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COTS DRONE DESIGN: A RAPID EQUIPAGE ALTERNATIVE FOR FORCE RECON COMPANIES

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THESIS

COTS DRONE DESIGN: A RAPID EQUIPAGE ALTERNATIVE FOR FORCE RECON COMPANIES

by

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December 2020

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13. ABSTRACT (maximum 200 words)

The Force Reconnaissance Group (FRG) of the Philippine Marine Corps (PMC) is a pioneer unit of the Armed Forces of the Philippines (AFP) in acquiring and utilizing small unmanned aircraft systems (SUAS) for aerial intelligence, surveillance, and reconnaissance (ISR). The sustainment of this ISR equipment, however, largely depends on ample resources that the FRG does not have. This organizational challenge results in an aerial ISR capability gap at the company level. Force Recon Companies (FRCs) do not have organic drones to support their aerial real-time reconnaissance, surveillance, and target acquisition requirements.

This study explored an alternative solution to address this capability gap: a low-cost commercial-off-the-shelf (COTS) drone design specific to the operational needs of FRCs. A systems engineering approach to SUAS design resulted in a micro traditional helicopter drone as the FRC COTS Drone design. The study produced a prototype FRC COTS Drone consisting of a four-part reconnaissance kit that includes a micro helicopter UAV, handheld controller, first person view (FPV) goggles, and FPV monitor. This effort can promote a culture of innovation in small unmanned systems, not just within the PMC, but the AFP as a whole. This study can also serve as a model for security cooperation between the United States and the Philippines through the integration of three fields: Philippine experience, U.S. technical expertise and resources, and the global commercial market.

14. SUBJECT TERMS COTS drone, Philippine Force Recon, COTS, Force Recon Companies, FRCs, Force Reconnaissance Group, FRG, Marine Special Operations Group, MARSOG, Philippine Marine Corps, PMC, Armed Forces of the Philippines, drone, UAV, small unmanned aircraft systems, SUAS, micro traditional helicopter, innovation, intelligence, surveillance, and reconnaissance, ISR	**15. NUMBER OF PAGES** 113
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COTS DRONE DESIGN: A RAPID EQUIPAGE ALTERNATIVE FOR FORCE RECON COMPANIES

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ABSTRACT

The Force Reconnaissance Group (FRG) of the Philippine Marine Corps (PMC) is a pioneer unit of the Armed Forces of the Philippines (AFP) in acquiring and utilizing small unmanned aircraft systems (SUAS) for aerial intelligence, surveillance, and reconnaissance (ISR). The sustainment of this ISR equipment, however, largely depends on ample resources that the FRG does not have. This organizational challenge results in an aerial ISR capability gap at the company level. Force Recon Companies (FRCs) do not have organic drones to support their aerial real-time reconnaissance, surveillance, and target acquisition requirements.

This study explored an alternative solution to address this capability gap: a low-cost commercial-off-the-shelf (COTS) drone design specific to the operational needs of FRCs. A systems engineering approach to SUAS design resulted in a micro traditional helicopter drone as the FRC COTS Drone design. The study produced a prototype FRC COTS Drone consisting of a four-part reconnaissance kit that includes a micro helicopter UAV, handheld controller, first person view (FPV) goggles, and FPV monitor. This effort can promote a culture of innovation in small unmanned systems, not just within the PMC, but the AFP as a whole. This study can also serve as a model for security cooperation between the United States and the Philippines through the integration of three fields: Philippine experience, U.S. technical expertise and resources, and the global commercial market.

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LIST OF ACRONYMS AND ABBREVIATIONS

AO	area of operations
AFP	Armed Forces of the Philippines
AGL	above ground level
ARC	Aviation Rulemaking Committee
ARS	amphibious reconnaissance and surveillance
ASG	Abu Sayyaf Group
BEC	battery eliminator circuit
C3	command, control, and communication
COTS	commercial-off-the-shelf
CPP	Communist Party of the Philippines
CT	counterterrorism
DA	direct action
DJI	Dà-Jiāng Innovations
ESC	electronic speed controller
FAA	Federal Aviation Authority
FC	flight controller
FPV	first person view
FRC	Force Recon Company
FRG	Force Reconnaissance Group
GCS	ground control system
GPS	global positioning system
GOPlat	gas and oil platform
GRS	ground reconnaissance and surveillance
ISIS	Islamic State of Iraq and Syria
ISR	intelligence, surveillance, and reconnaissance
MC	Marine Company
MET	mission essential task
METL	mission essential task list
MOUT	military operation on urban terrain
MSL	mean sea level

NPA	New People’s Army
NPS	Naval Postgraduate School
PMC	Philippine Marine Corps
PRRD	personal range reconnaissance drone
RSTA	reconnaissance, surveillance, and target acquisition
Rx	receiver
SME	subject matter expert
SCO	sniping and counter-sniping
SOF	special operations forces
SPIE	special insertion and extraction
SRS	special reconnaissance and surveillance
SUAS	small unmanned aircraft system
TTP	techniques, tactics, and procedures
TWR	thrust to weight ratio
Tx	transmitter
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
USMC	United States Marine Corps
VBSS	visit, board, search, and seizure
VTOL	vertical takeoff and landing

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To my family and relatives, thank you for your support and prayers. Lastly, to my wife, Loraine, thank you for inspiring me to keep on moving forward and to keep on aiming high throughout my journey at the Naval Postgraduate School. The thousands of miles and different time zones between us were never an issue.

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I. INTRODUCTION

A. CONTEXT

Cheap, fast, and accessible—these attributes are the great equalizers of the present age. Developing countries and non-state actors dive into these attractive features given the opportunity. The world's only true superpower, the United States, and many great powers, even with their unparalleled might, yield to these equalizers. In the military sphere, commercial-off-the-shelf (COTS) technology are crucial providers of these great equalizers. COTS components and rapid equipage have been shaping most of the defense and armed forces of nations around the globe, and the Republic of the Philippines is by no means an exception. Western and Asian countries have been adopting the use of COTS for their military and defense hardware and software. These nations have seen the benefits of COTS in the rapid equipage of their soldiers in the field. In particular, the unmanned systems such as drones that utilized military-grade components during their early years are now adopting COTS components.

The Force Reconnaissance Group (FRG) of the Philippine Marine Corps (PMC) has shown interest and has employed military-standard and COTS drones in real-world scenarios, albeit to a limited degree. The FRG, however, does not have the capacity to sustain the drone platforms. The FRG, particularly its Force Recon Companies (FRC), with all its organizational challenges, must not only find alternative ways to sustain its drone platforms, but also take the first steps towards drone technology research and development. COTS components offer a practical yet promising opportunity to initiate such research.

B. LITERATURE REVIEW

This section discusses how COTS components and the concept of rapid equipage have been applied to drone design and technology of military and defense forces of several countries.

