Framework for Multi-Rotor Unmanned Aerial Vehicles for Military Operations

by

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Dedication

To my family. Words cannot describe how grateful I am for your presence, support, and love in my life.
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# Table of Contents

List of Tables ........................................................................................................................................ iv

List of Figures ......................................................................................................................................... vi

Abstract.................................................................................................................................................. ix

Chapter 1: Introduction............................................................................................................................... 1
  1.1 Motivation ........................................................................................................................................ 4
  1.2 Research Questions ......................................................................................................................... 5
  1.3 Structure of the Dissertation ........................................................................................................... 5

Chapter 2: Literature Review ....................................................................................................................... 6
  2.1 UAVs in the Military ......................................................................................................................... 6
  2.2 Modularity in Robotics and UAVs ................................................................................................... 6
  2.3 Increasing Flight Time and Tethered UAVs ..................................................................................... 8
  2.4 Focus Group as Qualitative Research Tool .................................................................................... 10
  2.5 Usability Studies and the System Usability Scale ........................................................................... 11
  2.6 Human-Drone Interaction .............................................................................................................. 12

Chapter 3: Exploring the Concept of Modular MR-UAVs ........................................................................ 13
  3.1 Focus Group Research .................................................................................................................... 13
     3.1.1 Participants ............................................................................................................................... 13
     3.1.2 Methodology ........................................................................................................................... 13
  3.2 Results ........................................................................................................................................... 15
     3.2.1 Use Cases ............................................................................................................................... 15
     3.2.2 Modular MR-UAV Profile Ranking ......................................................................................... 16
     3.2.3 Qualitative Results .................................................................................................................. 16
     3.2.4 Requirements for a Modular MR-UAV .................................................................................... 18

Chapter 4: Estimating Flight Time and Optimizing Efficiency .................................................................. 20
  4.1 Powertrain Data Collection ............................................................................................................. 20
     4.1.1 Equipment ............................................................................................................................... 20
     4.1.2 Thrust-Stand Data Collection Procedures .............................................................................. 22
  4.2 Estimating Flight Time .................................................................................................................... 23
  4.3 Validating Flight Time Estimation .................................................................................................. 24
     4.3.1 Methodology ........................................................................................................................... 24
     4.3.2 Results ..................................................................................................................................... 25
  4.4 Optimizing Flight Time .................................................................................................................... 26
  4.5 Multi-rotor Designer Software ....................................................................................................... 30
     4.5.1 Propeller Selection ................................................................................................................... 31
     4.5.2 Motor Selection ....................................................................................................................... 32
     4.5.3 Designer .................................................................................................................................. 34
List of Tables

Table 3.1 Focus group research participants and their UAV experience........................................14
Table 3.2 Ranking for modular MR-UAV profiles........................................................................16
Table 4.1 MR-UAV prototypes used to validate flight-time estimation algorithm........................25
Table 4.2 Measured flight times for 3 prototypes ........................................................................26
Table 4.3 Comparison between measured and estimated flight time ........................................27
Table 5.1 Power-management board electronic components........................................................40
Table 7.1 Profiles implemented with the modular MR-UAV framework ................................60
Table 7.2 MR-UAV FMV profile powertrain module specifications ............................................63
Table 7.3 MR-UAV FMV profile characteristics.........................................................................64
Table 7.4 MR-UAV Tethered FMV profile powertrain module specifications ..........................67
Table 7.5 MR-UAV Tethered FMV profile characteristics ..........................................................67
Table 7.6 MR-UAV Payload Delivery profile powertrain module specifications .....................69
Table 7.7 MR-UAV Payload Delivery profile characteristics ....................................................70
Table 7.8 Controller module parts and cost ..............................................................................72
Table 7.9 Video module parts and cost ....................................................................................72
Table 7.10 Communication module parts and cost ....................................................................72
Table 7.11 FMV Profile powertrain module parts and cost ..........................................................73
Table 7.12 Tethered FMV Profile powertrain module parts and cost .......................................73
Table 7.13 Payload Delivery Profile powertrain module parts and cost ....................................74
Table 7.14 Cost and characteristics comparison for MR-UAV profiles .....................................74
Table 8.1 System Usability score .............................................................................................78
Table 8.2 Time required to assemble a MR-UAV profile using the framework .........................79
Table 8.3 Paired two-tailed T-Test analysis for delta time to assemble the modular MR-UAV .......... 79

Table 8.4 Time required to disassemble a MR-UAV profile................................................. 80

Table 8.5 Paired two-tailed T-Test analysis for delta time to disassemble the modular MR-UAV ....... 81

Table 8.6 Video study research participants, their military, and UAV experience .......................... 84
List of Figures

Figure 1.1 MR-UAV implemented using the modular framework .......................................................... 3

Figure 4.1 RCBenchmark 1585 thrust stand used to collect brush-less motors and propeller data .......... 21

Figure 4.2 RCBenchmark thrust stand data acquisition software ......................................................... 21

Figure 4.3 Step-by-step process select motor and propeller for efficient MR-UAV ................................. 27

Figure 4.4 Examples of Thrust(kgf) vs RPM plot used during the propeller selection process ............... 28

Figure 4.5 Example of Torque (kgf) vs RPM plot used during the propeller selection process .............. 29

Figure 4.6 Example of Propeller Efficiency (kgf/W) vs Thrust (kgf) plot used during the propeller selection process ........................................................................................................ 29

Figure 4.7 Example of Motor efficiency (ratio) vs Thrust (kgf) plot used during the motor selection process .............................................................................................................................. 30

Figure 4.8 Multi-Rotor Designer Software propeller selection and graphing window ...................... 31

Figure 4.9 Multi-Rotor Designer Software propeller filtering and selection window ....................... 32

Figure 4.10 Multi-Rotor Designer Software window to select desired propeller slot .......................... 33

Figure 4.11 Multi-Rotor Designer Software motor selection window .................................................. 33

Figure 4.12 Multi-Rotor Designer Software motor filtering and selection window .......................... 34

Figure 4.13 Multi-Rotor Designer Software window to select desired motor slot ............................. 34

Figure 4.14 Multi-Rotor Designer Software designer and flight time estimation window .................. 35

Figure 5.1 Tethered MR-UAV environment ......................................................................................... 37

Figure 5.2 Tethered power-management board circuit schematic .................................................. 39

Figure 5.3 MR-UAV used during tethered PMB flight testing ......................................................... 42

Figure 5.4 Custom tethered cable 3-D printed release system ........................................................ 42

Figure 6.1 Modular MR-UAV architecture, modules, and connections .............................................. 46
Figure 6.2 Controller module frame design from diagonal view .............................................. 47
Figure 6.3 Controller module frame design from bottom (left) and top (right) view ...................... 47
Figure 6.4 Carbon fiber controller module from diagonal view .................................................. 48
Figure 6.5 Arm frame design for the powertrain module (left) .................................................. 49
Figure 6.6 Carbon fiber powertrain module .............................................................................. 49
Figure 6.7 Video module frame design from front (left), side (right) and diagonal (bottom) view ...... 50
Figure 6.8 Video module prototype, including 3-D printed frame, camera, and antenna .................. 50
Figure 6.9 Communication module frame design from front(left), side(right) and diagonal (bottom) view .................................................................................................................. 51
Figure 6.10 Communication module. Including 3-D printed frame and antenna ............................... 51
Figure 6.11 Payload module frame design from diagonal(left), and top (right) view ......................... 52
Figure 6.12 Payload module frame design with a 3-D printed payload from diagonal-top(left), and diagonal-bottom (right) view ................................................................................. 52
Figure 6.13 Payload module with carbon fiber frame and 3-D printed payload ............................... 53
Figure 6.14 Step-by-step process to create a modular MR-UAV profile ......................................... 54
Figure 6.15 Relationship between MOT_THST_EXPO parameter value and propeller size .............. 57
Figure 6.16 Relationship between INS_GYRO_FILTER parameter value and propeller size .............. 57
Figure 6.17 Relationship between ATC_ACCEL_P_MAX/ATX_ACCEL_R_MAX parameters value and propeller size ........................................................................................................ 58
Figure 6.18 Relationship between ATC_ACCEL_Y_MAX parameter value and propeller size ......... 58
Figure 7.1 FMV Profile flight time vs payload with 1 battery (left) and 2 batteries(right) .............. 64
Figure 7.2 FMV Profile thrust vs ESC signal (left) and flight efficiency vs ESC signal (right) .......... 65
Figure 7.3 FMV Profile current vs ESC signal (left) and current vs thrust (right) ............................ 65
Figure 7.4 FMV Profile vibration vs ESC signal (left) and RPM vs ESC signal (right) ....................... 65
Figure 7.5 Tethered FMV Profile flight time vs payload ................................................................. 68
Figure 7.6 Tethered FMV Profile thrust vs ESC signal (left) and flight efficiency vs ESC (right) ...... 68
Figure 7.7 Tethered FMV Profile current vs ESC signal (left) and current vs thrust (right) .......... 69
Figure 7.8 Tethered FMV Profile Vibration vs ESC signal (left) and RPM vs ESC signal (right)............. 69
Figure 7.9 Profile Delivery Profile flight time vs payload ............................................................................ 70
Figure 7.10 Profile Delivery Profile thrust vs ESC signal (left) and flight efficiency vs ESC (right) ............................................................................................................................................... 70
Figure 7.11 Profile Delivery Profile current vs ESC signal (left) and current vs thrust (right) ............. 71
Figure 7.12 Payload Delivery Profile vibration vs ESC signal (left) and RPM vs ESC signal (right) ............................................................................................................................................... 71
Figure 8.1 Time required to assemble MR-UAV profile (6 trials)................................................................. 78
Figure 8.2 Time required to dissemble MR-UAV profile (6 trials)................................................................. 81
Figure 8.3 Participants opinion on framework assembly procedure difficulty ........................................... 81
Figure 8.4 Participants opinion on benefits of a modular MR-UAV to the military ................................. 85
Figure 8.5 Participants opinion on adoption of a modular MR-UAV by the military ............................. 86
Abstract

Multi-rotor Unmanned Aerial Vehicles (MR-UAV) are commonly used in a wide range of military operations. However, current MR-UAV models have limited payload capabilities and flight time, making it impractical for a single system to be well-suited for different applications. For instance, a drone designed to carry heavier equipment is not well suited for uses that require agility and speed. Therefore, military organizations employ multiple MR-UAV models, leading to complex logistics, training, and overall increased costs. This dissertation presents a modular MR-UAV framework that allows a user to quickly tailor the aircraft for different military operations by easily changing modular parts of the system. The framework allows military operators to tailor the MR-UAV characteristics (flight time, size, weight, and maximum payload) and functionalities (sensors and actuators) by choosing different framework modules.

This dissertation first presents a focus group research with subject matter experts to explore the concept and understand the user's requirements for a modular MR-UAV. Results from this study guided the design of the framework. During all three focus group sessions, participants expressed a need for an MR-UAV capable of switching from tethered to un-tethered flights. Therefore, this dissertation also presents the design and validation of a power management board that allows the modular MR-UAV to be powered from both power supplies (tethered and onboard battery) and switch its operation during flight. This work also presents a process to choose the hardware components (motors, propellers, electronic speed controllers, and batteries) to create the framework modules. This process includes an algorithm to calculate flight time using data collected from a thrust stand. It is also presented the design of a software tool that streamlines the selection of hardware components and flight time calculation.

Following, this dissertation presents the technical specifications of the MR-UAVs implemented with the framework. To evaluate the proposed design, two usability studies were conducted. Results from
these studies suggest that modular MR-UAVs can provide direct benefits to military operations in terms of usability, as well as to the military organizations in terms of logistics and cost, and are likely to be adopted. Lastly, future work considerations for modular MR-UAVs for military applications are discussed.
Chapter 1: Introduction

Unmanned Aerial Vehicles (UAV) are advantageous tools in military operations [1][2][3]. They are used for surveillance, deployment of equipment, providing battleground situational awareness, and general support to ground troops. The United States Air Force defines a UAV as "an aircraft that does not carry a human operator and is capable of flight with or without remote control" [4]. The two most common types of UAVs are fixed-wing and multi-rotors [5], other classifications are rotorcrafts and flapping-wings [6]. Additionally, military UAVs are also categorized into classes according to their weight: class 1 (less than 150kg), class 2 (between 150kg and 600kg), and class 3 (more than 600kg) [7]. The work presented in this dissertation focuses solely on class 1 multi-rotor UAVs (MR-UAV). MR-UAVs specifically provide advantages over other categories due to their ability to hover in 3D spaces as well as their precise maneuverability. However, current MR-UAVs are limited to relatively light payloads and short flight times. Therefore, an MR-UAV is limited to the amount of equipment it can carry at once, making it implausible for it to be used on applications with widely differing requirements. For instance, an MR-UAV designed to carry heavier payloads is not well suited for applications that require agility and speed.

Therefore, military organizations must acquire numerous MR-UAVs models, each being useful for a specific type of application. However, having multiple models can lead to difficult training programs as users must learn how to operate different systems, recall complex logistics due to various models and manufacturers, as well as incur overall increased costs. Therefore, this dissertation proposes a modular framework that allows military operators to quickly assemble an MR-UAV that fulfills the requirements of their application by selecting and connecting a set of modules. In other words, the user can tailor the MR-UAV for different applications by easily changing modular parts of the system.
In the field of robotics, modular systems have been defined as "systems that are composed of modules that can be disconnected and reconnected in different arrangements to form a new configuration enabling new functionalities" [8]. Based on this definition, this work defines a modular MR-UAV as a system that allows the user to select components to tailor its flight time, payload capability, sensors, and actuators. Although the current market contains many models of class 1 MR-UAVs, there is not a modular system that provides the above characteristics to its users. The first research study of this dissertation is a focus group research with subject matter experts, in this case, military personnel, to explore the concept and understand the user's requirements for a modular MR-UAV. A focus group approach was chosen because it is known as a powerful method to gather rich and detailed data from the perspective of the users who will benefit from the research [9]. This study consisted of three focus group sessions with a total of ten military personnel with UAV experience from different perspectives: operators, developers, and logistics. Additionally, a focus group approach is also beneficial because it is a user-centered design technique, which can be useful in the design of a product for high-stress environments such as military operations. These environments require the system to be easily operable and intuitive to avoid unnecessary workload for users, therefore, a user-centered design is appropriate in this case. Qualitative results from the focus group suggest various advantages of using a modular design in military operations: (1) ability to tailor UAV's flight characteristics (flight time, payload carrying ability), (2) ability to tailor communication channels (datalink and video), (3) aptitude to add specific functionalities required by various missions by adding sensors and actuators, (4) improved logistics, (5) reduced training time, (6) improved maintainability, and (7) reduced overall cost. Therefore, such results demonstrate that a modular MR-UAV can provide direct benefits to military operations in terms of usability, as well as to the military organizations in terms of logistics and cost.

The proposed framework, which can be seen flying in Figure 1.1 allows a user to quickly tailor a single MR-UAV for different applications by easily changing the modules of the system. This design was based on results from the focus group and consists of five modules that can be easily plugged in to assemble
an MR-UAV: controller, powertrain, video, communication, and payload modules. Furthermore, during all focus group sessions, participants expressed a need for an MR-UAV capable of flying while connected to a ground power station using a tethered cable and able to instantly switch to an onboard battery power supplied flight by dropping the cable. In other words, there is a need for an MR-UAV that can shift from tethered to battery operation without having to land. Therefore, this dissertation also presents the design and validation of a power management board that allows the modular MR-UAV to be powered from both power supplies (tethered and onboard battery) and switch its operation during flight. In addition to allowing the MR-UAV to shift from tethered to remote operation, the power management board also enhances the reliability of the system as redundancy is added to its power supply. In case of a tethered power supply failure, the system instantly switches to remote (battery) operation, preventing a crash.

Figure 1.1 MR-UAV implemented using the modular framework.

Two important concepts defined here and used throughout this dissertation are UAV Module, and UAV Profile. The first consists of a modular component that can be connected to the MR-UAV to add or modify a specific functionality or characteristic. For example, a sensor module can be plugged to add a specific sensing ability or a powertrain module can be added to achieve different flight characteristics.
Profile is a broader concept consisting of a set of modules that are carefully chosen to fulfill the requirements of a specific mission. For example, a profile designed for search and rescue missions will allow long flight times with advanced sensors for locating humans, while a profile for delivery can carry heavier payloads instead. This dissertation presents and validates a systematic process to choose the hardware components (motors, propellers, electronic speed controllers, and batteries) to create optimal modules that best fulfill the requirements of each profile. Additionally, an algorithm to calculate flight time using data collected from a dynamometer is presented, followed by the design of a software tool that streamlines the proposed hardware selection and flight time calculation process.

Following, this dissertation presents the technical specifications of a prototype based on the modular framework and built following the aforementioned process. To evaluate the proposed design, two usability studies were conducted. In the first study, 8 participants interacted with the framework, provided feedback, answered a standard usability questionnaire. Additionally, it was measured the average time to assemble and disassemble each profile. Following a remote study was conducted with 8 subject matter experts (military personnel). In this study, participants watched a video presenting the framework, assembly procedures, and three different profiles. Following the video, they provided insights, suggestions, and discussed how they believe the framework can benefit military organizations. Results of this study, together with results of the focus group study lead to future work considerations for modular MR-UAVs for military applications, which are also presented in this dissertation.