1. COTS in Military and Defense Forces

Many nations have considered COTS components in their defense-related acquisitions. A study conducted by two universities in the United States revealed that the militaries and defense forces of countries viewed as traditional leaders in military innovation are now integrating and contracting commercial markets to cope with their present-day challenges.[1] Common grounds for such bold actions—to settle with commercially made hardware and software instead of in-house military-standard materiel—are the practical advantages that COTS components offer against mounting problems such as rising fiscal constraints, rapidly evolving technology, bureaucratic procurement process, and untimely distribution of equipment to the individual soldier.[2] Most common applications of COTS are seen in command and control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR).[3]

Identified disadvantages of COTS products have been cited by several COTS researchers. Among the disadvantages are the pressure to accept the limitations and unmet features of the pre-determined or available COTS products which forces end-users to be more flexible and less specific with their requirements, and most COTS products are designed primarily by commercial companies to meet the needs of the general market and therefore their products may not comply with the end-user's required specifications.

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[1] Timothy Hawkins and Michael Gravier, "Integrating COTS Technology in Defense Systems: A Knowledge-Based Framework for Improved Performance," *European Journal of Innovation Management* 22, no. 3 (June 3, 2019): 508, https://doi.org/10.1108/EJIM-08-2018-0177.

[2] Jean-Christophe Mielnik and Stephane Lauriere, "Use of Software COTS Within C4ISR Systems: Contribution of Information Sharing to Enhanced Risk Management, the eCots Approach," *STAR* 45, no. 24 (December 2007): 31, http://search.proquest.com/docview/24031087/; T. A. Krinke and D. K. Pai, *COTS/ROTS for Mission-critical Systems* (Bloomington, Minnesota: General Dynamics Information Systems, 1999): 13, https://nepp.nasa.gov/DocUploads/36AA9B68-A52E-4DCE-802CD8FDE0CC9525/COTS%20and%20ROTS%20for%20mission%20critical%20systems.pdf; Jacques Gansler and William Lucyshyn, *Commercial Off the Shelf (COTS): Doing It Right* (College Park, Maryland: Center for Public Policy and Private Enterprise, 2008), 20−22 , http://www.dtic.mil/docs/citations/ADA494033.

[3] John Keller, "Use of COTS Components on the Rise in U.S. Military Communications and Surveillance Applications," *Military & Aerospace Electronics*, November 17, 2015, 1, https://www.militaryaerospace.com/computers/article/16713912/use-of-cots-components-on-the-rise-in-us-military-communications-and-surveillance-applications; Krinke and Pai, *COTS/ROTS for Mission-critical Systems*.

Further, the design of COTS components is constantly evolving to meet the demands of the commercial market, and because COTS products are designed for non-military operating environments, they are often not rugged and non-mission specific.[4]

2. Rapid Equipage

The concept of rapid equipage promises a feasible response for meeting today's challenges by tapping technological advances from the commercial market. Although there is very limited literature written about rapid equipage, the idea and its practice exist. The concept has caught the attention of not only state actors but also non-state actors, including terrorists and enemies of states. Rapid equipage on the actual battlefield is made possible through COTS components or low-cost solutions to materiel problems that otherwise would take too much time if procured through the usual process, to the point of being already over-taken by events.[5] The U.S. Army, as a model, has institutionalized the rapid equipage of its troops since 2002 through the activation of the Rapid Equipping Force (REF).[6] REF was established to provide the urgent requirements of soldiers in the field and focuses on immediate materiel solutions at the small-unit level.[7] This unit

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[4] Carina Alves and Anthony Finkelstein, "Challenges in COTS Decision-Making: A Goal-Driven Requirements Engineering Perspective," in *Proceedings of the 14th International Conference on Software Engineering and Knowledge Engineering* (London: University College London, 2002), 6, https://doi.org/10.1145/568760.568894; Terry Thames, "Using Commercial Off-the-Shelf (COTS) Equipment to Meet Joint Service Requirements," in *1998 IEEE AUTOTESTCON Proceedings* (Salt Lake City, Utah: IEEE, 1998), 204–209, https://doi.org/10.1109/AUTEST.1998.713445; Krinke and Pai, "COTS/ROTS for Mission-Critical Systems."

[5] Jen Judson, "Battlefield Tech Demands: Rapid Equipping Force Preps for Surge with New Army Brigades," *Defense News*, February 27, 2008, https://www.defensenews.com/land/2018/02/27/rapid-equipping-force-could-see-surge-in-work-as-armys-new-adviser-brigades-deploy/; David Vergun, "Rapid Equipping Force Bringing Swift Soldiers," United States Army, February 27, 2018, https://www.army.mil/article/201185/rapid_equipping_force_bringing_swift_solutions_to_soldiers.

[6] Judson.

[7] Judson.

effectively conducts rapid equipage through innovation, flexibility, and responsiveness that can be a model for the military and defense forces of other nations.[8]

Unmanned systems are some of the most applicable platforms for the application of COTS technology and rapid equipage. Among the different types of unmanned systems, the most widespread application of COTS technology can be seen on drones.

3. COTS Drones

Drone is the common term used to collectively address "unmanned aircraft systems (UAS) and small unmanned aircraft system ([S]UAS)."[9] Drones in the military are mostly used for intelligence, surveillance, and reconnaissance (ISR), with the smaller variety SUAS—weighing "under 55 pounds," according to the Federal Aviation Administration (FAA).[10] COTS drones are commonly used for short range real-time video surveillance to enhance situational awareness at the tactical level.[11] Pre-made COTS SUAS are used in many military and defense forces because of their low-cost and widespread commercial availability. An excellent example of the utilization of COTS drones, although offensive in nature, happened during the Syrian crisis. The Turkish military's "commercially available … cheap but effective domestic drone program … changed the military equation against Russia," revealing "that there are some wars that Russia is apparently not willing to fight."[12] The Russian military realized that it cannot afford to continue losing valuable

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[8] Alicia Baldauf and Jason Reherman, "Increasing Responsiveness of the Army Rapid Acquisition Process: The Army Rapid Equipping Force" (master's thesis, Naval Postgraduate School, 2011), 1, https://calhoun.nps.edu/bitstream/handle/10945/10753/11Jun%255FBaldauf%255FJAP%255FFinal.pdf?sequence=1&isAllowed=y.

[9] Brent Terwilliger et al., *Small Unmanned Aircraft Systems Guide: Exploring Designs, Operations, Regulations, and Economics* (Newcastle, Washington: Aviation Supplies & Academics, Inc., 2017), 23, http://ebookcentral.proquest.com/lib/ebook-nps/detail.action?docID=5631327.

[10] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 23.

[11] Jack McDonald, *Drones and the European Union: Prospects for a Common Future* (London: Chatham House, 2018), 4, http://search.proquest.com/docview/2010637183/.

[12] Mitch Prothero, "Turkey Used a New Weapon in Syria That Was So Effective It Looks like Russia Won't Dare Confront Turkey Directly," Insider, March 10, 2020, https://www.insider.com/turkey-drones-syria-russia-wont-confront-directly-2020-3?utm_source=yahoo.com&utm_medium=referral.

tanks to cheap Turkish drone attacks.[13] Unlike other larger and well-funded military forces, smaller armed forces, even with their readily available COTS components, still struggle to develop cost-effective solutions.[14] In the Philippine setting, selected units of the Armed Forces of the Philippines (AFP), including FRG, have employed pre-made COTS SUAS during the Marawi Crisis and numerous combat operations; these drones, however, are not mission-specific and are not capability-based.[15]

C. MOTIVATION

Compared to the defense forces of other countries, the AFP is generally lagging behind in terms of drones and will continue to do so if nothing is done to change this course. In the PMC, if not the whole AFP, there has not been any attempt to design an organization-specific drone platform. The trend has always been to procure pre-made commercial quadcopters, take advantage of foreign grants, and purchase sought after foreign-designed drones. No effort has been made for research, design, and development of an in-house drone. The presence of COTS components in the commercial market provides untapped possibilities to jumpstart such an effort. This study aims to trigger creativity, encourage the pursuit of technical know-how, and start a culture of innovation across the broader Philippine military organization in terms of drone design.

D. RESEARCH QUESTION

Fundamentally, this study asks the core question—what alternative low-cost drone prototype design can address the aerial ISR capability gap of FRCs? Pertinent information required to answer the research question will primarily originate from the organizational

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[13] Prothero, "Turkey Used a New Weapon in Syria That Was so Effective It Looks like Russia Won't Dare Confront Turkey Directly."

[14] McDonald, *Drones and the European Union*, 4.

[15] Philippine Marine Corps, *Operational Assessment on the Participation of Marine Operating Forces in the Joint Operations for the Liberation of Marawi City* (Taguig City, Philippines: Philippine Marine Corps, 2018), 50; Ian Garceron, "Urban Warfare: Lessons Learned from the Marawi Crisis" (master's thesis, Naval Postgraduate School, 2020), 52, https://calhoun.nps.edu/bitstream/handle/10945/65523/20Jun_Garceron_Adolf_Ian.pdf?sequence=1&isAllowed=y.

observations of FRCs on the features, specifications, and limitations of the current FRG SUAS, the Raven RQ-11B and DJI MAVIC Pro, and open source COTS hardware and software.

E. THESIS AND IMPORTANCE

A low-cost COTS drone design is a rapid equipage solution to FRC's aerial ISR capability gap. A low-cost COTS drone design could secure FRG's spot in the forefront of drone technology and ultimately reinforce a credible FRG that can live up to its core forte: reconnaissance.

A significant feature of this study is that it integrates three distinct fields: Philippine experience, academia, and the global commercial market. The Philippine experience is gleaned from the FRG's organizational challenges, ISR capability gap, and operational experience; the academic perspective is derived from the author's opportunity to tap diverse expertise and resources of the Naval Postgraduate School (NPS); and the global commercial market perspective comes from a survey of the vast selection of relevant COTS components. This study represents an attempt to plant the seeds of what someday may become widespread innovation in drone systems and technology in the AFP.

The study brings tactical and strategic implications not just to the AFP but also to the U.S. military, which has been the strongest ally of the Philippines in defense and security. On the tactical level, aside from enhancing the ISR capability of FRCs, the study can open their opportunities to become actual developers rather than just end-users of drones. The broader AFP, in partnership with U.S. entities, can learn and can be exposed to the technical skills and resources required for drone development. The output of this study is not necessarily confined to the Philippines; moreover, the results can present probable applications with other U.S. partner countries that share similar challenges and environments with the Philippines. Strategically, this study could have just presented the United States with an added opportunity to take the lead on the possible future development of unmanned systems technology in the region.

II. PROBLEM FRAMING

A. INTRODUCTION

The FRC is the focal organization of this thesis and is the primary special operations unit of the FRG. The origin of today's FRC can be traced back to 1950 through its forerunner, the Scout Raiders Platoon, which specialized in amphibious reconnaissance and amphibious raids.[16] A series of disbandment and reactivations led to the creation of the 61st Marine Recon Company in 1985 that eventually led to the activation of the Force Reconnaissance Battalion (FRBN) in 1989 which employed four FRCs.[17] In 2013, the FRBN was expanded and re-designated as the Marine Special Operations Group (MARSOG) with five special operations companies, a sniper company, a special boat company, and a service company.[18] In 2018, MARSOG was renamed Force Reconnaissance Group, but the same special operations identity, mission, and core tasks remained.[19] Even though currently addressed as a Marine Company, the title of Force Recon is still the commonly used term to address the special operations companies of the PMC; hence, the Force Recon Company is the focal organization of this study.

This chapter has five parts. The first part discusses the organizational challenges that the FRG and FRCs are facing in terms of aerial ISR. The second part provides the background of the focal organization, explaining what the FRCs are and what is expected from these companies as Marine special operations units. The third part illustrates the employment of FRG's drones in the operational environments where its FRCs are deployed. The fourth part provides an in-depth examination of the overall performance of FRG's two types of drones. The last part discusses the identified gap in the FRC drone capability and the corresponding alternative solution.

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[16] Philippine Marine Corps, *Force Reconnaissance Group Doctrine* (Taguig City, Philippines: Philippine Marine Corps, 2020), 1.

[17] Philippine Marine Corps, 1.

[18] Philippine Marine Corps, 1.

[19] Philippine Marine Corps, 1.

B. CHALLENGE

The main challenge of the FRG is the lack of financial resources that impedes the acquisition of new SUAS. This challenge also strains the much-needed repair and maintenance of existing drones against wear and tear. FRCs do not have special or extra funds, and their mother unit, FRG, does not have the leverage to request funds from higher headquarters to maintain the existing drones or procure badly needed new drones. It is understood that the PMC is also struggling to manage its meager funds to address concerns that outweigh the procurement of drones. Hence, FRG has mostly relied on external grants to acquire most of its advanced equipment such as armaments, night fighting system, protective equipment, and SUAS. The single existing military-grade drone, the Raven RQ-11B, for example, was acquired through the U.S. National Defense Authorization Act (NDAA) 2282 Grant Program as part the Counterterrorism (CT) Train and Equip Program for the PMC.[20] Three DJI Mavic Pros were also acquired as donations from generous entities, two of them from the non-profit organization Spirit of America in 2018, as facilitated by the Maritime Special Operations Force Liaison Element (MARSOFLE) to the Philippines. After the acquisition of the mentioned SUAS platforms, it became clear that the repair and maintenance of these systems would entail additional financial concerns.

C. THE ORGANIZATION OF THE FRG AND FRC

This section provides the organizational information about the FRG and FRCs.