1.1 Motivation

In his previous work in the field of human-drone interaction, the author researched how humans interact with UAVs[10], novelty control modalities such as brain-controlled UAVs[11][12][13][14], immersive user experiences such as First-Person View flying[15][16], and how to use UAVs to teach STEM [17]. These research projects motivated him to write a survey on the field of human-drone interaction, and while doing so, the author discovered that an MR-UAV which can be tailored to fulfill the requirements of different military applications does not exist. Currently available MR-UAVs are designed for a single
application and have limited modularity. Therefore, this dissertation is motivated by the inexistence of such a modular system. Additionally, the goal of this dissertation is to provide a framework that allows a military organization to have a single system to fulfill the requirements of all class 1 MR-UAV applications and to evaluate how users interact with modular MR-UAVs.

1.2 Research Questions

- Research question 1 - How can modularity be explored to increase the efficiency of MR-UAVs use in military organizations in terms of cost, performance, and usability?
- Research question 2 - What are military personnel views towards modular MR-UAV’s?
- Research question 3 - What benefits does a modular MR-UAV present to a military organization?
- Research question 4 – How can hovering flight time of MR-UAVs be accurately estimated based on motor and propeller data collected from a thrust stand?
- Research question 5 – What is the electronic circuit design required to enable MR-UAVs to shift its power supply from a tethered cable to an onboard battery without a significant voltage drop, allowing it to make the transition during flights?

1.3 Structure of the Dissertation

The rest of the dissertation is structured as follows. Chapter 2 presents the literature review related to the topics covered in this dissertation. Chapter 3 explores the concept of modular MR-UAVs in the military by presenting the focus group study performed with subject-matter experts and its results. Chapter 4 discusses how to estimate flight-time and optimize overall flight efficiency. Following, Chapter 5 presents the design and validation of the power-management board. The design of the modular MR-UAV framework is presented in Chapter 6, followed by the implementation of the prototype in Chapter 7. The evaluation of the system and its usability is discussed in Chapter 8. Lastly, Chapter 9 concludes this dissertation, summarizes its contribution, and discuss future directions.
Chapter 2: Literature Review

2.1 UAVs in the Military

The first uses of UAVs in military operations date back to 1917 during World War 1 when the United Kingdom employed radio-controlled aircraft loaded with explosives [18]. Following, during most of the twentieth century, States have explored the use of UAVs in military operations [1]. In 1996 the United States Air Force Scientific Advisory Board (SAB) conducted a study on the role of UAVs in the military, finding that such systems would play a key role in enhancing the nation’s military power [19]. UAVs can provide value in military operations, especially as they incorporate high levels of automation and become advanced robotic systems [20].

UAVs can provide various advantages to military operations. They provide high levels of situational awareness, a key component to achieve success in battleground environments [2]. Furthermore, they facilitate high-risk operations without endangering pilots [1][3]. Additionally, when compared to manned aircraft they increase portability due to their small footprint, lower cost, and they allow maneuvers that require accelerations higher than a human can pilot could withstand [1]. Furthermore, military UAVs range from small portable systems that can be carried on a backpack to large surveillance and weaponized aircraft such as the Global Hawk, Predator, Reaper, and Avenger [21]. Their application consists of supporting ground forces or participating in the targeting process [22]. While providing support, UAVs serve as Close Air Support (CAS), security over-watch, communication relay, and reconnaissance. In the targeting process, they can aid target development, target clearance, and battle damage assessment [22].

2.2 Modularity in Robotics and UAVs

Modular ground robots, capable of changing their shape are considered valuable systems, as they can adapt to different tasks and environments [23]. They are promising systems to provide versatility,
robustness, and low-cost [8][23]. Such modularity has been explored in ground robots of different shapes [24][25][26], and even on distributed robots [27]. However, the same research abundance is not found in modular UAVs, as few studies have explored such a concept. As UAVs are robotic systems, it is natural that they can also benefit from modularity.

Due to their growing popularity, MR-UAVs are considered a current hot research topic with studies ranging from human-drone interaction [10] to control theory [28]. However, the same research abundance is not found in modular UAVs, as few studies have explored such a concept. One study specifically presents Polidrone, a modular UAV framework with plug and play arm designs [29]. Polidrone allows the user to customize the system in terms of the number of arms (three to eight), and arm design customization (one motor, two motors, or one motor and one inflatable element per arm). Configurations with the inflatable element on the bottom of the arms allow Polidrone to land on water and uneven terrains, allowing amphibious operations. Furthermore, Polidrone is printed using a Fused Deposition Modeling (FDM) additive manufacturing process and allows a maximum takeoff weight of two kilograms.

An Amazon patent describes the process of using modular UAVs for deliveries [30]. Depending on the shipment requirements, the UAV is assembled with different parts based on various considerations (weight, route, safety, weather, etc.). However, this patent focuses on the process of using modular UAVs for delivery and does not provide details on the modular system itself.

Furthermore, modularity has also been previously explored in fixed-wing UAVs [31]. This system consists of a modular fixed-wing UAV designed for reconnaissance, data acquisition, and general research. It consists of a main body and wing modules that can be connected in a short configuration (two wing modules) for fast speed and long-range applications, or a long configuration (4 wing modules) for endurance and short take-off and landing operations. The system is easy to transport as it can be taken apart and easy to repair as wing modules are standard and interchangeable.

This dissertation differs from the aforementioned because it describes a design that allows the tailoring of the MR-UAV at higher levels than previous systems. The framework allows the user to
customize the flight characteristics (flight time, speed, maximum payload), sensors, and communication channels (video and datalink) to match the requirements of a specific operation. Additionally, this work is the first to explore the concept of modular MR-UAVs for military operations.

### 2.3 Increasing Flight Time and Tethered UAVs

As MR-UAVs usage continues to grow, various researchers have focused on developing alternatives to increase flight time. For instance, a review of power supply architectures for MR-UAVs is presented in [32]. In this work, the authors present and discuss the advantages and disadvantages of methods such as battery swapping [33][34], laser-beam recharging during flight [35][36][37], solar-powered [38], fuel-powered UAVs [39][40], tethered, and hybrid solutions. This work states the advantages of tethered MR-UAVs when compared to the other solutions: its ability to continuous operation, docking is not required, and the ability to also transfer data in real-time through the tether. The disadvantages consist of the requirement for a ground station, limited range of operation, and risk of MR-UAV damage when the tether is damaged. A discussion of the pros and cons of alternatives methods for powering surveillance MR-UAVs is also provided in [41]. This work includes alternatives such as attaching MR-UAVs to cableway and pantographs, mobile electric platforms that can transport and charge MR-UAVs, tethered and wireless charging solutions, as well as aerial docking stations powered by solar powers.

One approach to achieve continuous flight is to constantly swap discharged batteries for fully charged ones, which can be performed manually by the pilot or autonomously. For instance, Endless Flyer is a platform that autonomously exchanges MR-UAVs batteries allowing continuous flight indoors and outdoors [34]. This paper presents a system consisting of a landing station capable of automatically replacing a drained battery with a fully charged one without human intervention. The authors describe the design of the exchange platform, followed by their experiment results demonstrating that the prototype achieves a 90% success rate in the landing phase and 100% success rate in the battery exchange phase of the process. However, such a system does have a disadvantage when compared to tethered MR-UAV systems because there is a flight downtime while the battery is being replaced.
An important component of tethered MR-UAV systems is the ground control station, which serves as a power supply and controls the release and retreat of the cable. A detailed description of an autonomous base that controls the cable extension of a power-over-tether MR-UAV system can be seen in [42]. In this work, the authors present the autonomous platform that releases and retracts the tether cable, its control structure, specifications of a MR-UAV, and results of an experimental evaluation of the system. It is worth mentioning that their power-over-tether base does not communicate with the MR-UAV, instead, it estimates how much cable is necessary to provide a non-slacking tension on the cable without restricting the MR-UAV flight. Successful flights were achieved during the experiment with a small degradation in the trajectory due to the tension introduced by the tether cable.

Tethered MR-UAVs are usually employed in professional applications such as surveillance and exploration, however, they can also be used to enhance humans [43] and human-drone interaction. Falconer, a tethered MR-UAV prototype that serves as a personal companion is presented in [43]. The authors present the prototype as a method to provide an out of body experience to the user for applications such as perception augmentation, sports augmentation, and to engage telepresence. In this system, the user carries a large battery in a backpack, which is connected to Falconer through a 5-meter tether cable providing video-feedback in real-time. For instance, in a rock-climbing activity, users would be able to better plan their moves as the MR-UAV provides a broader image of their environment. The user can control (take-off, hover, and land) the MR-UAV using gestures, and the MR-UAV follows the user flying while connected to the backpack. The prototype was built using the Parrot Bebop2 MR-UAV because of its small size, light weight, and ability to fly both indoors and outdoors, characteristics desired in a companion MR-UAV. To decrease the gauge and weight of the tether cable, the power supply provides a higher voltage (48V), which is reduced on the MR-UAV to 12 V using a DC-DC circuit.

Previous related work cover MR-UAVs capable of flying while connected through a tethered, but without an onboard battery. In [44], the authors propose Evercopter, a continuous sensing system that allows multiple quad-copters to achieve continuous flight while connected to each other and a ground
station through tether cables. Additionally, the MR-UAVs at the end of the connected network are called leaf drones and can detach themselves to fly longer distances using the on-board battery. Differently than previously reviewed literature, Evercopter would allow MR-UAVs to fly both while connected to the ground power supply as well as when detached from the tether. The paper describes the control technique on how to attach and detach the leaf drones during flight using a magnet-based connector, it also presented a prototype using a custom-built power supply and Parrot ARDrones. However, details on the power management circuit that allows the MR-UAV to switch from tethered to the remote operation are not provided in the paper. Another work that explored the concept of a swarm of MR-UAVs connected through tethers is presented in [45]. In this work, the authors focus on the model and control approach used to coordinate each MR-UAV and the coordination of the swarm as a whole. Their system was tested through numerical simulations, and the authors suggest the implementation of a prototype in future work.

2.4 Focus Group as Qualitative Research Tool

Focus group research is a widely accepted method among research communities [46], and it has been used in a variety of settings ranging from business to academia [9]. It has been previously defined as "a research technique that collects data through group interaction on a topic determined by the researcher" [47], "an informal discussion among selected individuals about specific topics" [48] "qualitative data collection technique that capitalizes on the interaction within a group to elicit experimental data" [9], and "a technique involving the use of in-depth group interviews in which participants are selected base on a purpose" [49]. Simplifying, a focus group session consists of users having an informal conversation and providing insights about a specific topic, while a moderator guides the conversation. It is the moderator's job to keep the discussion on-topic while encouraging the participants to interact and talk freely [46]. This method presents advantages over one-on-one interviews, mainly because it uses group interaction to collect data and insights that would not be accessible without the participants interacting as a group [46]. These sessions are particularly useful to elicit user's understanding, opinions, and views about the topic [50] and its participants are selected based on the criteria that they can provide insights on the research topic [51].
Based on the above definitions and characteristics, it was decided that focus group sessions with subject-matter experts in the field of military UAVs would be a well-suited research strategy to explore the field of modular UAVs and elicit their user's requirements in a military environment.

2.5 Usability Studies and the System Usability Scale

Usability is an important quality for any system; however, it is not an easily defined term. Perhaps, this difficulty exists because usability is not a quality that exists with the system itself, instead, it is related to how a user interacts with it. Usability is related to user performance, satisfaction, and acceptability when interacting with a system [52]. Additionally, the concept has also been defined as “a general quality of the appropriateness to the purpose of any particular artefact” [53]. The System Usability Scale (SUS), was developed as a “quick and dirty” low-cost method to assess the usability of systems [53]. The SUS is a highly robust and versatile tool that allows a “usability practitioner to quickly and easily assess the usability of a given product” [54]. SUS is a Likert scale that collects a user's subjective evaluation of a system’s usability. This simple, ten-item scale is widely adopted within the research community; at the time of this writing, the original article has been cited more than 10000 times.

An empirical evaluation of SUS is provided in [54]. In this study, the authors analyzed 206 studies consisting of 2324 individual SUS results to provide a scoring benchmark. A SUS score can range from 0 to 100, and the authors found that the mean score over the 2324 surveys was 70.14 (standard deviation of 21.71), and the mean score for the 206 studies to be 69.69 (standard deviation of 11.87). This study found the least passable SUS score as 70, good scores between the high 70s and 80s, while the superior products scored better than 90. This same study found six beneficial approaches in using the SUS as “(1) providing a point estimate measure of usability and customer satisfaction, (2) comparing different tasks within the same interface, (3) compare iterative versions of the same system, (4) compare competing implementations of a system, (5) assessment of comparable user interfaces, and (6) compare different interface technologies” [54].
Human-robot interaction (HRI) studies often evaluate the usability of a robotic system. However, HRI studies are time, resource, and personnel consuming [55], therefore, they are typically conducted with a relatively small number of participants [55][56]. An alternative approach is to conduct remote HRI studies using videos followed by a questionnaire, instead of physical interaction. Similar results have been achieved when comparing in-person and video-based HRI studies [57][58]. Additionally, remote studies can be especially beneficial at the early stages of research, where a pilot and exploratory trials can be conducted before full live trials [48]. Studies comparing results from in-person and video-based studies suggest various advantages to remote studies, such as the ability to reach a larger number of participants in a short time, greater control for a standard methodology, and reach participants located in different geographic locations [55][56].

2.6 Human-Drone Interaction

As MR-UAV usage in the military continues to increase, it is important to understand how operators can interact with these systems. Although some knowledge can be derived from the field of human-robot interaction, MR-UAV's unique characteristic to freely fly in a 3D space, and unprecedented shape makes human-drone interaction (HDI) a research topic of its own [10]. Even though HDI is a growing research field, there is a lack of research on how users interact with modular MR-UAVs. Understanding this interaction can enable the research and development of MR-UAVs that better fulfill the users’ needs, and increases the usability of these systems.

Current HDI work consists of developing control modalities based on gesture [59], speech [60], brain-computer interfaces [11][12][13][14], and multi-modal interfaces [61]. Additionally, human-drone communication can be enhanced by adding new channels of information between the human and the system, such as using LEDs to communicate directionality [62], and drone's movement to acknowledge system attention [63]. Further examples of research in the field are the evaluation of interaction distances [64], social drones [65], developments of new use cases, and immersive first-person view flight experiences [15][16].
Chapter 3: Exploring the Concept of Modular Multi-Rotor UAVs

3.1 Focus Group Research

To first explore the concept of modular Multi-Rotor UAVs (MR-UAVs), three focus group sessions with subject-matter experts from the military were conducted, in this case, military personnel with UAV experience. The goal of this study was to explore the concept of a modular MR-UAV, understand the physical environment in which it would be used, and envisioned applications for it. This study was approved by the USF IRB department under the name of “Modular UAV – Focus Group” and IRB #00039142. The IRB approval letter can be seen in Appendix B. This chapter presents the methodology and results of this study, which contributes to this dissertation’s research questions one, two, and three.

3.1.1 Participants

A total of three focus group sessions were conducted, adding to a total of ten participants (n = 5, 2, 3). All ten participants were either active or retired military personnel and all of them had previous experience with military UAVs. As shown in Table 3.1, their experience ranged from UAV operators, engineers, maintainers, and logistics.

3.1.2 Methodology

Before each session, participants were explained the process of the experiment, informed that the session was audio recorded, and signed an informed consent form. Following, each participant provided an overview of their experience with UAVs. Furthermore, the session moderator guided the discussion to cover current uses of small UAVs, how the concept of a modular MR-UAV framework can be explored to better fulfill the needs of military organizations, and use cases for the proposed system. Finally, each session’s audio-recording was transcribed by two researchers. The session moderator used the following list of questions to guide the discussion:
Table 3.1 Focus group research participants and their UAV experience.

<table>
<thead>
<tr>
<th>Role / UAV Experience</th>
<th>Number of Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>User / Operator – participant has operated UAVs in missions (air support, surveillance, etc), during military career.</td>
<td>5</td>
</tr>
<tr>
<td>Manager - participant has played administrative roles related to UAV during military career: managed UAV offices, initiatives, purchases, etc.</td>
<td>2</td>
</tr>
<tr>
<td>Engineer - participant has developed, tested and built UAVs during military career.</td>
<td>1</td>
</tr>
<tr>
<td>Logistician – participant was responsible for the logistics involved with UAVs: ordering parts, transporting and storage.</td>
<td>1</td>
</tr>
<tr>
<td>3-D printer – participant was responsible for manufacturing 3-D printed parts for UAVs during deployment.</td>
<td>1</td>
</tr>
</tbody>
</table>

The following questions were utilized before explaining the concept of a modular MR-UAV:

- Please describe your experience with Unmanned Aerial Vehicles.
- How are small/portable UAVs currently being used in the military?
- What are possible new uses for small UAVs in the military?