1. FRG

The mission of the FRG is “to organize, train, equip, maintain, and sustain Marine Special Operations units in order to support the PMC in the accomplishment of its mission.”[21] FRG is the force provider of FRCs to AFP’s force employers in the operational area such as Marine brigades, joint task forces, and area commands. During Force Reconnaissance Course Test Missions and military campaigns that require the employment

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[20] Force Reconnaissance Group, *Maritime SOF Tactical UAS Project* (Cavite, Philippines: Force Reconnaissance Group, 2018), 4.

[21] Philippine Marine Corps, *Force Reconnaissance Group Doctrine*, 5.

of two or more FRCs for special operations in a single area of operations (AO), the FRG can be task-organized into the Task Group "Hunter" under joint task forces as a force employer of Marine special operations units.[22]

2. FRC

This section discusses the mission, mission essential tasks (MET), structure, and notable accomplishments of the FRCs.

a. Mission and Mission Essential Task List (METL)

The mission of the FRC is "to conduct special operations in support to the mission of the Force Reconnaissance Group."[23]An FRC provides special operations capability and deploys in support of Marine brigades, joint task forces, and area commands. The METL of an FRC is identified in Table 1.

Table 1. FRC METL.[24]

MET	Tasks
MET 1	Conduct amphibious reconnaissance and surveillance (ARS)
MET 2	Conduct ground reconnaissance and surveillance (GRS)
MET 3	Conduct special reconnaissance and surveillance (SRS)
MET 4	Conduct direct action (DA)
MET 5	Conduct counterterrorism (CT)
MET 6	Conduct sniping and counter-sniping operations (SCO)
MET 7	Conduct specialized infiltration and exfiltration (SPIE)

Even with the overall special operations METL and the outstanding real-world accomplishments of FRCs in combat, reconnaissance still remains the forte of an FRC as

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[22] Philippine Marine Corps, 11.

[23] Philippine Marine Corps, 9.

[24] Adapted from Force Reconnaissance Group, *Force Reconnaissance Group Training and Readiness Manual* (Cavite, Philippines: Philippine Marine Corps, 2018), 13.

reflected in the ISR-specific METs 1, 2, and 3. An FRC strives and is expected to give on the highest priority to ISR missions and ISR tasks in support of a mission involving METs 4, 5, 6, and 7. Most ISR techniques, tactics, and procedures (TTP) of FRCs are based on TTPs taught in United States Marine Corps (USMC) Reconnaissance X, U.S. Army Pathfinder, U.S. Army Ranger, and U.S. Navy Underwater Demolitions Team Courses, as revealed by Maj. Renato Bobiles, a graduate of the four courses and the author of the Force Reconnaissance Course of the PMC.[25]

b. Structure and Activities

The structure of an FRC enables effective combat and ISR missions. An FRC with an average actual personnel total of 45 officers and enlisted personnel compared to an ideal of 78 operators is fully capable of conducting and directing the full spectrum of the FRC METL. An FRC is designed to conduct DA and CT, and to direct all ISR missions, including ARS, GRS, and SRS. Given the need to emphasize aerial ISR as a core capability, the employment of SUAS for aerial ISR is placed as a task under the special reconnaissance METL of FRCs.[26]

The next lower echelon of an FRC is the 16-man team, considered a platoon echelon. Although a 16-man team has only half the number of a typical Marine rifle platoon, a 16-man team is fully capable of conducting CT and DA such as raids, ambush, amphibious raids, visit board search and seizure (VBSS), and gas oil platform (GOPlat) takedown. A 16-man team is also capable of directing all ISR missions that an FRC can direct.

The next lower echelons depict the importance of reconnaissance as the bread and butter of the Force Recon Marines. The 8-man team and the 4-man team, the smallest and principal reconnaissance units of an FRC, are specifically structured to independently conduct all the ISR METS—ARS, GRS, and SRS—including SCO. ARS encompasses

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[25] Renato Bobiles, personal communication, February 6, 2019.

[26] Philippine Marine Corps, *Marine Special Operations Doctrine* (Taguig City, Philippines: Philippine Marine Corps, 2020), 33; Force Reconnaissance Group, *Force Reconnaissance Group Training and Readiness Manual*, 43.

beach survey, hydrographic survey, and surf observation while GRS consists of area, point, route, zone, and camp reconnaissance. SRS includes post-strike reconnaissance, target acquisition, and SUAS ISR.

c. Notable Accomplishments

Due to FRC's nature of deployment as providers of Marine special operations capability to Marine brigades, joint task forces, and area commands during crisis and campaigns, FRCs have been involved in thousands of DA and CT missions all over the country. The following are some of the notable and successful accomplishments of FRCs throughout the years: neutralization of Boy Clarin and his lawless band in San Jose, Occidental Mindoro in 1984; raids on the hideouts of renegade soldiers in Metro Manila in the late 1990s; a raid against the main headquarters of the Communist Party of the Philippines-New People's Army (CPP-NPA) in Sagada, Mountain Province in 1988; the capture of Camp Al-Madinah of the Abu Sayyaf Group (ASG) and rescue of Luis Anthony Biel III in 1992; the rescue of Father Cirilo Nacorda, and American national Jeffrey Schilling; the neutralization of ASG sub-leaders Mihadon Arok and Sabri Isah in 2005; neutralization of one of the Federal Bureau of Investigation's (FBI) most wanted terrorists and the emir of the ASG, Khadaffy Janjalani, in Patikul, Sulu in 2006; the neutralization of ASG sub-leader Albader Parad in Sulu in 2009; and the neutralization of ASG sub-leader Alhabsy Misaya in 2017; moreover, the FRCs also played a significant role in the liberation of Marawi City against the Islamic State in Southeast Asia; the neutralization of ASG sub-leaders Tuan Wars and Abu Nahal Maulid in Patikul, Sulu in 2018, and the neutralization of the top three leaders of the CPP-NPA's Bienvenido Vallever Command, Magramo, Rosal, and Celnon, in Palawan in 2020.[27]

FRCs take pride in their accomplishments in combat and their Marine special operations capabilities. Committed to upholding the reputation of their founding

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[27] Philippine Marine Corps, *Force Reconnaissance Group Doctrine*, 1−3; "AFP to Honor Troops Who Killed Janjalani," GMA News TV, January 22, 2007, https://www.gmanetwork.com/news/story/27765/news/nation/afp-to-honor-troops-who-killed-janjalani/; Celeste Formoso, "Top Ranking NPA and 4 Others Killed in Military Raid," Palawan News Online, September 3, 2020, https://palawan-news.com/top-ranking-npa-and-4-others-killed-in-military-raid-government-sustains-1-casualty/.

organizations, the FRCs strive to preserve reconnaissance as their forte. As experienced by the FRCs in the battlefield, reconnaissance and overall ISR are significantly enhanced through the employment of drones. The succeeding sections elaborate on the drones that FRG has in its inventory.

D. DRONE EMPLOYMENT

The FRG is one of the pioneer units of the AFP to acquire and utilize SUAS. The FRG was able to employ drones during actual operations, both in urban and jungle settings. FRCs have been supported by ISR from SUAS operated by the FRG command group in the command post; however, FRCs themselves do not have their own drones. SUAS ISR, while having presented FRCs with advantages, have also revealed some gaps, especially in aerial ISR capability.

1. Urban Setting

The Marawi Crisis, the biggest military operation in urban terrain (MOUT) campaign ever fought by the AFP, offered the opportunity for the extensive use of drones in the battlefield. The five-month long crisis was fought against the combined forces of the Islamic State of Iraq and Syria (ISIS)-backed Maute Group and a faction of the ASG that started on 25 May 2017 and lasted until 21 October of the same year at Marawi City, Lanao del Sur, Mindanao, Philippines.[28] The FRG, with its four FRCs, a sniper company, and a service company, was an indispensable part of the successful campaign. FRCs conducted hundreds of raids, search and rescue, sniping and counter-sniping, and reconnaissance missions, among others. For the first three months of the crisis, the FRG was the only unit of the AFP that possessed a military-grade drone, AeroVironment’s Raven RQ-11B, a fixed-wing SUAS. The FRG, like other AFP units that participated during the crisis, also used a DJI Mavic Pro, a commercial quadcopter, for ISR. It should be noted that FRCs were the only units during the Marawi Crisis that were capable of nighttime combat and recon missions because of their robust night-fighting system and were the only units

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[28] Force Reconnaissance Group, *After Operations Report (Marawi City Crisis)* (Cavite, Philippines: Force Reconnaissance Group, 2017), 2; Philippine Marine Corps, *Operational Assessment on the Participation of Marine Operating Forces in the Joint Operations for the Liberation of Marawi City*, 1.

supported with night aerial ISR because of FRG’s night capable Raven RQ-11B. Both the Raven RQ-11B and the Mavic Pro were used extensively, averaging four to eight flights per day.[29] Both SUAS provided a huge advantage to FRG units, particularly the FRCs. These SUAS, however, also had limitations and disadvantages that hindered the performance of FRCs on the front lines. These limitations and disadvantages will be discussed in more detail later in the chapter.

2. Jungle Setting

The jungles and mangrove areas of the Province of Sulu, Southern Mindanao, Philippines also presented opportunities as well as challenges to the ISR application of the FRG’s two SUAS. For almost two decades, the U.S. forces in Sulu have provided AFP units, including FRCs, with aerial ISR support. It is only in 2018 that the FRG was able to support its own FRCs with aerial ISR in the province. The characteristics of a tropical jungle, especially the extra thick canopy and rich vegetation, challenged the performance of the Raven RQ-11B and the Mavic Pro. This challenge contributed to the less than optimal utilization of FRG SUAS, which denied the chance for an even more enhanced performance of FRCs on the front lines through aerial ISR capability.

E. EXISTING DRONE OPTIONS

This section of the study examines how the two types of drones owned by the FRG were able to satisfy the tactical level capabilities expected from SUAS. According to the U.S. Army, an “Organic and direct UAS support at the tactical level allows commanders to analyze and weight the effort, provide responsive support to subordinate echelons, and shorten the gap between sensor and shooter.”[30] The advantages, disadvantages, features, specifications, and limitations of the Raven RQ-11B and the Mavic Pro are discussed.

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[29] Force Reconnaissance Group, 17−91.

[30] U.S. Army UAS Center of Excellence, *Eyes of the Army: U.S. Army Roadmap for Unmanned Aircraft Systems 2010–2035* (Alabama: U.S. Army UAS Center of Excellence, 2010), 22, https://fas.org/irp/program/collect/uas-army.pdf.

1. Raven RQ-11B Analog

The U.S. Army Roadmap for UAS 2010–2035 labels the Raven RQ-11B as "a man-portable, hand-launched, small unit UAS. It provides reconnaissance and surveillance capability to support [Situational Awareness] SA, security, target acquisition (TA), and [Battle Damage Assessment] BDA at [Line of Sight] LOS (ranges up to 10 kilometers)."[31] Similarly, AeroVironment, the company that develops the fixed-wing SUAS describes the Raven as:

> a lightweight Unmanned Aircraft System (UAS) designed for rapid deployment and high mobility for both military and commercial applications, requiring low-altitude intelligence, surveillance, and reconnaissance (ISR). Raven is the most prolific small UAS deployed with the U.S. Armed Forces. The vehicle can be operated manually or programmed for autonomous operation, utilizing the system's advanced avionics and precise GPS navigation.[32]

a. Benefit to the Soldier

Figure 1 illustrates the maximized potential and employment of Raven by the U.S. Army on the battalion-and-below ground-maneuver elements in the battlefield: remote video terminal, mobile security, route recon/convoy security, mission hand-off, situation development, target acquisition, rear security force protection, and point/area reconnaissance.[33] The Raven RQ-11B "provides an organic, on-demand asset … and … system [that] provides the small unit commander [with] a responsive tactical Reconnaissance, Surveillance and Target Acquisition [RSTA] capability through real-time, full-motion video and sensor data via the hand controller."[34] During the Marawi Crisis and combat operations in Sulu against local and foreign terrorists, the Raven provided FRG with a significant capability to conduct aerial ISR missions and tasks in support to SA,

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[31] U.S. Army UAS Center of Excellence, 22.

[32] "Raven Future State Datasheet," AeroVironment, accessed June 16, 2019, https://www.avinc.com/images/uploads/product_docs/Raven_FutureState_Datasheet_05142020.pdf.

[33] U.S. Army UAS Center of Excellence, *Eyes of the Army*, 23.

[34] "RQ-11B Raven Small Unmanned Aircraft System (SUAS)," *USAASC* (blog), United States Army Acquisition Support Center, June 14, 2020, https://asc.army.mil/web/portfolio-item/aviation_raven-suas/.

target handover, security, TA, point reconnaissance, area reconnaissance, force protection, BDA, and camp security assessment.[35]

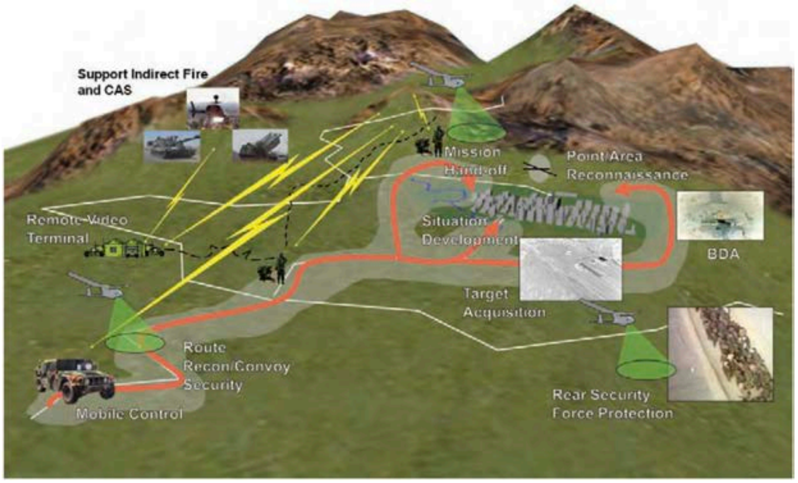

Figure 1. Raven Operations and Missions.[36]

b. Specifications and Key Features

The specifications and features detailed in Figures 2 and 3 such as 10 km range, 60–90 minutes endurance, hardware, and 152 m above ground level (AGL) operating altitude apply to FRG's Raven RQ-11B Analog except for the stabilized gimbal payload (camera) and digital data link (DDL).[37] FRG's Raven has a fixed camera and an analog data link but is scheduled for an upgrade to stabilized gimbal payload and international DDL system in the near future.[38] Figure 4 shows the FRG's ISR Team conducting pre-flight checks during the Marawi Crisis in 2017.