At this point, the moderator provided an overview of a modular MR-UAV concept and proceeded with the following questions:

- What advantages do you foresee with the use of a modular MR-UAV?
- What MR-UAV profiles do you foresee useful?
- What problems and challenges do you foresee with the proposed project?
- Discuss a payload UAV for carrying equipment. What kind of equipment do you envision? Any thoughts you would like to share about a payload UAV?
• Discuss an agile UAV, capable of fast flying with possible shorter flight times and lower payloads.

What are your thoughts on this MR-UAV? How could it be used?

• Discuss an UAV with longer flight times and small payloads. What equipment would be useful?

What are your thoughts on this profile?

At the end of each session, to rank the profiles participants envisioned to be the most useful for the initial version of the modular framework, they were given a paper and pencil and asked to write down in order (vote) 3 modular MR-UAV profiles that they believed to be the most useful for military operations. These were the three profiles implemented in this dissertation.

3.2 Results

3.2.1 Use Cases

Participants from all sessions stated that UAVs are currently broadly used in the military for different applications. A trend found among different discussed use cases is the use of the UAV to provide full-motion video (FMV). For instance, class 1 UAVs are being used for surveillance and reconnaissance missions. Participants stated that FMV plays a crucial role during ground operations and preparation missions. Participants also discussed that class 1 UAVs are currently designed for specific missions such as target acquisition support. Lastly, another use case discussed by various participants was the use of these systems as relay nodes. In the words of a participant “to raise a 100 feet communication tower can be expensive and slow, it is much cheaper and faster to deploy an UAV”.

During every session, participants also discussed new use cases for class 1 UAVs and how their overall usage can be improved. One desired functionality brought up during all three sessions is the ability for tethered UAV’s to release the tether cable during the flight to operate while supplied by an onboard battery. For instance, this would allow a tethered surveillance UAV hovering above a military base to drop the cable to inspect a suspicious activity beyond its visual range. Participants stated that the UAVs they used had to be either powered from the cable or a battery, but did not provide the ability to switch operation during flight. Participants were also interested in the development of use cases such as autonomous target
and facial recognition, autonomous mapping to recreate high-resolution high-fidelity representations of target regions, and the improvement of the payload-carrying ability of current systems.

3.2.2 Modular MR-UAV Profile Ranking

As described, each participant was asked to vote for three modular MR-UAV profiles they believed to be the most useful at the moment. Due to time other commitments, two participants had to leave the session before the voting phase, therefore only 24 votes were acquired. The voting results are presented in Table 3.2 Ranking for modular MR-UAV profiles.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Profile</th>
<th>Number of votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full-motion video (FMV) UAV for surveillance/reconnaissance</td>
<td>9 (37.5%)</td>
</tr>
<tr>
<td>2</td>
<td>Payload UAV for delivering packages</td>
<td>7 (29.1%)</td>
</tr>
<tr>
<td>3</td>
<td>Tethered UAV for surveillance</td>
<td>4 (16.6%)</td>
</tr>
<tr>
<td>4</td>
<td>Communication relay node</td>
<td>2 (8.3%)</td>
</tr>
<tr>
<td>5</td>
<td>3-D mapping UAV</td>
<td>1 (4.1%)</td>
</tr>
<tr>
<td>6</td>
<td>Mothership UAV that releases small UAVs to collect intel and report back to mothership UAV</td>
<td>1 (4.1%)</td>
</tr>
</tbody>
</table>

3.2.3 Qualitative Results

The discussion during the focus group suggest a need for MR-UAVs and that they can be beneficial in military operations. All ten participants expressed that this system would be useful to their needs and that it is a novel concept. For instance, one participant summarized this system’s advantages as “the fact that you can have one drone that you can send out and take care of multiple issues”. A summary of the key advantages discussed by participants can be seen below:

- Mission-specific flight characteristics - the modularity of the system allows the user to tailor its flight-time, and maximum payload capability. Therefore, the military operator can select the
modules and assemble a system that fulfills the requirements of a specific mission in terms of these characteristics.

- **Mission-specific functionality** - operators can also customize which sensors and actuators modules are plugged in the MR-UAV according to the requirements of their mission. For instance, if the system will be used for a search-and-rescue operation, a high definition and a thermal camera can be plugged into the system. Another example would be the use of a radio-frequency scanner module that can be used to monitor data communication in an area (useful for electronic warfare), in this case. These two use cases differ in requirements, but the operator would be able to use the same MR-UAV in both of them by connecting the appropriate module.

- **Mission-specific communication channels** - depending on the operating environment, the user can select the best communication channel (datalink and video) for that operation. Users can tailor communication protocol, power, and frequency. For instance, when operating in a heavily interfered Wi-Fi environment, the user can use a 900MHz radio instead of a 2.4GHz.

- **Improved logistics** - as modules can be stored and transported separately, it presents a smaller footprint than a regular MR-UAV making it easier to store and transport. Additionally, it also allows the MR-UAV to be carried on backpacks during on-foot operations. Furthermore, logistics is also enhanced because a smaller number of systems need to be maintained as a single MR-UAV can replace various other systems.

- **Improved maintainability** - maintainability is increased as broken modules can be easily replaced by working ones. Such a feature even allows operators to fix systems out in the field without requiring special tools.

- **Shorter training times** - modularity decreases the number of systems that operators must be trained on; therefore, it decreases training time. For instance, users would not require training in how to fly an MR-UAV for surveillance and another for deliveries. As the same platform is used in both operations, a single training is required.
• Decrease in overall cost - the above advantages also decrease the overall cost involved with an MR-UAV, including the training, logistics, and operational costs.

3.2.4 Requirements for a Modular MR-UAV

As participants discussed their desired characteristics in a modular MR-UAV framework, some requirements emerged as essential. These requirements are discussed below.

• Flight time versus payload – participants discussed how most applications require a balance between flight time and the ability to carry payloads of different weights. They stated that the ability to easily tailor these characteristics would be a beneficial characteristic of the modular MR-UAV. This requirement leads to the development of a powertrain module, later discussed in Chapter 6.

• Adjustable communication – participants also stated that one of the most beneficial features would be to have the ability to tailor the communication channels with the MR-UAV. Such ability would allow the operator to tailor the MR-UAV to operate in environments with different radio-frequency interference. Also, by picking frequencies, the operator can achieve different operational range and characteristics such as signal penetration. This requirement leads to the development of the communication and video modules discussed in Chapter 6.

• Easy assembly procedures – Soldiers operate MR-UAVs under high-stress environments; therefore, it is important that the assembly procedures should be as simple and quick as possible and require the least number of tools.

• Size – a modular MR-UAV would be used in two scenarios. First, carried by a soldier in a backpack, a use case where smaller size and weight are important considerations. Secondly, as a tool for military bases and convoys, in which case, size and weight are not as important. Therefore, the modular framework must allow the implementation of different sizes of MR-UAVs.

• Easy maintenance – military UAVs are operated in harsh environments. Participants discussed that it is common to brake systems and that they should be easily maintainable. Additionally, participants described that when possible, parts should be 3-D printed because they have access to
3-D printers in the military bases and could easily print broken parts. They also suggested that 3-D parts are beneficial because it would allow them to modify them as needed.

- **Cost** – participants stated that among all the other advantages of a modular system, the cost would be one of the main driving factors that would differentiate this system from other currently employed systems.
Chapter 4: Estimating Flight Time and Optimizing Efficiency

This chapter presents the methodology to estimate hovering flight time, and how to optimize flight efficiency through the selection of hardware components for the modular Multi-Rotor Unmanned Aerial Vehicle (MR-UAV). Additionally, it is present a software tool designed to streamline the process of developing profiles for the modular framework. This chapter focuses on this dissertation’s research questions one and four.

4.1 Powertrain Data Collection

This section discusses how to collect data related to the thrust generating components: brush-less motor and propeller. The procedure presented to estimate flight time relies on UAV thrust, propeller efficiency, motor efficiency, battery capacity, UAV weight, and payload weight. Such data is required to estimate flight-time and increase flight efficiency as discussed in the sections below.

4.1.1 Equipment

The 1585 series thrust stand and dynamometer manufactured by RCBenchMark was utilized to collect data. This is a research-grade device that allows optimization of the electric propulsion system. The thrust stand and setup utilized to collect data can be seen in Figure 4.1. Additionally, the software interface for the thrust stand can be seen in Figure 4.2. This interface allows users to manually control the data collection, or autonomously through scripting. The 1585 series can measure motor and propeller combinations of up to 5 kgf of thrust, 1.5 Nm of torque, 2750 Watts of power, and 22 inches propeller.
Figure 4.1 RCBenchmark 1585 thrust stand used to collect brush-less motor and propeller data.

Figure 4.2 RCBenchmark 1585 thrust stand data acquisition software.

The RCBenchMark 1585 thrust stand allows the following measurement:

- Torque (Nm)
- Thrust (kgf)
- Voltage (V)
• Current (A)
• Rotation per minute (RPM)
• Motor winding resistance (Ohm)
• Acceleration and vibration (g)

Additionally, using the above measurements, the thrust stand calculates the following indirect measurements:
• Motor efficiency (%)
• Propeller efficiency (g/W)
• Overall efficiency (g/W)

4.1.2 Thrust Stand Data Collection Procedures

For each powertrain combination of motor and propeller, a data log is recorded following these procedures:

1. Install the brush-less motor in the 1585 thrust stand.
2. Install the propeller in the motor shaft. It is important to install the propeller in a pusher configuration to minimize ground effect due to the stand’s mechanical structure.
3. Power the 1585 thrust stand with a lithium-polymer battery matching the number of cells desired for this powertrain combination.
4. Verify that the rotation direction matches the pusher configuration. If not, reverse the rotation by exchanging two cables between the motor and electronic speed controller from the thrust stand.
5. Start the data collection by running the Javascript code presented in Appendix A. This script controls the motor output from 0 to 100% by increasing the output 10% at a time. At each step:
   1. Wait 3 seconds for rotation speed settlement.
   2. Collect 100 measurements.
   3. Average measurements.
   4. Save results in the log file.
4.2 Estimating Flight Time

Flight time can be interpreted as a function of the usable battery capacity and the required power for flight. The algorithm below is based on the algorithm presented by [66]. An ideal motor would convert all of the consumed electrical power to mechanical power; however, brush-less motors present less than ideal efficiency because of heat losses. Therefore, the motor efficiency was added to the algorithm. Additionally, parameters regarding the electronic components and payload power consumption were also included. Lastly, a battery discharge limit was also added as lithium-polymer batteries should not be fully discharged as it causes physical damage to the cells.

Battery capacity is represented in Watts/hour and can be calculated as follows:

\[
BattCapacity(Watts/\text{Hour}) = ElectricCharge(\text{Amperes}/\text{Hour}) \times NumberofCells \times 3.7(\text{Volts})
\]

As mentioned above, lithium-polymer batteries should not be fully discharged to prevent physical damage to the cells. Therefore, the usable battery capacity becomes:

\[
AvailableBatteryCapacity(W/\text{h}) = BatteryCapacity(W/\text{h}) \times Dischargelimit
\]

The UAV all-up-weight (AUW) is calculated following:

\[
AUW(kg) = UAVweight(kg) + Batteryweight(kg) + Payloadweight(kg)
\]

The required thrust per propeller to hover during flight is:

\[
ThrustperPropeller(kg) = \frac{AUW}{\text{Number of Propellers}}
\]

The propeller efficiency is the ratio between the generated thrust by the mechanical power required to spin it:

\[
PropellerEfficiency(N/W) = \frac{\text{Thrust}(N)}{\text{MechanicalPower}(W)}
\]

which can also be re-written as:

\[
PropellerEfficiency(N/W) = \frac{\text{Thrust} \ (N)}{\text{Torque}(Nm) \times RotationSpeed(\frac{\text{rad}}{s})}
\]

The overall efficiency can be calculated as follows:
Overall Efficiency (N/W) = Motor Efficiency (%) * Propeller Efficiency (N/W)

The mechanical power to hover the UAV is:

\[
\text{Mechanical Power (Watts)} = \frac{AUW (kg)}{\text{Overall Efficiency At Thrust Propeller} (N/W)}
\]

The total power required by the UAV is:

\[
\text{Power (W)} = \text{Mechanical Power (W)} + \text{Avionics Electrical Power (W)} + \text{Payload Electrical Power (W)}
\]

Finally, flight time can be estimated:

\[
\text{Flighttime (min)} = \frac{\text{Available Battery Capacity (W/h)}}{\text{Power (W)} \times 60}
\]

4.3 Validating Flight Time Estimation

In this section, a methodology to measure flight time is presented, which allows to calculate the accuracy of the flight time estimation algorithm above.

4.3.1 Methodology

Flight time is directly related to the MR-UAV power consumption. Although the electronic circuits onboard of the MR-UAV can provide a power consumption value, such values rely on the on-board current sensor. These measurements are dependent on the sensor calibration, which if done improperly can provide inaccurate values. Therefore, to reliably and consistently calculate the flight time without depending on the onboard electronics, these procedures were followed:

1. Connect a fully charged battery to the MR-UAV.
2. Command the MR-UAV to take-off to 10 feet.
3. Autonomously hover the UAV for 10 minutes.
4. Land UAV and remove battery.
5. Fully recharge battery, recording the energy capacity transferred from the charger to battery.
6. Calculate power consumption per minute following:
\[ \text{PowerPerMinute} = \frac{\text{RechargedPower}}{\text{Flighttime (10min)}} \]

7. Calculate flight time following:

\[ \text{Flighttime} = \frac{\text{Batterycapacity} \times \text{Batterylimit}}{\text{PowerPerMinute}} \]

8. Repeat steps (1)-(7) during three flights, and calculate average flight time.

The above procedures were also repeated during flight using three different MR-UAV prototypes to test the algorithm with different multi-rotor configurations. The prototypes included different number of battery cells, weight, motor speed (KV) and different size propellers. For the first two prototypes, the experiment was performed first without any payload, and secondly while the quad-copter was carrying a 500grams payload. The third prototype was only used without a payload as the 500grams extra weight would decrease the MR-UAV to a thrust-to-weight ratio below 2 to 1. The specification for each prototype used to validate the time estimation algorithm can be seen in Table 4.1 below.

**Table 4.1 MR-UAV prototypes used to validate flight-time estimation algorithm.**

<table>
<thead>
<tr>
<th>Prototype #</th>
<th>Motor</th>
<th>Propeller</th>
<th>Weight (grams)</th>
<th>Battery</th>
<th>Battery Weight (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EMAX 2213 935Kv</td>
<td>APC</td>
<td>920</td>
<td>4 cell</td>
<td>447</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10x45MR</td>
<td></td>
<td>4500mah</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>EMAX 3510 600Kv</td>
<td>APC</td>
<td>1370</td>
<td>4 cell</td>
<td>447</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15x55MR</td>
<td></td>
<td>4500mah</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>EMAX 2213 935Kv</td>
<td>APC</td>
<td>920</td>
<td>3 cell</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10x45MR</td>
<td></td>
<td>500mah</td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 Results

The measured flight time for each prototype can be seen in Table 4.2. This table displays the power consumption for each of the three flights, the calculated flight time, and the average flight time.
Additionally, Table 4.3 presents a comparison between the measured flight times and estimated flight times using the algorithm presented in Section 4.2. As seen, the highest flight estimation accuracy was achieved with prototype 2 (99.72% without carrying a payload, 98.96% while carrying a 500gram payload). The lowest estimation accuracy (97.97%) was achieved with prototype 3. Overall, the average accuracy of all 5 tested scenarios was 98.94%, which validates that this algorithm can be used to estimate the hovering flight time of brush-less motor MR-UAVs.

4.4 Optimizing Flight Time

Optimizing flight time requires finding a balance between the propeller and brush-less motor efficiency. Increasing the size of the propeller increases its efficiency, however, it also increases the torque necessary to spin it. Brush-less motors on the other hand present high-efficiency when spinning at fast speeds with low torque. In other words, although increasing the propeller size will increase the propeller efficiency it will decrease the motor efficiency due to higher torque demand. Therefore, a balance between the propeller and motor efficiency is necessary to increase overall flight efficiency and flight time. The algorithm shown in Figure 4.3 was first presented by [66], and implemented the Multi-Rotor Designer software tool (later presented in Section 4.5). This algorithm is also used in the process of creating profiles for the modular MR-UAV (later discussed in Chapter 6).

Table 4.2 Measured flight times for 3 prototypes. PC = power consumption (mah), FT = flight time (min).