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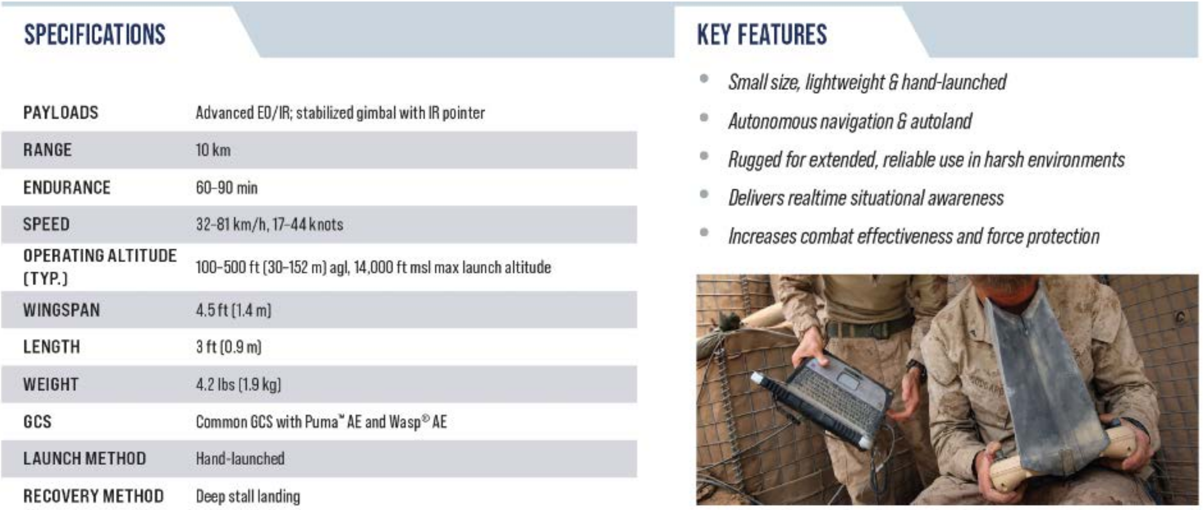
[35] Force Reconnaissance Group, *After Activity Report on ISR Operations (Marawi City Crisis)* (Cavite, Philippines: Force Reconnaissance Group, 2017), 1−11; Force Reconnaissance Group, *After Activity Report on ISR Operations (Test Mission 2018)* (Cavite, Philippines: Force Reconnaissance Group, 2018), 1−5; Force Reconnaissance Group, *Significant Observations and Comparison Between Raven and DJI Mavic Pro During Marawi Crisis* (Cavite, Philippines: Force Reconnaissance Group, 2018), 1−2.

[36] Source: U.S. Army UAS Center of Excellence, *Eyes of the Army*, 23.

[37] Force Reconnaissance Group, *Maritime SOF Tactical UAS Project*, 4.

[38] Force Reconnaissance Group, 4.



SPECIFICATIONS

PAYLOADS	Advanced EO/IR; stabilized gimbal with IR pointer
RANGE	10 km
ENDURANCE	60–90 min
SPEED	32–81 km/h, 17–44 knots
OPERATING ALTITUDE (TYP.)	100–500 ft (30–152 m) agl, 14,000 ft msl max launch altitude
WINGSPAN	4.5 ft (1.4 m)
LENGTH	3 ft (0.9 m)
WEIGHT	4.2 lbs (1.9 kg)
GCS	Common GCS with Puma™ AE and Wasp® AE
LAUNCH METHOD	Hand-launched
RECOVERY METHOD	Deep stall landing

KEY FEATURES

- *Small size, lightweight & hand-launched*
- *Autonomous navigation & autoland*
- *Rugged for extended, reliable use in harsh environments*
- *Delivers realtime situational awareness*
- *Increases combat effectiveness and force protection*

Figure 2. Raven RQ-11B Data Sheet 2019.[39]

Figure 3. Raven RQ-11B Analog.[40]

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[39] Source: AeroVironment, "Raven Future State Datasheet."

[40] Source: "Raven RQ-11 B," AeroVironment, accessed October 14, 2020, https://www.avinc.com/tuas/raven.

ISR Team of FRG conducting pre-flight checks before launching the Raven RQ-11B Analog for an aerial ISR mission during the Marawi Crisis in 2017.

Figure 4. ISR Team of FRG with the Raven RQ-11B Analog.[41]

c. *Limitations and Disadvantages*

Several known limitations and disadvantages of the Raven RQ-11B Analog were noted during the Marawi Crisis and combat operations in Sulu. In addition, it must be taken into account that because FRG directly operates and controls the Raven, FRG receives real-time information; however, there is a critical time delay on further handing over pertinent information down to the FRCs. Without an organic SUAS, the FRCs do not necessarily enjoy the real-time situational awareness and an on-demand asset essential to gathering crucial information whenever and wherever needed.[42] Table 2 shows the limitations and disadvantages of FRG's Raven.

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[41] Source: Force Reconnaissance Group, *Significant Observations and Comparison Between Raven and DJI Mavic Pro During Marawi Crisis*, 2.

[42] Force Reconnaissance Group, unpublished data, May 10, 2020; Force Reconnaissance Group, 1–2.