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC</td>
<td>FT</td>
<td>PC</td>
<td>FT</td>
</tr>
<tr>
<td>P1 – No payload</td>
<td>1950</td>
<td>18.46</td>
<td>1920</td>
<td>18.75</td>
</tr>
<tr>
<td>P1 – 0.5 kg Payload</td>
<td>2930</td>
<td>12.28</td>
<td>3070</td>
<td>11.72</td>
</tr>
<tr>
<td>P2 – No payload</td>
<td>1611</td>
<td>22.34</td>
<td>1720</td>
<td>20.93</td>
</tr>
<tr>
<td>P2 – 0.5 kg Payload</td>
<td>2531</td>
<td>14.22</td>
<td>2630</td>
<td>13.68</td>
</tr>
<tr>
<td>P3 – No payload</td>
<td>2530</td>
<td>17.39</td>
<td>2630</td>
<td>16.73</td>
</tr>
</tbody>
</table>
Table 4.3 Comparison between measured and estimated flight time.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Average Measured Flight Time (min)</th>
<th>Estimated Flight Time (min)</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 – No payload</td>
<td>18.82</td>
<td>19.05</td>
<td>98.78%</td>
</tr>
<tr>
<td>P1 – 0.5 kg Payload</td>
<td>12.09</td>
<td>12.01</td>
<td>99.25%</td>
</tr>
<tr>
<td>P2 – No payload</td>
<td>21.56</td>
<td>21.51</td>
<td>99.72%</td>
</tr>
<tr>
<td>P2 – 0.5 kg Payload</td>
<td>13.88</td>
<td>13.74</td>
<td>98.96%</td>
</tr>
<tr>
<td>P3 – No payload</td>
<td>17.01</td>
<td>16.67</td>
<td>97.97%</td>
</tr>
<tr>
<td></td>
<td>Average Estimate Accuracy</td>
<td>98.94%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.3 Step-by-step process to select motor and propeller for efficient MR-UAV [66].

- Step 1 - the designer estimates the weight of the final product to calculate the required thrust per propeller. This step consists of an estimation as the selected propeller, motor, and battery will impact the final MR-UAV weight.
• Step 2 – the thrust required per propeller is known from the previous step. A thrust stand such as the RCBenchMark 1585 can be used to collect thrust, torque, and rotation speed from different propellers using the same motor. Propeller data can be analyzed independently of the motor because the thrust generated is a function of the rotation speed. Plotting Thrust vs. RPM, Torque vs. RPM, and Propeller Efficiency vs. Thrust provides valuable information to the developer during the propeller selection process. Examples of these graphs can be seen in Figures 4.4, 4.5, and 4.6.

• Step 3 – once the propeller is selected. A thrust stand can be used to test the propeller with different motors. Plotting the motor efficiency vs. thrust (see Figure 4.7), allows the selection of the most efficient motor to achieve the desired thrust using the previously selected propeller.

![Graph of Thrust vs RPM](image.png)

**Figure 4.4 Example of Thrust (kgf) vs RPM plot used during the propeller selection process.**
Figure 4.5 Example of Torque (kgf) vs RPM plot used during the propeller selection process.

Figure 4.6 Example of Propeller Efficiency (kgf/W) vs Thrust (kgf) plot used during the propeller selection process.
• Step 4 – In the last step, a battery is selected through an iterative process using the flight time estimation algorithm presented in Section 4.2.

• Iteration – The selected motor, propeller, and battery might change the estimated AUW of the MR-UAV. In this case, steps 1-4 can be iterated to verify that the selected components are still the most efficient with the updated weight.

4.5 Multi-rotor Designer Software

This Section presents the design of a software tool named Multi-Rotor Designer (MRD). This software was developed to streamline the process described in Section 4.4) to select hardware components for the powertrain modules of the modular MR-UAV framework. This tool allows users to quickly plot and compares motors and propeller data. Additionally, it also implements the flight time estimation algorithm presented in Section 4.2. The MRD software presented three main windows. First, the “Propeller” window (Section 4.5.1) allows users to select up to 4 propellers for data comparison. Similarly, the “Motor” window (Section 4.5.2) allows users to select up to 4 motors for data comparison. Lastly, the “Designer” (Section 4.5.3) window allows the user to enter system parameters (battery capacity and weight, payload weight, MR-UAV weight) and it estimates the flight time for the selected powertrain (motor/propeller configuration).
4.5.1 Propeller Selection

The propeller selection screen can be seen in Figure 4.8. The screen is divided into three areas. The menu selection (marked as 1 in Figure 4.8), allows the user to change between the available screens. The propeller selection (marked as 2 in Figure 4.8) allows the user to add a new propeller to the graphs (Select Propeller push-button) or remove a propeller (Clear push-button), additionally, it displays the selected propeller information (name, size, pitch, weight). Lastly, in the graphing area (marked as 3), the Thrust vs RPM, Torque vs RPM, and Propeller Efficiency vs Thrust graphs are generated. As discussed in Section 4.4, these are the most relevant graphs during the propeller selection process.

![Multi-Rotor Designer Software propeller selection and graphing window.](image)

If the user selects to add a new propeller (pressing the Select Propellers push-button), the screen in Figure 4.9 is displayed. This screen allows the user to filter the desired propellers from the local MRD database, consisted of logs from the 1585 RCBenchMark thrust stand. Propellers can be filtered based on size and maximum thrust. Once a propeller is chosen, it can be added to any of the four slots (area 2 of Figure 4.9), by double-clicking it and selecting the slot on the displayed screen (Figure 4.10).
4.5.2 Motor Selection

The motor selection screen can be seen in Figure 4.11. The screen is divided into three areas. Similar to the propeller selection screen presented above, this screen also presents a menu selection (marked as 1 in Figure 4.11). Additionally, it allows the user to add a new motor to the graphs (see area 2) (List Motors push-button), remove a motor (Clear push-button), and displays the selected motor information (name, size, advertised KV, measured KV, weight). In the same area (2), the user can click on the Select Motor push-button to use specific motor data in the design calculations in the Designer screen (discussed in the next section). In the graphing area (marked as 3), the user can select the desired data to plot for each axis, which is displayed in the large graph at the center of the screen. For instance, Figure 4.11 displays the Motor Efficiency vs Electronic Speed Controller (ESC) signal for the four selected motors.

![Figure 4.9 Multi-Rotor Designer Software propeller filtering and selection window.](image)
Figure 4.10 Multi-Rotor Designer Software window to select desired propeller slot.

Figure 4.11 Multi-Rotor Designer Software motor selection window.

If the user selects to add a new motor (pressing the List Motors push-button), the screen on Figure 4.12 is displayed. This screen allows the user to filter the desired motor from the local MRD database, which consists of logs from the RCBenchMark 1585 thrust stand. Motors can be filtered based on stator height, width, and motor KV. Once a motor is chosen, it can be added to any of the four slots (area 2 of Figure 4.11), by double-clicking it and selecting the slot on the displayed screen (Figure 4.13).
4.5.3 Designer

The last screen in the tool is the Designer screen, which can be seen in Figure 4.14. On this screen, the user can enter the details of the desired MR-UAV, including its’ estimated weight, battery capacity, battery weight, number of battery cells, and number of propellers. This screen displays the information from the currently selected motor. Additionally, it uses the user input, selected motor and propeller data to calculate the total weight of the aircraft, maximum thrust, maximum thrust to weight ratio, and hovering flight time. The hovering flight time is calculated using the algorithm presented in Chapter 4. This screen also displays two additional graphs that aid the user in the MR-UAV design process. The graph on the left
plots the flight time based on the payload the UAV would be carrying. The graph on the right plots the flight time versus the ESC signal (throttle input), giving designers insight on how the MR-UAV flight time will be impacted by the flight style (e.g. slow and steady vs. aggressive flying).

The designer window allows users to modify parameters such as weight and battery selection and see how it will impact the MR-UAV performance (flight-time, payload, maximum thrust). This screen can be a valuable tool to implement the modular MR-UAV profile design process later discussed in Chapter 6.

![Multi-Rotor Designer Software designer and flight time estimation window.](image)

**Figure 4.14 Multi-Rotor Designer Software designer and flight time estimation window.**
Chapter 5: Power Management Board for Tethered and Remote Operation

This chapter presents and validates the electronic circuit for a Power Management Board (PMB) that allows UAVs to switch from tethered to battery-powered flight without landing. This functionality was elicited as required during the focus group research presented in Chapter 3. This chapter answers this dissertation’s research question five.

5.1 Power-Over-Tether UAVs

As discussed in Chapter 2, a current challenge of multi-rotor UAVs is their limited flight time. For instance, the flight times of commercial, off-the-shelf-models are usually 31 minutes or less [10]. To mitigate the flight time constraint, researchers have explored the use of solar-power energy [38], battery swapping [34], fuel cell [67], the hybrid internal combustion engine and electric motors [68] and tethered solutions [69][70][71]. The latter is further discussed in this chapter.

Tethered MR-UAVs are connected to a ground station through a cable, creating a direct link for power and real-time data transfer. A tethered MR-UAV system environment can be seen in Figure 5.1. Power-over-tether systems allow unlimited flight times at the expense of limiting the flight range due to the cable length. Alternatively, tethered MR-UAVs can be connected to vehicles [72], increasing the range of the system. For instance, this approach has been used to monitor oil pollution on the seas by having the tethered MR-UAV connected to a ship [73]. Applications for tethered MR-UAVs are diverse, ranging from providing live coverage for activities in a venue [70] to assisting firefighting [74]. Besides providing an unlimited power supply, ground stations must also provide a control mechanism to release and retrieve the tether cable without causing unnecessary tension to pull against the MR-UAV. The gauge of the cable must be calculated according to its length and the MR-UAV’S current requirement to mitigate the voltage drop.
on long cables. Furthermore, the tethered MR-UAV itself differs from standard ones because it requires a power management board (PMB) allowing it to be powered by the tethered power supply.

![Multi-Rotor Drone](image)

**Figure 5.1 Tethered MR-UAV environment.**

Additionally, a malfunction in the tether system (e.g., cable tearing, power supply failure) may cause a MR-UAV to crash. To mitigate the latter, [75] discusses a tethered MR-UAV with safety measures in case of malfunctions, for instance, a parachute can be deployed to decrease the damage in accidents. Another solution that mitigates both of these constraints is to add a redundant power source to the system, such as an on-board battery. For instance, in case of a tethered power supply failure, the system would switch its power source to the on-board battery. Additionally, if the applications require flights further than
the cable length allows, the MR-UAV can drop the cable and rely on the battery without needing to land the system. Although previous work has discussed applications where MR-UAVs can fly both using a power-over-tether or an onboard battery [44], there is no discussion on the power management board required to allow a MR-UAV to be connected to two power supplies simultaneously.

This dissertation further explores the concept of an MR-UAV capable of switching from tethered to battery operation during flight. The contribution presented in this chapter is the technical specifications and evaluation of a power management board (PMB) based on the LTC4412 Low Loss PowerPath Controller, allowing an MR-UAV to be connected to a tether cable and an on-board battery and instantly switch between these power sources when required. When tethered, the MR-UAV is powered from the ground power supply. The MR-UAV can switch to battery operation by dropping the tether cable under the pilot command, or in case of a malfunction in the tethered system. In this case, the PMB switches the MR-UAV power source to the on-board battery. Furthermore, this work presents the results of two experiments designed to measure the electrical characteristics and viability of the PMB. To validate the design, the circuit was first tested in a lab by measuring its output when switching between power inputs. Following, the feasibility of the PMB was tested in flight with a custom MR-UAV. Following, this chapter discusses the use-case scenarios for UAVs equipped with this power-management board in military operations.

5.2 Power Management Board Schematic

The schematic for the PMB electric circuit can be seen in Figure 5.2. As shown, the circuit has two inputs, one meant to be connected to a tethered power supply and one to an on-board battery. The circuit is based on the LTC4412 chip, which controls the circuit output with a P-channel MOSFET transistor. The LTC4412 is a low-loss power controller and an adequate solution for applications that require uninterruptible power supplies. According to the manufacturer datasheet, this chip allows automatic and near-ideal switching between power supplies; therefore, it is a suitable solution to switch the MR-UAV power supply between the tethered cable and onboard battery. In other words, if power is provided at the tether input, the LTC4412 will sense the voltage and turn off the MOSFET transistor allowing the current...
from the tethered input to freely flow to the output. Otherwise, the LTC4412 will turn on the transistor allowing the current from the battery to flow to the output. A capacitor is added to filter the circuit output and a Schottky diode to prevent back-current to the tethered input. A Schottky diode was used because of its low voltage drop when compared to a regular p-n junction diode. Additionally, the Schottky diode presents a fast switching speed, an important characteristic of this application. The Stat pin indicates the current power selection, which can be connected to an LED or to a digital input on the MR-UAV flight controller to notify the software of the system’s current power selection. The number of Electronic Speed Controllers (ESC) depends on the UAV configuration, for instance, a quadcopter requires four ESCs and a hexacopter requires six ESCs.

![Tethered Power-Management Board Circuit Schematic](image)

**Figure 5.2 Tethered power-management board circuit schematic.**

5.2.1 Circuit Specifications

The PMB electronic components were selected to exceed the power requirements of most MR-UAVs. At its current version and with the following components, the PMB is rated for inputs up to 35 volts and a maximum current flow of 60 amperes. The Table 5.1 presents a list of the components used to build the PMB. At the current configuration, the PMB supports a current of up to 60 amps, and if necessary, a higher current rating Schottky diode can be used for higher currents.
Table 5.1 Power-management board electronic components.

<table>
<thead>
<tr>
<th>Electronic Component Type</th>
<th>Component Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power path controller</td>
<td>LTC4412ES6</td>
</tr>
<tr>
<td>Transistor</td>
<td>MOSFET P-CH 60V 120A</td>
</tr>
<tr>
<td>Schottky Diode</td>
<td>DSS60-0045B-ND 45V 60A</td>
</tr>
<tr>
<td>Capacitor</td>
<td>220μF 35V</td>
</tr>
</tbody>
</table>

5.3 Experiment 1: Power-Management Board Validation in a Laboratory

The PMB circuit is based on a low loss integrated circuit (LTC4412), however, before testing the circuit in-flight, it is important to understand the systems' electrical characteristics to ensure its feasibility for the intended application. In this experiment, the goal was to measure the amplitude and duration of the voltage drop on the circuit output when switching its power input. The experiment was repeated to match the voltage of different lithium-polymer batteries commonly used to power MR-UAVs: 3, 4, 5, and 6 cells and their correspondent voltages 11.1V, 14.8V, 18.5V, and 22.2V.

5.3.1 Experiment 1: Methodology

Each input of the PMB circuit was connected to an independent output of an Instek GPS-3303 power supply. The circuit's output was connected to a Tektronix MSO-2022B oscilloscope. The oscilloscope was calibrated and set to trigger if there was a 0.1V voltage drop on the output line. For each test, two power supplies were connected to the circuit and monitored the output using the oscilloscope. Following, the power supply channel on the tethered input was disconnected while monitoring for voltage drops on the output line. First, the system was tested with the output connected to the resistor to simulate a load. The test for different voltage inputs (11.1V, 14.8V, 18.5V, and 22.2V) were repeated with a resistance chosen to pull 1 ampere due to the power supply maximum current rating.

Additionally, to ensure that the flight controller board would not reset or disarm the multi-rotor during the power switch, the circuit was connected to a custom-built MR-UAV without propellers and
repeated the test at 11.1V and 14.8V as the maximum input rating for this multi-rotor is 4 cell batteries (14.8V). First, the circuit was tested while the MR-UAV was disarmed (motors not spinning), and later while it was armed (motors spinning). During the first test, the current load was measured to be approximately 0.40 amperes due to onboard electronics (e.g. flight controller, sensors, etc.). While armed and without propellers, the load was measured to be approximately 2.5 amperes.

5.3.2 Results

Under all testing scenarios (resistor load, disarmed UAV, and armed UAV), there was not a visually noticeable voltage drops on the output line monitored on the oscilloscope screen. Additionally, the oscilloscope did not trigger under any occasion, confirming that there was not a voltage drop of 0.1V or higher on the output line. Furthermore, the UAV did not reboot or disarm when switching power supplies. Therefore, the results showed that the PMB works as intended and it is appropriate for further testing with in-flight scenarios.

5.4 Experiment 2: Power Management Board Validation during Flight

This second experiment was designed to validate the PMB functionality during flight. Therefore, a total of 30 flights were performed, in which the MR-UAV started in tethered operation and switched to battery operated (released tether) during flight.

5.4.1 Equipment

The PMB circuit was tested on the MR-UAV displayed in Figure 5.3. This is the prototype of the modular MR-UAV later presented in Chapter 6. This prototype is based on the following components: PixHawk Mini 4 flight controller, EMAX 2212 935Kv motors, Holybro Tekko electronic speed controllers, APC 10-inch propeller. The system was tested using a 5500mah 3 cell and a 4500mah 4 cell battery. Lastly, to remotely disconnect the tether cable during the flight, the custom 3-D printed connector and release system with a 20-gram servo displayed in Figure 5.4 were used.
Figure 5.3 MR-UAV used during tethered PMB flight testing.

Figure 5.4 Custom tethered cable 3-D printed release system.

5.4.2 Experiment 2: Methodology

To test the operation at two different voltages, the following procedures were performed with a 3-cell and a 4-cell battery. For each configuration, 15 flights and power switching were performed, the number of flights was chosen because of the flight time (when powered by a battery) of the prototype, allowing to test the system at different battery levels from fully charged to fully discharged.

- Connect MR-UAV to tethered power supply and battery.
• Take off and hover at 10 feet for 1 minute.
• Drop tether cable (switch to remote operation).
• Hover for 1 minute and land MR-UAV.

5.4.3 Results

All 30 flights were completed with a successful transition from tethered to remote operation. The MR-UAV did not reboot or disarm in any occasion. Therefore, the results of this experiment in addition to the previous experiment demonstrate that the PMB worked as intended.

5.5 Conclusion and Discussion

The above results demonstrate that the circuit design and components selected for the PMB are well-suited to be used in MR-UAV applications. The ability to instantly switch the MR-UAV power source from a ground power supply to an on-board battery provides advantages. First, powering MR-UAV from two different sources adds a beneficial redundancy to its operation. For instance, if the ground power supply of a tethered MR-UAV fails due to a power outage or circuit failure, the circuit automatically switches the power input to the on-board battery, preventing a crash. Additionally, MR-UAVs do not need to be designed either for tethered or remote operations, a single system can fulfill both uses. Therefore, allowing a variety of new applications where continuous flight time and eventual flights beyond the tethered cable length are required. The following subsections describe the use cases in which our PMB could be beneficial.

5.5.1 Stationary Tethered MR-UAV

The unlimited flight-time of tethered MR-UAVs is especially useful for applications that require a continuous view of a stationary location from an above perspective, also referred to as birds-eye view. However, in certain situations, it might be desired to fly the MR-UAV further than the tethered cable allows. For instance, a tethered MR-UAV can be used for surveillance of military bases, in which case it would hover at a high altitude without having to fly further distances. In case of suspicious activities outside the surveillance camera range, the tethered MR-UAV could switch to remote operation (without requiring landing) and fly to the area to inspect the activity.
5.5.2 Non-stationary Tethered MR-UAV

The unlimited flight times of tethered MR-UAV can also be an asset for providing a bird's eye view above a moving vehicle. For example, tethered MR-UAV can provide high-altitude images for military convoys, or naval ships. Previous work has used MR-UAV tethered to ships to monitor oil pollution on the seas [73]. The ability to switch from tethered to remote operations can also be beneficial in these cases, for instance, the MR-UAV could fly to the pollution area to better inspect the target without requiring the ship to maneuver and change its course. Similarly, a tethered MR-UAV can provide a birds-eye view of a moving military convoy while connected to a ground vehicle. In case of a suspicious activity detected ahead, the MR-UAV can transition to remote operation (drop tether cable) to inspect the activity before the convoy approximates to close distances of the activity.

5.5.3 Tethered Network of MR-UAVs

Lastly, the PMB presented in this dissertation allows for the creation of a network of tethered MR-UAVs, where individual ones can detach from the others as necessary. This work complements the work of [44] (presented in Chapter 2), where the concept of a sensing network of tethered MR-UAV was presented. In such work, the MR-UAV at the end of the network were called leaf drones and are capable of detaching from the network during flight. However, details about the electric circuit were not presented in [44].
Chapter 6: Design of a Modular Multi-Rotor UAV

This chapter presents the design of the modular Multi-Rotor Unmanned Aerial Vehicle (MR-UAV) framework and it focuses on this dissertation’s research question one.

6.1 Introduction

Recalling the definition provided in Chapter 1, this dissertation defines a modular MR-UAV as a system that allows the user to select and connect components to tailor its flight time, payload capability, sensors, and actuators. This dissertation also defines two important design concepts elicited during the focus group research presented in Chapter 5: modules and profiles.

- **UAV Module** - a component that can be connected to the MR-UAV to add or modify a specific functionality or characteristic. For example, a sensor module can add a specific sensing ability or a powertrain module can be added to achieve different flight characteristics.

- **UAV Profile** – a set of modules that are carefully chosen to fulfill the requirements of a specific mission. For example, a profile designed for surveillance will allow long flight times with advanced sensors while a profile for delivery will achieve higher payload capabilities instead.

6.2 System Architecture

The modular MR-UAV framework consists of five modules that can be connected without tools (i.e. soldering iron, wrench, screwdriver, etc.) to assemble an MR-UAV. The rationale behind the content of each module was based on the input from the stakeholders during the focus group. The components of each module were chosen to fulfil the requirements elicited by the stakeholders. Additionally, the essential components of an MR-UAV were categorized and components with similar objectives (i.e. video camera and video transmitter) were placed on the same module to enhance the system’s modularity and usability. An operator decides which modules to connect based on the flight characteristics and functionalities desired.
for a specific mission. An architecture diagram of the system can be seen in Figure 6.1, specifying the modules and their connections. A more detailed description of each module can be seen in the sub-sections below.

![Figure 6.1 Modular MR-UAV architecture, modules, and connections.](image)

### 6.3 Modules

#### 6.3.1 Controller Module

This module contains the essential electronics to achieve a stable flight in an MR-UAV: the flight controller executing the system and control software, flight sensors (e.g. accelerometer, gyroscope, barometer, compass, GPS), and a power distribution board. Additionally, this module also serves as the mechanical structure that connects and holds every other module and the battery. The 3-D models for the frame can be seen in Figures 6.2 and 6.3. Additionally, the implemented controller module, which was cut from carbon-fiber can be seen in Figure 6.4.
Figure 6.2 Controller module frame design from diagonal view.

Figure 6.3 Controller module frame design from bottom (left) and top (right) view.
6.3.2 Powertrain Module

This module holds equipment related to generating thrust: brush-less motors, propellers, and electronic speed controllers. These components are placed on the modular arm frame shown in Figure 6.5. According to the profile requirements, the length of the arm should be customized according to the propeller size, allowing its free rotation. The Powertrain module is connected to the controller module through an MR-60 3-pin connector (power, ground, and signal). The 3-D models for the frame can be seen in Figures 6.5. Additionally, the implemented powertrain module, which was cut from carbon-fiber can be seen in Figure 6.6.
Figure 6.5 Arm frame design for the powertrain module (left). Arm frames connected together to assemble MR-UAV (right).

Figure 6.6 Carbon fiber powertrain module.

6.3.3 Video Module

This module performs image acquisition and transmission equipment. It carries a camera, which is chosen according to the requirements of each mission in terms of resolution, weight, and type (e.g. RGB, infrared, thermal, etc.). Additionally, a video transmitter of different frequencies (e.g. 5.8GHz, 1.3Ghz, etc.) can be employed depending on the area in which it will be employed, its RF interference, and mission requirements. The video module has two connections with the controller module: power and a datalink.
which allows On-Screen Display flight information in the video. Optionally, this module can also contain a gimbal for video stabilization. The 3-D models for the frame can be seen in Figure 6.7. Additionally, the implemented video module, which was 3-D printed can be seen in Figure 6.8.

Figure 6.7 Video module frame design from front (left), side (right), and diagonal (bottom) view.

Figure 6.8 Video module prototype, including 3-D printed frame, camera, and antenna.
6.3.4 Communication Module

This module creates a data link between the UAV and the ground control station. It carries a radio transmitter and its antenna. Similar to the video module, the frequency (e.g. 900MHz, 2.4Ghz, etc.) can be decided according to the operational environment. For instance, when operating in an environment with 2.4GHz interference, the operator can use a 900MHz module. This module requires a power and serial data connection to the controller module. The 3-D models for the frame can be seen in Figure 6.9. Additionally, the implemented communication module, which was 3-D printed can be seen in Figure 6.10.

Figure 6.9 Communication module frame design from front (left), side (center), and diagonal (right) view.

Figure 6.10 Communication module, including 3-D printed frame and antenna.
6.3.5 Payload Module

This module carries a sensor or actuator for specific operations. Examples of payloads include delivering packages, specialized cameras integrated with a companion computer to execute artificial intelligence algorithms, and communication relay modules among others. The 3-D models for the frame can be seen in Figures 6.11 and 6.12. Additionally, the implemented communication module, which was cut from carbon fiber and 3-D printed can be seen in Figure 6.13.

![Figure 6.11 Payload module frame design from diagonal (left), and top (right) view.](image)

![Figure 6.12 Payload module frame design with a 3-D printed payload from diagonal-top (left), and diagonal-bottom (right) view.](image)
Figure 6.13 Payload module with carbon fiber frame and 3-D printed payload.

6.4 Profile Development Process

Due to the possible number of hardware combinations in an MR-UAV profile, a step by step process to pick the hardware components becomes necessary. The process used to create the modular MR-UAV profiles is presented in Figure 6.14 and further discussed below.

1. Specify Profile Sensors & Actuators - The first step in building a new MR-UAV profile is to specify the application in which it will be used. In this step, it is necessary to select the actuator and sensors that will be required for the application.

2. Define Flight-Time Requirement - Specify the desired the flight time (in minutes) required for the application.

3. Define Size Requirement - The application (specified in step 1) will determine if the MR-UAV size is a constraint. For example, a system that will be carried in a backpack might be limited to a specific propeller size and weight, while a system that will be carried on a vehicle might not have the same constraints.
Figure 6.14 Step-by-step process to create a modular MR-UAV profile.

4. Estimate take-off all-up-weight - Add the weight for all payload components, including: sensors, actuators, extra (payload) batteries, (delivery) package.

5. Select Powertrain Components - The powertrain database contains information regarding the brush-less motors and propeller combinations. In this step, it should be filtered to match the payload and flight time requirements for the application of this profile. The Multi-Rotor Design tool can be used to streamline this process. In this step, the designer selects motors and propeller combinations
to find the most efficient combination that fulfill the requirements specified in steps 1, 2, and 4. If size was defined as a constraint in step 3, the right selection will be the one that fulfills the above requirements with the minimum propeller size. If size is not a design constraint, the designer should aim for a combination that fulfills the weight requirement (step 4) at a maximum flight time (at least what is specified in step 2).

6. Estimate Flight Time - The Multi-Rotor Design Tool requires the payload requirement and battery parameters (weight, voltage, capacity) to estimate the flight time. Note: Steps 5 and 6 might require multiple iterations to confirm if the battery weight requires a new adjustment for motors and propellers. The Multi Rotor Designer tool will estimate the hover flight time. Additionally, the software will plot the flight time versus the payload weight and throttle input. These extra plots are useful for designers to understand the prototype flight characteristics, for example, the relationship between extra payload and decreased flight time.

7. Implementation & Tuning – Once all components are selected and the prototype assembled, it requires tuning. Tuning procedures can be found in Section 6.5.2 below.

8. Test Profile - Lastly, the prototype is ready for flight testing. Additionally, the procedures specified in Chapter 3 can be used to validate the flight time.

6.5 Software

6.5.1 Flight Controller Software

The modular MR-UAV framework is based on the Ardupilot open-source flight controller software [76]. Ardupilot is the most commonly used open-source flight controller, and it is maintained by over 400 contributors [77]. The software provides fully autonomous features, it is widely used and reliable [78]. Ardupilot is optimized to run on 32-bit ARM microcontrollers and can be used on a large variety of electronic boards [78][79]. This flight controller software can be employed in a wide range of MR-UAVs sizes and applications, making it suitable for the modular MR-UAV framework. Additionally, the Ardupilot project is well documented with clear instructions on the tuning process, which is beneficial for a project
such as the modular MR-UAV where various component configurations will be used. Ardupilot supports the widely accepted Micro Air Vehicle Link (MAVLINK) data protocol and can communicate with various ground control stations such as QGroundControl, MissionPlanner, APM Planner, MavProxy, DroidPlanner, and UGCS [77].

6.5.2 Tuning Flight Parameters

Ardupilot provides an extensive list of tuning parameters that must be configured to match the current configuration of the modular MR-UAV. The flight controller manual recommends adjusting battery, motor, and PID Controller settings as described below. Additionally, once the MR-UAV has been tuned using these parameters, Ardupilot provides an auto-tune functionality that allows the final fine-tuning of the MR-UAV. Once an MR-UAV profile has been tuned, the parameters are saved in a tuning parameter file. Each profile has a tuning file that can be selected before a mission.

- Battery Parameters:
  - MOT_BAT_VOLT_MAX - Adjusts the battery voltage compensation maximum voltage. Value = 4.2V * number of battery cells.
  - MOT_BAT_VOLT_MIN - Adjusts the battery voltage compensation minimum voltage. Value = 3.3V * number of battery cells.
  - MOT_THST_EXPO – Adjusts the motor thrust curve expo. The value is dependent on the propeller size following the graph on Figure 6.15.

- PID Controller Parameters
  - INS_ACCEL_FILTER – Adjust the accelerometer filter cutoff frequency. Default value of 15Hz was used for all modular prototypes.
  - INS_GYRO_FILTER – Adjust the gyroscope filter cutoff frequency. Value is dependent on propeller size and should be adjusted accordingly to Figure 6.16.
  - ATC_ACCEL_P_MAX – Maximum acceleration in the pitch axis. Value is dependent on propeller size and should be adjusted accordingly to Figure 6.17.
Figure 6.15 Relationship between MOT_THST_EXPO parameter value and propeller size. Data from [76].

Figure 6.16 Relationship between INS_GYRO_FILTER parameter value and propeller size. Data from [76].

- **ATC_ACCEL_R_MAX** - Maximum acceleration in the roll axis. Value is dependent on propeller size and should be adjusted accordingly to Figure 6.17.
Figure 6.17 Relationship between ATC_ACCEL_P_MAX/ATC_ACCEL_R_MAX parameters value and propeller size. Data from [76].

- ATC_ACCEL_Y_MAX - Maximum acceleration in the yaw axis. Value is dependent on propeller size and should be adjusted accordingly to Figure 6.18.

Figure 6.18 Relationship between ATC_ACCEL_Y_MAX parameter value and propeller size. Data from [76].

- ACRO_YAW – Conversion between pilot command for yaw input and desired rate of rotation in the yaw pilot yaw input into a desired rate of rotation. Value = 0.5 * ATC_ACCEL_Y_MAX /4500.
- ATC_RAT_PIT_FLTD – Rate controller derivative frequency for the pitch axis. Value = \( \text{INS\_GYRO\_FILTER} / 2 \).
- ATC_RAT_PIT_FLTT - Rate controller target frequency for the pitch axis. Value = \( \text{INS\_GYRO\_FILTER} / 2 \).
- ATC_RAT_RLL_FLTD - Rate controller derivative frequency for the pitch axis. Value = \( \text{INS\_GYRO\_FILTER} / 2 \).
- ATC_RAT_RLL_FLTT - Rate controller target frequency for the roll axis. Value = \( \text{INS\_GYRO\_FILTER} / 2 \).
- ATC_RAT_YAW_FLTE – Rate controller error frequency for the yaw axis. Default value of 2 used for all modular prototypes.
- ATC_RAT_YAW_FLTT - Rate controller target frequency for the yaw axis. Value = \( \text{INS\_GYRO\_FILTER} / 2 \).

- Motor Parameters
  - MOT_PWM_MAX – Maximum PWM signal sent to electronic speed controller. Default value of 2000 was used for all modular prototypes.
  - MOT_PWM_MIN – Minimum PWM signal sent to electronic speed controller. Default value of 1000 was used for all modular prototypes.
  - MOT_SPIN_MAX – Maximum signal where the motor output saturates. Default value of 0.95 was used for all modular prototypes.
  - MOT_THST_HOVER – Motor output at hover. Default value of 0.25 was used for all modular prototypes.
Chapter 7: Prototyping a Modular MR-UAV

In this chapter, the implemented prototype to test the modular MR-UAV framework is presented. This chapter focuses on this dissertation’s research questions one and three. Three profiles based on the voting results from the focus group study discussed in Chapter 3 were implemented. Each profile and its characteristics are discussed in Table 7.1. The same controller, communication, and video module were used for all three profiles; their characteristics are presented in Sections 7.1, 7.2, and 7.3. However, the powertrain and payload modules differ, and their specification for each profile can be seen in sections 7.4, 7.5, and 7.6.

Table 7.1 Profiles implemented with the modular MR-UAV framework

<table>
<thead>
<tr>
<th>Profile</th>
<th>Discussion</th>
<th>High-level characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMV</td>
<td>The Full-Motion Video (FMV profile can be used for surveillance, reconnaissance, and search-and-rescue missions. Its main goal is to provide a birds-eye view of an area with a real-time view to ground troops, especially when larger UAVs or satellite images are not available or not suitable for the application. As this profile will be carried by troops in backpacks, size and weight become an important constraint.</td>
<td>• Long flight times.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Small size to be carried on backpacks.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Continuous video.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ability to carry a heavier payload not required.</td>
</tr>
<tr>
<td>Tethered</td>
<td>The Tethered FMV profile can be used to provide an uninterrupted birds-eye view of a military base (if stationary) or over a military convoy in the move (if connected to a ground vehicle) when powered through tethered power supply to battery power supply in-flight.</td>
<td>• Ability to switch from tethered power supply to battery power supply in-flight.</td>
</tr>
</tbody>
</table>
### Profiles implemented with the modular MR-UAV framework

<table>
<thead>
<tr>
<th>Profile</th>
<th>Discussion</th>
<th>High-level characteristics</th>
</tr>
</thead>
</table>
| Tethered FMV | The tethered cable. The MR-UAV shall be able to detach the tethered cable (in-flight) to fly beyond the cable’s length. For instance, if suspicious activity is detected beyond the camera range, the MR-UAV can drop the tethered cable to inspect the situation at a closer range. As this profile is not intended to be carried in a backpack, size and weight are not a constraint. | • Continuous video.  
• Unlimited flight time when tethered and long flight time when battery operated.  
• Small size (i.e. to fit in a backpack) is not required for this application.  
• Ability to carry a heavier payload not required.  
• Ability to carry tethered cable required. |
| Payload Delivery | The payload delivery profile must be able to carry and release a package in the desired location. During all three focus group sessions (see Chapter 5), participants stated the need for an MR-UAV capable of delivering whole-blood bags for emergency transfusion. The MR-UAV would be ready for deployment at a near-by quick-response team location and capable of carrying at least 1500 grams. Additionally, this profile could be carried in backpacks for delivery during missions. | • Ability to carry at least 1500 grams payload.  
• Small size to be carried on backpacks.  
• Ability to release a package. |
7.1 Controller Module

The controller module is shared among all modular MR-UAV profiles as it contains the electronics required for any application. In this implementation, the controller module contains four components, the flight controller board, the tethered power management board described in Chapter 4, the GPS sensor, and the carbon fiber frame.