Table 2. Limitations and Disadvantages of Raven RQ-11B Analog.[43]

Factor	Description
Cost	System acquisition cost: USD 170,000.00
	Maintenance and repair cost: High
	Not Capable of indoor flying (inside buildings)
	Not Capable of flying inside the jungle (below tree lines and bushes)
Stealth	Silhouette can easily be detected by the enemy
	Loud and distinct sound
Data Link	No multiple screen display for operating troops
Resolution	Low quality video
	Low quality photograph
Hardware	Spare parts not commercially available
	Spare parts originate from CONUS
	Hard to repair
	Requires at least two to four personnel to carry and operate the whole system
	Too many parts to set up before flight
Launch and Recovery	Requires an open area for launch and recovery

The limitations and disadvantages of Raven RQ-11B Analog are based on the organizational data provided by FRG; 4 x FRCs: 61st Marine Company (MC), 62MC, 63MC, and 64MC; Headquarters and Service Company; ISR Team; and G-2 Section.

d. *Key Strengths and Advantages*

The Raven RQ-11B Analog provided the FRG with aerial ISR/RSTA capability to support the situational awareness required by the FRCs conducting actual combat and reconnaissance missions. Significantly, FRCs are the only units of the AFP that were capable of conducting night combat and reconnaissance missions during the Marawi Crisis because of their robust night-fighting system. These critical night missions were supported by the Raven, which is capable of sensing infrared (IR) signatures during low visibility through its IR camera. This key feature, along with other strengths and advantages of the Raven RQ-11B, enhanced the performance of the FRCs, not just in Marawi, but also in Sulu. Table 3 shows the key strengths and advantages of the Raven RQ-11B.

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[43] Adapted from Force Reconnaissance Group, unpublished data, May 10, 2020; Force Reconnaissance Group, 1−2.

Table 3. Key Strengths and Advantages of Raven RQ-11B.[44]

Factor	Description
Operational Performance	Day and Night capable camera (IR camera for night flying)
	Long endurance (61−90 mins of flight time)
	Extensive distance coverage (10 km range)
	Substantial take-off altitude (100−500 ft AGL)
	Accurate MGRS location
Functionality	Autonomous
	Autoland
	Rugged design
	Water resistant

The key strengths and advantages of the Raven RQ-11B Analog are based on the organizational data provided by FRG: 4 x FRCs: 61MC, 62MC, 63MC, and 64MC; Headquarters and Service Company; ISR Team; and G-2 Section.

2. DJI Mavic Pro

The DJI Mavic Pro is a commercial quadcopter drone developed by Dà-Jiāng Innovations and is widely used by many industries, defense, and security organizations around the globe, including the Philippine military.[45] Compared to other commercial drones, the Mavic Pro offers “more flying time, a larger flight range and cinema-quality video footage.”[46] The FRG and other units of the AFP have utilized Mavic Pro for aerial ISR/RSTA. DJI packages the Mavic Pro as:

> a small yet powerful drone that turns the sky into your creative canvas easily and without worry, helping you make every moment an aerial moment. Its compact size hides a high degree of complexity that makes it one of DJI’s most sophisticated flying cameras ever. 24 high-performance computing cores, an all-new transmission system with a 4.3 mi (7 km) *range, 5 vision

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[44] Adapted from Force Reconnaissance Group, unpublished data, May 10, 2020; Force Reconnaissance Group, 1−2.

[45] Saim Saeed, “Europe Buys Chinese Drones, Even as U.S. Expresses Data Concerns,” *Politico*, September 8, 2019, https://www.politico.eu/article/europe-buys-chinese-drones-even-as-us-expresses-data-concerns/; Anna Ahronheim, “IDF to Continue Using Drones That U.S. Army Deemed Unsafe,” *The Jerusalem Post*, August 6, 2017, https://www.jpost.com/israel-news/us-army-order-troops-to-stop-using-chinese-made-dji-drones-501741; Garceron, “Urban Warfare,” 206; Force Reconnaissance Group, *After Activity Report on ISR Operations (Marawi City Crisis)*, 1−11.

[46] Photo Insider, “DJI Mavic Air vs. Mavic Pro – Drone Comparison,” *Unique Photo* (blog), February 1, 2018, https://www.uniquephoto.com/photoinsider/dji-mavic-air-v-mavic-pro.

> sensors, and a 4K camera stabilized by a 3-axis mechanical gimbal, are at your command with just a push of your thumb or a tap of your finger.[47]

Although the U.S. military had banned the use of DJI drones in 2017, including Mavic Pros due to cyber security risks, many foreign defense and security organizations continue to use DJI drones.[48] The Mavic Pro is shown in Figures 5 and 6.

Figure 5. DJI Mavic Pro.[49]

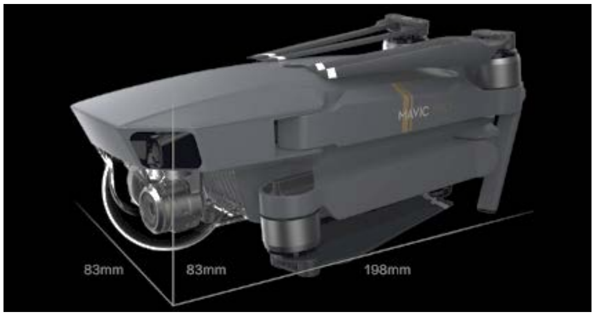

Figure 6. Folded DJI Mavic Pro with Dimensions.[50]

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[47] "DJI Mavic Pro," DJI, accessed June 20, 2020, https://www.dji.com/mavic.

[48] Gary Mortimer, "US Army Calls for Units to Discontinue Use of DJI Equipment," *SUAS News - The Business of Drones* (blog), August 4, 2017, https://www.suasnews.com/2017/08/us-army-calls-units-discontinue-use-dji-equipment/; Ahronheim, "IDF to Continue Using Drones That U.S. Army Deemed Unsafe"; Garceron, "Urban Warfare," 55; Force Reconnaissance Group, *After Activity Report on ISR Operations (Marawi City Crisis)*, 1−11; Saeed, "Europe Buys Chinese Drones, Even as U.S. Expresses Data Concerns."

[49] Source: Photo Insider, "DJI Mavic Air vs. Mavic Pro."

[50] Source: DJI,"DJI Mavic Pro."

a. Benefit to the Soldier

The FRG employs DJI Mavic Pro in order to provide aerial RSTA to FRCs in tandem or in lieu of the Raven. The Mavic Pro complements the ISR missions that cannot be performed by the Raven due to the geographical features of the objective area, obstacles, lapsed battery endurance, and operational security (OPSEC) considerations, among others. This drone was extensively employed during the Marawi Crisis and combat operations in Sulu to support SA, security, TA, route reconnaissance, point reconnaissance, area reconnaissance, force protection, BDA, and camp security assessment.[51]

b. Specifications and Key Features

Table 4 shows the specifications of the Mavic Pro such as its 6.92 km range, 27 minutes' endurance, and 5,000 m max altitude.[52] Compared to the Raven, Mavic Pro has higher flight altitude but lesser endurance and range. As shown in Table 5, Mavic Pro has key features such as high definition day camera with gimbals and precision hover that allows the drone to stay at a fixed point and altitude for a certain amount of time.[53]

Table 4. Specifications of DJI Mavic Pro.[54]

Factor	Description
Payloads	3-axis gimbal
Range	4.3 mi (6.92 km)
Endurance	27 minutes
Speed	40 mph (65 km/h)
Max Altitude	16,404 feet (5,000 m)
Weight	1.62 lbs (734 g)
Size	7.79 x 3.26 x 3.26 inches (198 x 83 x 83mm)

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[51] Force Reconnaissance Group, After Activity Report on ISR Operations (Marawi City Crisis), 1−11; Force Reconnaissance Group, After Activity Report on ISR Operations (Test Mission 2018), 1–4; Force Reconnaissance Group, Significant Observations and Comparison Between Raven and DJI Mavic Pro During Marawi Crisis, 1−2.