The Pixhawk 4 Mini flight controller manufactured by Holybro was used because it met all requirements for this application in a small form factor computer. The board contains the required sensors for flight, for instance, it contains two inertial (accelerometer and gyroscope) chips, the ICM20689 and BMI055. Additionally, it also carries a magnetometer (IST8310), a barometer (MS5611), and it has eight Pulse-Width Modulation (PWM) outputs. The board size is relatively small (38x55x15.5mm) and it only weighs 37.2 grams. A GPS sensor/antenna (uBlox Neo M8N) was also connected to the flight controller board.

The controller module also acts as a power management board for all other modules. Therefore, the Holybro Pm06 power distribution board was used in addition to the tethered management board (see Chapter 4).

7.2 Communication Module

The communication module is dependent on the application being used. For this dissertation, the standard Mavlink protocol was used over a radio datalink for all profiles. The Crossfire long-range radio manufactured by TBS was used because of its low-latency, low-power consumption, low weight, its FCC certification, configurability, and support to Mavlink datalink protocol.

7.3 Video Module

The video module is also dependent on the application. For this dissertation, all profiles used the same video module. The implemented module is based on the TBS Unify Pro 5.8 GHz analog video transmitter and a Foxeer Predator V4 Micro camera was used due to its small size, low-cost, and low-weight.
7.4 Full-Motion Video Profile – Powertrain Module

The full-motion video profile provides real-time video to users. Additionally, it aims to achieve low-weight, small-size, and longer flight times. As intended, such characteristics make this profile well-suited for surveillance, reconnaissance, and search-and-rescue applications. For this dissertation, a standard RGB camera was used, but it could be easily replaced by other camera styles (i.e. thermal). The powertrain module specifications can be seen in Table 7.2. Additionally, the flight characteristics for this profile can be seen in Table 7.3.

Table 7.2 MR-UAV FMV profile powertrain module specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Brand: EMAX 2213 – 935 KV</td>
</tr>
<tr>
<td>Propeller</td>
<td>APC 10x47</td>
</tr>
<tr>
<td>Electronic Speed Control</td>
<td>Holybro Tekko32 F3 35amp</td>
</tr>
<tr>
<td>Battery</td>
<td>4 cells, 7000mah or</td>
</tr>
<tr>
<td></td>
<td>2 x 4 cells 7000mah</td>
</tr>
</tbody>
</table>

As shown above, this profile allows flights of 26 minutes and 30 seconds when using a single battery. As this profile is not intended to carry an extra payload, the operator can optionally add a second battery to achieve 32 minutes and 30-second flight. As the flight efficiency decreases with the weight increase, the relation between the extra battery capacity and flight time is not linear. Nonetheless, if the application requires longer flight times the operator can add a second battery to achieve the 6 extra flight minutes.

The FMV Profile characteristics can be seen in the Figures below. First, Figure 7.1 demonstrates how a weight increase decreases the flight time of this profile for both one or two battery configurations. Following, Figure 7.2 shows the thrust generated per motor and the flight efficiency for this motor and propeller combination. Figure 7.3 provides an overview of the power consumption by plotting the current
consumption vs the throttle (ESC) signal and the generated thrust. Lastly, Figure 7.4 plots the vibration signature (per motor) and the RPM for this profile.

**Table 7.3 MR-UAV FMV profile characteristics.**

<table>
<thead>
<tr>
<th>Value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Time</td>
<td>26 minutes and 30 seconds (1 battery)</td>
</tr>
<tr>
<td></td>
<td>32 minutes and 30 seconds (2 batteries)</td>
</tr>
<tr>
<td>Maximum Payload</td>
<td>691 grams (1 battery)</td>
</tr>
<tr>
<td></td>
<td>125 grams (2 batteries)</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>4350 grams</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>17 amperes/motor</td>
</tr>
<tr>
<td>All-Up-Weight</td>
<td>1486 grams (1 battery)</td>
</tr>
<tr>
<td></td>
<td>2052 grams (2 batteries)</td>
</tr>
</tbody>
</table>

**Figure 7.1** FMV Profile flight time vs payload with 1 battery (left) and 2 batteries (right).
Figure 7.2 FMV Profile thrust vs ESC signal (left) and flight efficiency vs ESC signal (right).

Figure 7.3 FMV Profile current vs ESC signal (left) and current vs thrust (right)

Figure 7.4 FMV Profile vibration vs ESC signal (left) and RPM vs ESC signal (right)
7.5 Tethered-FMV Profile – Powertrain and Payload Module

The tethered full-motion video profile provides real-time video to users. While powering through the tethered cable, this profile can fly continuously, making it suitable for military base surveillance and to provide a birds-eye view of military convoys (while connected to a ground vehicle). Additionally, the MR-UAV can detach itself from the tethered cable in flight to switch to battery power, allowing it to fly beyond the tether cable range. As this profile is not intended to be carried on a backpack, size and weight are not a constraint. For this dissertation, a standard RGB camera was used, but it could be easily replaced by other camera styles (i.e. thermal). The powertrain module specifications can be seen in Table 7.4. Additionally, the flight characteristics for this profile can be seen in Table 7.5.

An essential consideration to the Tethered MR-UAV is that it must be able to carry the weight of the tethered cable. Additionally, the voltage drop on the tethered cable must also be considered to ensure appropriate power to the MR-UAV. The prototype specified in this dissertation was designed to carry 100 feet 12-gauge wire, connected to a 20-volt ground power supply. With such characteristics, approximately 16.8V (the same as a fully charged battery) will be provided to the MR-UAV after the voltage drop due to the wire resistance. Future profile with the purpose of higher flights should use lower KV motors and higher number of cell batteries, in which case, the higher voltage and lower current would decrease the voltage drop on the tethered cable.

7.6 Payload Delivery Profile – Powertrain and Payload Module

The payload delivery profile is capable of carrying and dropping a package. The specifications of this profile enable the MR-UAV to carry a payload of up to 1700 grams. The powertrain module specifications can be seen in Table 7.6. Additionally, the flight characteristics for this profile can be seen in Table 7.7.

As shown below, this profile allows a maximum payload of 1717 grams. However, the maximum flight time of 17 minutes is decreased as the payload increases. The payload vs flight time relationship can be seen in Figure 7.9. Following, Figure 7.10 shows the thrust generated per motor and the flight efficiency
for this motor and propeller combination. Figure 7.11 provides an overview of the power consumption by plotting the current consumption vs the throttle (ESC) signal and the generated thrust. Lastly, Figure 7.12 plots the vibration signature (per motor) and the RPM for this profile.

Table 7.4 MR-UAV Tethered FMV Profile powertrain module specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Brand: EMAX 3510 – 600 KV</td>
</tr>
<tr>
<td>Propeller</td>
<td>APC 15X55MR</td>
</tr>
<tr>
<td>Electronic Speed</td>
<td>Holybro Tekko32 F3 35amp</td>
</tr>
<tr>
<td>Controller</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>Brand: Ovonic, 4 cell, 1550 mah</td>
</tr>
</tbody>
</table>

Table 7.5 MR-UAV Tethered FMV Profile characteristics

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Time</td>
<td>Unlimited (tethered)</td>
</tr>
<tr>
<td></td>
<td>9 minutes and 45 seconds (battery)</td>
</tr>
<tr>
<td>Maximum Payload</td>
<td>1900 grams</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>6750 grams</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>18 amps/motor</td>
</tr>
<tr>
<td>All-Up-Weight</td>
<td>1480 grams</td>
</tr>
</tbody>
</table>
Figure 7.5 Tethered FMV Profile flight time vs payload

Figure 7.6 Tethered FMV Profile thrust vs ESC signal (left) and flight efficiency vs ESC signal (right)
Figure 7.7 Tethered FMV Profile current vs ESC signal (left) and current vs thrust (right)

Figure 7.8 Tethered FMV Profile vibration vs ESC signal (left) and RPM vs ESC signal (right)

Table 7.6 MR-UAV Payload Delivery Profile powertrain module specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Brotherhobby 2812, 900KV</td>
</tr>
<tr>
<td>Propeller</td>
<td>APC 1047</td>
</tr>
<tr>
<td>Electronic Speed</td>
<td>Holybro Tekko32 F3 35amp</td>
</tr>
<tr>
<td>Controller</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>Brand: Ovonic, 4 cell, 4500mah</td>
</tr>
</tbody>
</table>
Table 7.7 MR-UAV Payload Delivery Profile characteristics

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Time</td>
<td>17 minutes and 3 seconds</td>
</tr>
<tr>
<td>Maximum Payload</td>
<td>1717 grams</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>6304 grams</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>26 amps/motor</td>
</tr>
<tr>
<td>All-Up-Weight</td>
<td>1435 grams</td>
</tr>
</tbody>
</table>

Figure 7.9 Payload Delivery Profile flight time vs payload.

Figure 7.10 Payload Delivery Profile thrust vs ESC signal (left) and flight efficiency vs ESC signal (right)
This section provides an overview of the cost for the modular framework and each of the three implemented profiles. The values presented are consistent to the market value at the time of this writing. As discussed above, the three implemented profiles shared the same controller, video, and communication modules. The price of each of these modules can be seen in Tables 7.8, 7.9, and 7.10. The powertrain and payload module for each profile differed, and the prices for these modules can be seen in Tables 7.11, 7.12, and 7.13.
Table 7.8 Controller module parts and cost.

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixhawk 4 Mini + Ublox NEO-M8N GPS</td>
<td>1</td>
<td>$189.00</td>
<td>$189.00</td>
</tr>
<tr>
<td>Tethered PMB components</td>
<td>1</td>
<td>$8.32</td>
<td>$8.32</td>
</tr>
<tr>
<td>Frame – carbon fiber bottom and top plate</td>
<td>1</td>
<td>$20</td>
<td>$20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$217.32</strong></td>
</tr>
</tbody>
</table>

Table 7.9 Video module parts and cost.

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foxeer Predator V4 Micro Camera</td>
<td>1</td>
<td>$36.99</td>
<td>$36.99</td>
</tr>
<tr>
<td>TBS Unify Pro 5.8GHz Video transmitter</td>
<td>1</td>
<td>$39.99</td>
<td>$39.99</td>
</tr>
<tr>
<td>Lumenier Micro AXII 5.8GHz Antenna</td>
<td>1</td>
<td>$12.99</td>
<td>$12.99</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$89.97</strong></td>
</tr>
</tbody>
</table>

Table 7.10 Communication module parts and cost.

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossfire nano radio transmitter</td>
<td>1</td>
<td>$24.99</td>
<td>$24.99</td>
</tr>
<tr>
<td>Crossfire 900MHz T antenna</td>
<td>1</td>
<td>$5.99</td>
<td>$5.99</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$30.98</strong></td>
</tr>
</tbody>
</table>

7.8 Conclusion and Profiles Comparison

This chapter presented the implementation of the modular MR-UAV framework, the characteristics, and cost of each profile. A summary of the flight characteristics for each profile can be seen in Table 7.14. For instance, the FMV profile achieved a maximum flight time of 32 minutes, and the payload profile achieved a maximum payload carrying ability of 1700 grams.
Furthermore, the price of each profile is found by summing the costs of each module separately and is also shown in Table 7.14. The final cost for profile 1 is $604.91, for profile 2 is $653.62, and for profile 3 is $627.55. A military organization requiring all three profiles for their applications would have an associated cost of $1,885.68. However, the modularity of the system can decrease the overall cost as some modules are shared among different profiles. For instance, if an organization does not plan to use the different profiles simultaneously, they could purchase one unit of the controller, communication, and video module in addition to the powertrain module required for each profile. In this case, the overall cost to purchase all three profiles would decrease approximately 35% to $1,209.54. This demonstrates how the framework enables modularity to decrease overall cost for an organization that required MR-UAVs for multiple applications.
Table 7.13 Payload delivery Profile powertrain module parts and cost.

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powertrain module (motor, ESC, propeller, carbon fiber arm)</td>
<td>4</td>
<td>$56.82</td>
<td>$227.28</td>
</tr>
<tr>
<td>Payload Module (carbon fiber plate, release mechanism)</td>
<td>1</td>
<td>$24.00</td>
<td>$24.00</td>
</tr>
<tr>
<td>Battery</td>
<td>1</td>
<td>$38.00</td>
<td>$38.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>$289.28</td>
</tr>
</tbody>
</table>

Table 7.14 Cost and characteristics comparison for MR-UAV profiles.

<table>
<thead>
<tr>
<th>Flight Time</th>
<th>Payload</th>
<th>AUW</th>
<th>Size</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMV Profile</td>
<td>26 min and 30 sec (1 battery)</td>
<td>691 grams (1 battery)</td>
<td>1486 grams (1 battery)</td>
<td>$604.91</td>
</tr>
<tr>
<td></td>
<td>32 min and 30 sec (2 batteries)</td>
<td>125 grams (2 batteries)</td>
<td>2052 (2 batteries)</td>
<td></td>
</tr>
<tr>
<td>Tethered FMV Profile</td>
<td>Unlimited (tethered)</td>
<td>1900 grams</td>
<td>1480 grams</td>
<td>Large (15-inch propeller)</td>
</tr>
<tr>
<td></td>
<td>9 min and 45 sec (battery)</td>
<td>1430 grams</td>
<td>1480 grams</td>
<td>Large (15-inch propeller)</td>
</tr>
<tr>
<td>Payload Delivery Profile</td>
<td>17 min and 3 seconds</td>
<td>1717 grams</td>
<td>1435 grams</td>
<td>Small (10-inch propeller)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 8: Evaluating the Usability of a Modular MR-UAV

To evaluate the usability, receive feedback on the initial prototype, and further elicit considerations for modular MR-UAVs, two usability studies were conducted. First, an in-person usability study with 8 participants was conducted. Each participant interacted with the modular MR-UAV framework, answered a questionnaire, and the standard System Usability Scale. The second study was conducted remotely, and 8 military users participated. In this study, they watched a video describing the modular MR-UAV framework and prototype and completed a questionnaire using Qualtrics. The first (in-person) usability study was not conducted with military personnel due to restrictions caused by the COVID-19 pandemic. Therefore, a follow-up (remote) study was conducted to collect data from military personnel. The first study was not conducted in-person. This chapter describes the participants, methodology, and results of these usability studies and contributes to research questions one, two, and three.

8.1 Usability Study

This section describes the participants, methodology, and results of the first usability study conducted in-person. This study was approved by the University of South Florida IRB department (Study#001375). The IRB approval letter can be seen in Appendix C.

8.1.1 Study Design

The goal of this study was to evaluate how users interact with the modular MR-UAV framework. Participants of this study used the modular framework to build 6 MR-UAV profiles, two for each of the implemented profiles (FMV, tethered FMV, and payload delivery). Participants provided their demographics information, military experience, and experience with UAVs before interacting with the framework. To introduce the framework concept, and teach how to assemble profiles, a video was played prior to the interaction as well. A member of the research team kept track of the time required to assemble
and disassemble each profile, and any errors during the assembly. Additional data were collected to evaluate using a Qualtrics survey to evaluate the interaction. The System Usability Scale[53] standard research tool was used to give a usability score to the framework. Additionally, participants provided qualitative results regarding (1) their opinion about the system, (2) assembly procedures, difficulties, and possible improvements in the framework, (3) advantages and disadvantages in the system, (4) and any additional comments. Also, participants were asked to give a score between 1 and 5 (Likert scale) on the assembly procedures.

8.1.2 Participants

A total of eight participants were part of this study. Of these, five were male and three were female. Additionally, five of them were between 18 and 24 years old, and three were between 24 and 34. Also, four participants identified as Caucasian, two as Hispanics, and two as Asians. Lastly, six participants have previously operated hobbyist UAVs, and three of them have served or currently serve in the military (less than five years of experience).

8.1.3 Study Procedures

Each participant individually attended one session that lasted approximately 45 minutes. The following procedures were performed during the sessions:

1. A member of the research team explained the experiment, and provided an informed consent form for the participant to review and sign.

2. Pre-experiment questionnaire using a provided laptop and Qualtrics link.

3. The participant watched a video explaining the concept of the modular MR-UAV, the prototype, and how to assemble profiles.

4. A member of the research team provided an instruction manual to the participant.

5. The participant followed the instructions to assemble a total of 6 MR-UAVs, twice for each profile (FMV, Tethered-FMV, and Payload Delivery).
6. The participant completed the post-questionnaire (through Qualtrics) using a provided laptop.

8.1.4 Results

The System Usability Scale (SUS) score for each participant, the average, and standard deviation can be seen in Table 8.1. These results demonstrate a high usability score for the framework, with an average score of 86.5. As discussed in Chapter 2, good scores fall between the high 70s and 80s according to [54]. Additionally, the lowest on this study was 75, which still a reasonable score and above the 70.14 average score of studies surveyed by [54].

The time each participant took to assemble the MR-UAV profiles can be seen in Table 8.2 and Figure 8.1. As shown, the average assembly time was 89.7 seconds (standard deviation 19.7). However, as the data shows, participants significantly decreased the assembly time as they conducted the experiment. The average time for the first assembly trial was 119.6 seconds, while the average time for the sixth (and last) assembly was 71.5 seconds. As shown the in Table 8.3, the average decrease and time between the first and last trial was 48 seconds with a p value smaller than 0.000 (paired two-tailed T-Test); this table shows the average decrease in all the trials and the corresponding p value. Such pattern can be easily seen in Figure 8.1. Additionally, the time it took participants to disassemble each profile can be seen in Table 8.4 and Figure 8.2. The average disassemble time was 36.8 seconds (standard deviation = 5.6 seconds). The decrease in the time do disassemble was also significant (p smaller than 0.05), and the statistical analyses can be seen in Table 8.5.

Overall, participants provided positive feedback after interacting with the framework. When asked about what they believed to be the framework advantages, all 8 participants responded that the ability to tailor the MR-UAV characteristics is a strong advantage. Additionally, 3 participants noted that the MR-UAV is robust with comments such as “it feels really sturdy” and “the frame material is strong”. The easiness to carry and store was also elicited as an advantage by 3 participants, and the ability to easily fix the MR-UAV in case of a malfunction/crash was discussed by other 2 participants. Furthermore, as shown
in Figure 8.3, all 8 participants selected that the assembly procedures were extremely easy to follow. A participant stated “it is quite easy to put together since everything clicks in place”.

**Table 8.1 System Usability score**

<table>
<thead>
<tr>
<th>Participant</th>
<th>System Usability Scale Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>92.5</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>92.5</td>
</tr>
<tr>
<td>7</td>
<td>77.5</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>Average</td>
<td>86.5</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6.4</td>
</tr>
</tbody>
</table>

**Figure 8.1 Time required to assemble MR-UAV profile (6 trials)**
Table 8.2 Time required to assemble a MR-UAV profile using the framework

<table>
<thead>
<tr>
<th>Participant</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Trial 6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>149</td>
<td>108</td>
<td>81</td>
<td>89</td>
<td>66</td>
<td>68</td>
<td>93.5</td>
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<tr>
<td>2</td>
<td>111</td>
<td>91</td>
<td>90</td>
<td>85</td>
<td>91</td>
<td>83</td>
<td>91.8</td>
</tr>
<tr>
<td>3</td>
<td>108</td>
<td>100</td>
<td>82</td>
<td>78</td>
<td>64</td>
<td>74</td>
<td>84.3</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>106</td>
<td>78</td>
<td>68</td>
<td>64</td>
<td>70</td>
<td>87.7</td>
</tr>
<tr>
<td>5</td>
<td>109</td>
<td>90</td>
<td>79</td>
<td>101</td>
<td>69</td>
<td>59</td>
<td>84.5</td>
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<tr>
<td>6</td>
<td>113</td>
<td>95</td>
<td>93</td>
<td>74</td>
<td>63</td>
<td>58</td>
<td>82.7</td>
</tr>
<tr>
<td>7</td>
<td>118</td>
<td>115</td>
<td>90</td>
<td>93</td>
<td>80</td>
<td>78</td>
<td>95.7</td>
</tr>
<tr>
<td>8</td>
<td>109</td>
<td>108</td>
<td>100</td>
<td>98</td>
<td>90</td>
<td>82</td>
<td>97.8</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>119.6</strong></td>
<td><strong>101.6</strong></td>
<td><strong>86.6</strong></td>
<td><strong>85.7</strong></td>
<td><strong>73.3</strong></td>
<td><strong>71.5</strong></td>
<td><strong>89.7</strong></td>
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<tr>
<td><strong>Standard deviation</strong></td>
<td>14.8</td>
<td>8.4</td>
<td>7.3</td>
<td>10.9</td>
<td>11.1</td>
<td>8.9</td>
<td>5.36</td>
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<tr>
<td><strong>Standard deviation (all)</strong></td>
<td>19.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.3 Paired two-tailed T-Test analysis for delta time to assemble the modular MR-UAV.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Trial 2 Δ</th>
<th>p</th>
<th>Trial 2 p value</th>
<th>Trial 3 Δ</th>
<th>p value</th>
<th>Trial 4 Δ</th>
<th>p value</th>
<th>Trial 5 Δ</th>
<th>p value</th>
<th>Trial 6 Δ</th>
<th>p value</th>
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<tr>
<td>1</td>
<td>18 0.009</td>
<td>33 0.003</td>
<td>33.875 0.004</td>
<td>46.25 0.001</td>
<td>48.125 0.000</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>15 0.006</td>
<td>15.875 0.017</td>
<td>28.25 0.001</td>
<td>30.125 0.000</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.875 0.846</td>
<td>13.25 0.003</td>
<td>15.125 0.002</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>4</td>
<td>12.375 0.022</td>
<td>14.25 0.019</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.875 0.4889</td>
<td>9</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each participant assembled a 6 MR-UAVs, adding to a total of 48 assemblies. Out of these, 3 assembly errors were made as 3 participants placed the powertrain in wrong positions once (counterclockwise versus clockwise). However, all 3 participants noticed the error and fixed it before delivering the assembled prototype. Nonetheless, these mistakes demonstrated a procedure that can be improved in the
future. One participant suggested “modifying the pins between the modules in such a way that prevents the user from connecting the system incorrectly”. Two other participants noted that the powertrain connectors “are easy to connect, but not as easy to disconnect”, suggesting another area for future improvements.

**Table 8.4 Time required to disassemble a MR-UAV profile**

<table>
<thead>
<tr>
<th>Participant</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Trial 6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>27</td>
<td>26</td>
<td>29</td>
<td>23</td>
<td>25</td>
<td>27.5</td>
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<td>48</td>
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<td>3</td>
<td>37</td>
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<td>38.3</td>
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<tr>
<td>7</td>
<td>40</td>
<td>40</td>
<td>38</td>
<td>37</td>
<td>38</td>
<td>37</td>
<td>38.3</td>
</tr>
<tr>
<td>8</td>
<td>38</td>
<td>39</td>
<td>38</td>
<td>36</td>
<td>37</td>
<td>35</td>
<td>37.2</td>
</tr>
<tr>
<td>Average</td>
<td>39.9</td>
<td>39.1</td>
<td>37.2</td>
<td>37</td>
<td>33.9</td>
<td>33.5</td>
<td>36.8</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>4.2</td>
<td>6.2</td>
<td>5.6</td>
<td>5.1</td>
<td>4.4</td>
<td>4.4</td>
<td>3.9</td>
</tr>
<tr>
<td>Standard deviation (all)</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 8.2 Time required to disassemble MR-UAV profile (6 trials)

Table 8.5 Paired two-tailed T-Test analysis for delta time to disassemble the modular MR-UAV.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Δ</th>
<th>p</th>
<th>Δ</th>
<th>p</th>
<th>Δ</th>
<th>p</th>
<th>Δ</th>
<th>p</th>
<th>Δ</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.80</td>
<td>2.625</td>
<td>0.314</td>
<td>2.875</td>
<td>0.154</td>
<td>6</td>
<td>0.012</td>
<td>6.375</td>
<td>0.026</td>
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<td>0.04</td>
<td>2.125</td>
<td>0.397</td>
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<td>0.026</td>
<td>5.625</td>
<td>0.003</td>
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</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>0.897</td>
<td>3.375</td>
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<td>3.75</td>
<td>0.007</td>
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<td></td>
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<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.375</td>
<td>0.775</td>
</tr>
</tbody>
</table>

Figure 8.3 Participants opinion on framework assembly procedure difficulty
8.2 Remote Usability Study

This section describes the participants, methodology, and results of the second usability study conducted remotely. This study was conducted remotely due to the constraints imposed by the COVID-19 pandemic, which happened during this work. Furthermore, this study was approved by the University of South Florida IRB department (Study #00219). The IRB approval letter can be seen in Appendix D.

8.2.1 Study Design

To further evaluate the framework, subject-matter experts participated in this fully remote study. After agreeing to the informed consent form, and watching a video describing the modular MR-UAV framework, profiles, and assembly procedures, participants provided qualitative results through a Qualtrics survey. The survey included the following questions.

1. What do you think of the modular multi-rotor UAV framework??
2. How beneficial do you believe the modular multi-rotor UAV would be to military organizations?
   This question consisted of a 5 answer Likert scale.
3. How likely do you think military organizations would adopt modular multi-rotor UAVs? This question consisted of a 5 answer Likert scale.
4. What are the main advantages that you see in the modular UAV framework presented in the video?
5. What are the main disadvantages that you see in the modular UAV framework presented in the video?
6. As you have seen in the video, to assemble a multi-rotor UAV using the framework you clamp the powertrain modules between the payload and controller modules. Following this, you slide the communication and video modules to the controller module. Do you have any specific comments on the assembling procedures displayed on the video?
7. Do you have any suggestions on how to improve the prototype?
8. Two of the presented profiles are intended for being carried in a backpack. They weigh approximately 3.2 pounds. Is this an appropriate weight to be carried during operations?
9. How does the 3.2 pounds weight compare to other small UAVs systems that are carried during operations?

10. Would you tailor the system's characteristics before each operation (and only take those specific modules during it) or carry extra modules and tailor the system's characteristics in the field during the operation?

11. The framework was used to create a full-motion video (FMV) profile. In this profile the multi-rotor UAV is relatively small, can be carried in a backpack, weighs 3.1 pounds, fly for 32 minutes and a half, and provide real-time video. What do you think about the FMV profile?

12. By connecting a different set of modules, you can create the delivery profile. In this profile the multi-rotor UAV is relatively small, can be carried in a backpack, weighs 3.2 pounds, and carry a payload of 3.8 pounds for 7 minutes. What do you think about the delivery profile?

13. By connecting a different set of modules, you can create the tethered FMV profile. In this profile the multi-rotor UAV can have unlimited flight time while connected to the tethered power supply. Additionally, the MR-UAV can drop the tethered cable during flight to fly using the on-board battery for 30 minutes. What do you think about the tethered FMV profile?

14. Do you have any additional comments?

8.2.2 Participants

A total of eight participants completed this remote study. All eight participants were either active or retired military personnel and all of them had previous experience with military UAVs. The UAV experience for each participant is shown in Table 8.6. As shown, their experience ranged between UAV operators, engineers, maintainers, and logistics.

8.2.3 Study Procedures

This study was fully conducted remotely using a Qualtrics link. The procedures below were followed by each participant:
Each participant accessed the study through a Qualtrics link. The first page presented the study and the informed consent form. Following, the participant provided an overview of their experience with UAVs and their military background. The participant was then presented with a video describing the modular MR-UAV framework and prototype. At the end of the video, the participant was asked to fill-out the following questionnaire.

1. The first page presented the study and the informed consent form.
2. Participants filled the initial questionnaire containing demographics and previous experience background.
3. In the following page, participants watched a video introducing the modular MR-UAV framework, profiles, and assembly instructions. The video can be found at https://www.youtube.com/watch?v=lB0MpOukez4.
4. The participant provided qualitative results in the form of open-ended questions and Likert scale questions (described in the study design).

<table>
<thead>
<tr>
<th>Participant</th>
<th>Role / UAV Experience</th>
<th>Military Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operational, and logistics.</td>
<td>Between 5 and 10 years</td>
</tr>
<tr>
<td>2</td>
<td>Operational.</td>
<td>Between 10 and 15 years</td>
</tr>
<tr>
<td>3</td>
<td>Operational.</td>
<td>More than 15 years</td>
</tr>
<tr>
<td>4</td>
<td>Operational.</td>
<td>Between 5 and 10 years</td>
</tr>
<tr>
<td>5</td>
<td>Development.</td>
<td>More than 15 years</td>
</tr>
<tr>
<td>6</td>
<td>Operational and development.</td>
<td>Between 5 and 10 years</td>
</tr>
<tr>
<td>7</td>
<td>Operational, development, and maintenance.</td>
<td>Between 5 and 10 years</td>
</tr>
<tr>
<td>8</td>
<td>Operational.</td>
<td>More than 15 years</td>
</tr>
</tbody>
</table>
8.2.4 Results

Participants responses suggest that modular MR-UAVs is a novel concept in the military, and that it can be beneficial to military organizations with comments such as “this is a really great idea”, “why don’t we have it already?”, “looking forward to having it out in the field”, and “it opens up the possibility of many other features in the future”. All of the participants stated that they have not seen modular UAVs during their military career. Additionally, participants expressed positive view towards the concept of modularity in MR-UAVS. One participant stated “modularity is already implemented in various military systems, it can benefit UAVs as well”, which supports the claim of another participant: “modularity is an important aspect in the military, take for example the weapon soldiers use, they are also modular. It would be beneficial to have modular UAVs”. Another participant expressed his belief that in the future most small UAVs will present some sort of modularity. As show in Figure 8.4 6 out of 8 participants selected that a modular MR-UAV would be extremely beneficial, 1 participant selected beneficial, and another selected slightly beneficial. As seen in Figure 8.5, 5 out of the 8 participants said it is extremely likely that military organizations would adopt modular MR-UAVs, and the remaining 3 participants selected that the adoption is somewhat likely.

![Figure 8.4 Participants opinion on benefits of a modular MR-UAV to the military](image-url)
Figure 8.5 Participants opinion on adoption of a modular MR-UAV by the military

After watching the video, participants elicited various advantages in the system, including the ability to tailor the flight characteristics and sensors, the ability to change from tethered to battery operated flight, portability and storability, easy maintainability, and easy to train in a single system. Participants saw the framework as a “single system for multiple applications” and “a multi-use system”. One participant summarized the framework’s benefit as “the ability to modify your tool for the specific mission set is crucial in special operations. The fact that modularity for mission requirements is the main theme of this system will, be its most redeeming quality”. The ability to tailor the communication link was also widely approved by the participants. One participant stated “I think the ability to replace the communication link is extremely good, this is a game-changer”, while another said “the ability to change the command control frequency is amazingly convenient”. Participants suggested development of modules capable of frequency hopping and low-probability intercept protocols. They also expressed a desire for a 2,4GHz Wifi protocol. Such suggestions can be developed in future modules.

Although participants were asked to elicit possible disadvantages of the modular MR-UAV framework, most of them said they didn’t see any. One participant expressed that the only disadvantage he
could see is that the framework is still “stuck on a quad copter form”. This response is aligned with the response from two other participants when asked about suggestions on how to improve the framework. Both of these participants expressed interest in expanding the capability of the framework to ground and water operations. Considering that the electronics required for unmanned fixed-wing aerial, ground and water vehicles are already present in the controller module, the framework could indeed be expanded to such environments. This could potentially increase the benefits of the modular framework and can be explored in future studies.

In the video, participants were presented a step-by-step procedure to assemble the modular MR-UAV. Following, they were asked for the feedback on the assembly procedures. All participants stated that the procedures are simple and adequate with comments such as “the procedures are simple enough”, “easy to follow” and “the platform is beautifully made to be plug and play”. A participant further explained: “simplicity is paramount. Imagine putting that together in the pitch-black wearing night vision optics and covered in sand. The simplicity of assembly of the modular MR-UAV is definitely a strength”. Additionally, two participants noticed and approved the fact that the system does not require any tools for assembly, as they stated “most likely loose tools would be lost in the field”. Another participant suggested an improvement to “modify the arm so that once you connect it to the system it doesn’t require a separate connector”. Such suggestion is beneficial to the system as it would decrease the number of steps and further simplify the assembly procedures. One participant discussed that as the number of modules and profile increased, it becomes of paramount importance to have a well-documented easy-to-follow assembly guide and managing process. Lastly, one participant stated that military environment and operators put their equipment under harsh environments, and the system should be hard to break and easy to repair.

During the focus group, it was agreed that the MR-UAV profile would be decided during mission planning stages, and that users would not carry extra modules to be able to tailor the system in-the-field due to weight constraints. The results of this study also support such claim, as all participants agreed that the profile would be decided prior to each mission. However, participants stated that they might bring extra
modules as spare parts depending on the application. Additionally, they discussed that there might be use cases where a container with all the modules for different profiles is beneficial, such as in convoys and outposts. Therefore, there are two use cases for the modular MR-UAV framework:

- **Backpack carried foot mission** – in this use case, the profile is decided during the mission planning stage. Soldiers will only take the specific modules designated for that mission in a backpack.
- **Framework available in convoy or post** – in this use case a container with all the modules for the framework is carried in a convoy, or is held at an outpost. Users are able to decide what modules as needed.

Participants stated that the FMV profile is useful for a variety of commonly used applications, including reconnaissance and surveillance. In fact, various participants mentioned that this profile’s characteristics are very similar to UAVs they currently employ. However, participants did state that the modular MR-UAV presents advantages when compared to currently used models because it allows the replacement of sensors, and the communication link. A participant explained “this profile reminds me a lot of the DJI Mavic. Except that the Mavic uses a 2.4GHz communication link with no option to change, rendering it nearly useless for what I would want it for”. Another participant also inquired about the system range, and explained that a minimum range of 5 kilometers should be provided.

The payload delivery profile raised different opinion among participants. Three of them stated that the maximum payload (3.8 pounds) for this profile is adequate for such a small UAV. A participant specifically stated that it would be ideal to “deliver whole blood to wounded soldier” and another stated “it is a great carry weight and is right around what I needed 2 deployments ago”. Two other participants (totaling 5 out of 8) also agreed that this profile provide an adequate carrying weight, but they would like a longer flight time to be able to deliver packages at longer distances. Lastly, the 3 remaining participants stated that the payload capacity is too small for their applications. One of them stated “it makes more sense to use it as a scout to relay to a bigger platform to drop bigger payloads”, and another “I see promise behind this profile, but I would be interested to see if the engineers can increase the overall payload”. Although
responses varied, all participants agreed that a delivery profile is necessary, in the words of a participant “bottom line, this has many different real-world operational possibilities”. It is worth mentioning, that the modularity of the system would allow development of profiles for heavier payloads. This was also noticed by a participant who stated “the fact that the system is modular leads me to believe that future modifications and profiles would allow for larger payloads, which is great”.

The tethered FMV profile was widely praised by participants. Most of them described this profile as their “favorite”, “super interesting for various applications”, “great concept that would be very useful and likely to be adopted”. More specifically, participants stated that this profile would benefit “surveillance applications of squad sized elements”, in convoys, and military bases. Another participant stated “this sounds like it would be a great force protection profile. Like a crow nest on a pirate ship. Could be used for attaching to an armored convoy if it is capable of maintaining a decent speed and pilot tracking”. Two participants raised concerns regarding the autonomy of this profile in situations such as crossing bridges and near telephone wires. These responses demonstrate a need for high autonomy, to a point that the tethered MR-UAV can act as an independent agent and avoid obstacles during flight. However, the above responses support desire and requirement for a tethered MR-UAV capable of switching to battery operated flight, which was elicited as a novel concept during the focus group research.

The FMV and payload delivery profile are designed to be carried on backpacks during foot operations. Therefore, weight is an important aspect for these profiles. At the current version, these profiles weigh 3.1 and 3.2 pounds. All of the participants agreed that this is an adequate weight for these profiles, in fact, majority of them stated that this weight is lighter than other small UAVs they currently employ, and one participant stated “my equipment is usually 35-70 pounds. So, the system is by no means too heavy”. Therefore, it is concluded that this weight is adequate for its intended use, and suggested that the development of future profiles that will be carried in backpacks to weight similarly.
Chapter 9: Contributions, Conclusion and Future Work

9.1 Contributions

This research explores the concept of modularity in class 1 MR-UAVs in military operations. The key contributions are summarized below.

9.1.1 Main Contribution

- Designed, implemented, and evaluated a modular framework that allows military operators to quickly assemble without tools a Multi-Rotor Unmanned-Aerial Vehicle (MR-UAV) with customized flight characteristics (maximum payload, flight time), sensors, and actuators to fulfill requirements of a specific military mission.

9.1.2 Contributions to Military Organizations (Stakeholders)

- Ability to use a single framework to fulfill requirements of all class 1 MR-UAVs applications.
- Design considerations for modular MR-UAVs elicited from an initial focus group research and a later usability study on the modular prototype built.
- Ability to switch the power supply of MR-UAVs from tethered to onboard without the need to land the aircraft.

9.1.3 Contributions to the Human-Drone Interaction Research Community

- An evaluation of how users interact with modular MR-UAVs.
- A step-by-step process to select hardware components (sensors, actuators, propeller, motors, batteries, electronic speed controllers) for modules of the framework to achieve desired characteristics.
- Design of a software tool that streamlines the process of selecting hardware components and flight time calculation.
9.1.4 Other Contributions

- Validation of a flight time calculation algorithm based on brush-less motor and propeller data collected using a thrust-stand/dynamometer.
- Design of a power-management board that allows UAVs to instantly switch the power source from a ground station using a tethered cable to an onboard battery allowing new applications for tethered MR-UAVs.

9.2 Conclusion

MR-UAVs are operated in a wide range of military operations, and many of these applications have broadly different requirements. Therefore, organizations are required to purchase different MR-UAV models, one well suited for each type of application. For instance, one MR-UAV can be used for long flight time low carrying weight applications (i.e. surveillance), while another is designed to carry heavier payloads for short times (i.e. delivery). This demand for various models creates challenges for the users, such as training operators on how to pilot different MR-UAVs, and increased costs. Additionally, a commercial-off-the-shelf MR-UAV might not fully fulfill the requirement of a specific application as it was not necessarily implemented for those requirements. Such constraints motivated the work in this dissertation to explore the concept of a modular MR-UAVs framework, which would allow a single system to fulfill the requirements of all class 1 MR-UAVs for military organizations.

The first step of this work included interacting with subject-matter experts through focus group research. During this study, participants provided insights towards the idea, discussed applications, elicited requirements, and defined concepts such as modules and profiles for the framework. All participants expressed that this system would be useful for their organizations and demonstrated a positive perception of the concept. Following, this dissertation presents the design of the modular framework. The framework consists of five modules (controller, powertrain, video, communication, and payload), that allows the user to combine modules to quickly assemble an MR-UAV that best fulfills the requirements of the desired application.
To validate the design of the framework, a prototype was implemented and tested. The framework was used to build 3 modular MR-UAV profiles, one for surveillance (long flight time), one for delivery (heavier payload), and the third MR-UAV profile allows the switching form tethered to the battery power supply during flight. The latter required the design and implementation of a power-management board using a low-power path controller to control the MR-UAV input power supply source. The electric circuit was implemented and validated both in a laboratory and during flight.

To facilitate the process of selecting hardware components for the modules of the framework, this dissertation presented an algorithm to estimate flight time, which is incorporated in a process of building modular profiles. The algorithm was validated and an average accuracy of 98.94% was achieved for hovering flight time estimation. Additionally, it is also presented the design of a software tool named Multi-Rotor Designer. This tool allows developers to analyze brushless motors and propeller data (acquired from a thrust stand), evaluate how all-up-weight and battery selection impact the MR-UAV (in terms of flight time, thrust to weight ratio, and maximum payload), and streamlines the MR-UAV design process. Lastly, it was presented the results for two usability studies, one study conducted in person where users interacted with the framework and one video study conducted remotely. The modular MR-UAV framework received an average score of 86.5 on the standard System Usability Survey, which can be considered a high score based on the literature review. Also, participants considered the modular framework highly beneficial and likely to be adopted by military organizations, easy to assemble, and it took participants on average 1 minute and 29 seconds to assemble a MR-UAV using the framework.

The work presented in this dissertation shifts the paradigm of designing an MR-UAV for a single specific goal to a modular design that allows tailoring for various applications. This dissertation focused on exploring such a concept for military organizations. The results of this work demonstrate that the concept of modularity can be beneficial for such stakeholders. Additionally, as discussed in the future directions section below, the contributions of this work can be extended for general MR-UAV research and to the civilian world.
9.3 Future Directions

This dissertation explored the use of modular MR-UAVs in a military environment. However, the benefits of modular MR-UAVs can extend to other fields in the civilian world. One field specifically that can benefit from a modular framework is the MR-UAV research community. As research applications also have widely differing requirements, a modular MR-UAV that can be tailored for each research study can potentially present benefits to the community and should be further explored.

The flight efficiency of MR-UAVs assembled using the modular framework can be increased with improvements to the mechanical structure of the frame. More specifically, mechanical analyses of the frame dynamics and materials can improve its efficiency and decrease weight without compromising durability. Furthermore, various components of MR-UAVs are shared with class 1 fixed-wing UAVs. For instance, the electronics components from the controller module (flight controller, power distribution board, flight sensors), batteries, brushless motors, and propellers can also be used on fixed-wing UAVs. Therefore, future work can explore the ability to use the same framework for both types of UAVs. This would require design modifications on the controller module frame as it is the module that connects all other modular parts of the system.

The Multi-Rotor Designer tool was developed to streamline the process of components for the MR-UAV framework. However, the software itself can be further expanded in future work. For instance, usability studies can be conducted to evaluate and increase the system’s usability. Currently, the software accesses motor and propellers data from local log files, but in future versions, a cloud-based architecture could be employed to allow different MR-UAV developers and researchers to upload data they recorded with their equipment. This approach would allow different military organizations to increase the database size and, if the software is expanded to civilian use, it could become a standard UAV design software where users from various fields could contribute and utilize it.

The tethered power-management board presented in this dissertation allows MR-UAVs to switch from tethered to a battery power supply during flight. However, it is not possible to switch from battery to
tethered operation as the release mechanism does not enable re-attachment of the tethered cable without landing. A system that allows both the release and re-attachment of the cable would allow the creation of further applications. For instance, a network of tethered MR-UAVs could be used to provide a birds-eye view of a larger military operational area with the ability of individual systems to detach and reattach to the network as necessary. Lastly, the work presented in this dissertation focuses on the electrical circuit necessary to allow the switch in the power supply. In future work, this circuit can be integrated with other research projects that focus on the ground control station that controls the tethered cable release without causing tension on the line, such as the work presented in [42].
References


99


Appendix A: RCBenchMark 1585 Data Collection Script

The script below controlled the RCBenchMark 1585 thrust stand for brush-less motor and propeller data collection. The script is provided with the RCBenchMark data collection software.

/* ////////////////// Discrete steps V2 ///////////////////

The script will sweep between the input values "minVal" and "maxVal". The sweep will be made in discrete "stepsQty" steps. Each step will consist of a settling time "settlingTime" after which a new log entry will be recorded. To reduce noise, "samplesAvg" will be averaged and recorded. This script uses the improved steps2 function, that can introduce a cooling time, as well as a slew-rate limiter for smooth step transitions.

The '.' represents a sample is recorded. 5 steps will record 6 data rows (one for zero).

^ Motor Input
|                __. maxVal
|               __./ \  
|                __./  
|                __./  
|                __./  
|               __./ \  
|              minVal __./  
|             escInit___./  
|___________________________> Time

///////////// User defined variables ///////////// */
var escStart = 1000;  // ESC idle value [700us, 2300us]
var minVal = 1100;   // Min. input value [700us, 2300us]
var maxVal = 2000;   // Max. input value [700us, 2300us]

// step parameters
var params = {
    steps_qty: 10, // Number of steps
    settlingTime_s: 3, // Settling time before measurement
    cooldownTime_s: 0, // If the motor needs to cool down between steps. Zero disables cooldown.
    cooldownThrottle_us: 1175, // Cool down faster when slowly spinning
    cooldownMinThrottle: 1500, // Only activates the cooldown time for high throttle
    max_slew_rate_us_per_s: 50 // Limits torque from throttle changes
};

var samplesAvg = 100;  // Number of samples to average
var repeat = 0; // How many times to repeat the same sequence
var filePrefix = "StepsTestV2";

///////// Beginning of the script ///////////

//Start new file
rcb.files.newLogFile({prefix: filePrefix});

//Tare the load cells
rcb.sensors.tareLoadCells(initESC);
//Arms the ESC

function initESC(){
  //ESC initialization
  rcb.console.print("Initializing ESC...");
  rcb.output.set("esc", escStart);
  rcb.wait(startSteps, 4);
}

//Start steps

function startSteps(){
  takeSample(ramp);
}

// Records a sample to CSV file

function takeSample(callback){
  rcb.sensors.read(function (result){
    // Write the results and proceed to next step
    rcb.files.newLogEntry(result, callback);
  }, samplesAvg);
}

// Start the ramp up function

function ramp(){
  rcb.output.steps2("esc", minVal, maxVal, stepFct, finish, params);
// The following function will be executed at each step.
function stepFct(nextStepFct){
    takeSample(nextStepFct);
}

// Ramp back down then finish script
function finish(){
    // Calculate the ramp down time
    var rate = params.max_slew_rate_us_per_s;
    var time = 0;
    if(rate>0){
        time = (maxVal-escStart) / rate;
    }
    rcb.output.ramp("esc", maxVal, escStart, time, endScript);
}

//Ends or loops the script
function endScript() {
    if(--repeat > 0){
        if(repeat === 0){
            rcb.console.print("Repeating one last time...");
        }else{
            rcb.console.print("Repeating " + repeat + " more times...");
        }
    }else{  
        rcb.console.print("Repeating " + repeat + " more times...");
    }
}
startSteps();

} else {
    rcb.endScript();

}
Appendix B: IRB #00039142 Approval

6/6/2019

Dante Tezza
Computer Science and Engineering
15215 Livingston Ave Apt 53
Lutz, FL 33559

RE: Expedited Approval for Initial Review
IRB#: Pro00039142
Title: Modular Drone Requirements - Focus Group

Study Approval Period: 6/5/2019

Dear Mr. Tezza:

On 6/5/2019, the Institutional Review Board (IRB) reviewed and APPROVED the above application and all documents contained within, including those outlined below. Please note this study is approved under the 2018 version of 45 CFR 46 and you will be asked to confirm ongoing research annually in place of a full Continuing Review. Amendments and Reportable Events must still be submitted per USF HRPP policy.

Approved Item(s):
Protocol Document(s):
Study Protocol - Version 1 - 05-23-19

Consent/Assent Document(s)*:

*Please use only the official IRB stamped informed consent/assent document(s) found under the "Attachments" tab. Please note, these consent/assent documents are valid until the consent document is amended and approved.

It was the determination of the IRB that your study qualified for expedited review which includes activities that: (1) present no more than minimal risk to human subjects, and (2) involve only procedures listed in one or more of the categories outlined below. The IRB may review research through the expedited review procedure authorized by 45 CFR 46.110 and 21 CFR 56.110. The research proposed in this study is categorized under the following expedited review
category.

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB via an Amendment for review and approval. Additionally, all unanticipated problems must be reported to the USF IRB within five (5) business days.

We appreciate your dedication to the ethical conduct of human subjects research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5038.

Sincerely,

[Signature]

Kristen Salomon, Ph.D., Chairperson
USF Institutional Review Board
Appendix C: IRB #0002019 Approval

UNIVERSITY OF SOUTH FLORIDA

EXEMPT DETERMINATION

January 14, 2021

Dante Tezza
15215 Livingston Ave
Apt 53
Lutz, FL 33559

Dear Mr. Tezza:

On 1/13/2021, the IRB reviewed and approved the following protocol:

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<th>Initial Study</th>
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<td>STUDY000219</td>
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<tr>
<td>Review Type</td>
<td>Exempt 2</td>
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<tr>
<td>Title</td>
<td>Modular MR-UAV Framework - Questionnaire</td>
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<tr>
<td>Funding</td>
<td>None</td>
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<tr>
<td>Protocol</td>
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</table>

The IRB determined that this protocol meets the criteria for exemption from IRB review.

In conducting this protocol, you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Please note, as per USF policy, once the exempt determination is made, the application is closed in BoliIRB. This does not limit your ability to conduct the research. Any proposed or anticipated change to the study design that was previously declared exempt from IRB oversight must be submitted to the IRB as a new study prior to initiation of the change. However, administrative changes, including changes in research personnel, do not warrant a modification or new application.

Ongoing IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities impact the exempt determination, please submit a new request to the IRB for a determination.

Institutional Review Boards / Research Integrity & Compliance
FWA No. 00001669
University of South Florida / 3702 Spectrum Blvd, Suite 165 / Tampa, FL 33612 / 813-974-6636
Sincerely,

Various Menzel
IRB Research Compliance Administrator
Appendix D: IRB #0001375 Approval

EXEMPT DETERMINATION

October 16, 2020

Dante Tezza
15215 Livingston Ave
Apt53
Lutz, FL 33559

Dear Mr. Tezza:

On 10/15/2020, the IRB reviewed and approved the following protocol:

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<th>Initial Study</th>
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<td>STUDY001375</td>
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<tr>
<td>Review Type:</td>
<td>Exempt 3</td>
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<tr>
<td>Title:</td>
<td>Usability evaluation of modular drones for the military.</td>
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<tr>
<td>Funding:</td>
<td>None</td>
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<td>Protocol:</td>
<td>* Protocol, Version #1, 10-14-2020;</td>
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The IRB determined that this protocol meets the criteria for exemption from IRB review.

In conducting this protocol, you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Please note, as per USF policy, once the exempt determination is made, the application is closed in BellsIRB. This does not limit your ability to conduct the research. Any proposed or anticipated change to the study design that was previously declared exempt from IRB oversight must be submitted to the IRB as a new study prior to initiation of the change. However, administrative changes, including changes in research personnel, do not warrant a modification or new application.

Ongoing IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities impact the exempt determination, please submit a new request to the IRB for a determination.
Sincerely,

Various Menzel
IRB Research Compliance Administrator