[52] DJI, "DJI Mavic Pro"; Photo Insider, "DJI Mavic Air vs. Mavic Pro – Drone Comparison."

[53] DJI; Photo Insider.

[54] Adapted from DJI.

Table 5. Key Features of DJI Mavic Pro.[55]

Factor	Description
4K Ultra HD Video	Miniaturized ultra-precise 3-axis gimbal capable of stabilizing the camera even during high-speed motion for smooth video and sharp photos
Precision hover	Forward and downward vision sensors for precision hover indoors or in places without GPS
No bumps and scrapes	Flight autonomy technology to sense obstacles up to 49 ft (15 m) away that allows the Mavic to bypass them or brake to hover, reducing accidents
Transportability	Foldable and portable

c. Limitations and Disadvantages

The DJI Mavic Pro supports the aerial ISR/RSTA requirements of the FRG; however, the FRCs noted several known limitations and disadvantages. Like the Raven, the Mavic Pro is not an organic on-demand asset of an FRC; thus, it does not provide optimum on-demand real-time situational awareness to the end-users on the ground. Table 6 shows the limitations and disadvantages of the Mavic Pro.

Table 6. Limitations and Disadvantages of DJI Mavic Pro.[56]

Factor	Description
Cost	System acquisition cost: USD 999.00 Price in Philippines: PHP 79,900.00 or USD 1,536.54
	Maintenance and repair cost: USD 149.00
Operational Performance	Not capable of night flying
	Not capable of flying inside the jungle (below tree lines and bushes)
	No MGRS location indicator
Stealth	Silhouette can easily be detected by the enemy

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[55] Adapted from Photo Insider, "DJI Mavic Air vs. Mavic Pro – Drone Comparison."

[56] Adapted from Force Reconnaissance Group, unpublished data, May 10, 2020; Force Reconnaissance Group, *Significant Observations and Comparison Between Raven and DJI Mavic Pro During Marawi Crisis*, 1–2; Jonathan Feist, 12/2/2020 10:54:00 AM"Drones," DJI Philippines, accessed June 16, 2020, https://dji.com.ph/shop; "DJI Mavic Pro & Platinum Repairs," Dronefly, accessed June 16, 2020, https://www.dronefly.com/mavic-pro-repair.html?utm_source=google&utm_medium=cpc&utm_campaign=803781244&adgroupid=53286657522&utm_content=285494480130&utm_term=mavic%20pro%20repair%20cost&MatchType=e&placement=&gclid=Cj0KCQjwuJz3BRDTARIsAMg-HxW20ciG2ylk3O6WYQ994fWT1XRdYJBZ5ucPqEx6iVWNUwCaz5N4K2EaAvt0EALw_wcB.

	Loud and distinct sound
Data Link	No multiple screen display for operating troops
	Small memory storage
	No safety feature for stored video data
Hardware	Most spare parts are available only from DJI
	Parts and frame not durable

The limitations and disadvantages of the DJI Mavic Pro are based on the organizational data provided by FRG; 4 x FRCs: 61MC, 62MC, 63MC, and 64MC; Headquarters and Service Company; ISR Team; G-2 Section; and several drone websites.

The DJI Mavic Pro was considered by many industries and individual users as top of its class when it was launched in 2016.[57] The Mavic Pro retained the reputation for the next few years; however, as of the moment, DJI had released more advanced quadcopters to the market, although at a much higher price.[58] According to the DJI official website, as of July 2, 2020, the Mavic Pro is no longer in production.[59]

d. Key Strengths and Advantages

A key strength of the DJI Mavic Pro is its high definition camera that can capture and record high quality photos and videos compared to the Raven. High definition videos and pictures allow better assessment of the situation. Another key strength of the Mavic Pro is its vertical and take-off landing feature, which allows launch and recovery even in areas surrounded by trees and structures as compared to the Raven which requires a sizeable open and flat area for launch and recovery. Table 7 shows the key strengths and features of the Mavic Pro.

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[57] Feist.

[58] Feist.

[59] "DJI Mavic Pro & Mavic Pro Platinum," DJI, accessed July 2, 2020, https://www.dji.com/mavic.

Table 7. Key Strengths and Advantages of DJI Mavic Pro.[60]

Factor	Description
Operational Performance	Better and higher quality video and photos compared to Raven
	Relatively long endurance (27 mins flight time)
	Extensive distance coverage (6.92 km range)
	Substantial take-off altitude (5000 m)
	Can stare and hover directly above targets
	Forward and backward motion obstacle avoidance
Functionality	Autonomous
	Fail safe
Launch and Recovery	Vertical take-off and landing

The key strengths and advantages of the DJI Mavic Pro Analog are based on the organizational data provided by FRG; 4 x FRCs: 61MC, 62MC, 63MC, and 64MC; Headquarters and Service Company; ISR Team; and G-2 Section.

F. IDENTIFIED CAPABILITY GAP

1. Lack of Aerial ISR Platform on the Company Level

FRG has only one RAVEN RQ-11B and only three MAVIC Pros. The severely limited quantity of these SUAS forces Headquarters FRG to operate and maintain these precious pieces of equipment centrally. This understandable course of action, however, denies the FRCs from accessing and exploiting the capabilities of these drones within the company level where the actual contact and fight happen. In the next five years, FRG is expecting the delivery of one Puma All Environment (AE) RQ-20B, a larger, more advanced, and more powerful SUAS that is similar in employment and dynamics to the Raven. Like the Raven, the Puma will also be centrally operated by Headquarters FRG.

Case in point, FRCs do not have organic drones—and thus, lacks on-demand aerial ISR capability within the company level. The lack of drones and aerial ISR capability denies the FRCs the game changing and lifesaving “UAS support to tactical echelons … and … the Warfighter [‘s] tactical advantage through near real-time situational awareness

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[60] Adapted from Force Reconnaissance Group, unpublished data, May 10, 2020; Force Reconnaissance Group, *Significant Observations and Comparison Between Raven and DJI Mavic Pro During Marawi Crisis*, 1−2.

… and the ability to dynamically retask.”[61] By not possessing organic SUAS on the company level, FRCs have no access to “organic, real-time reconnaissance, surveillance and target acquisition (RSTA) capability in a lightweight air vehicle (AV),” the primary benefit of a Group 1 UAS according to the U.S. Army.[62] In fact, the RAVEN RQ-11B and most commercial quadcopters are Group 1 UAS,[63] but this asset is not directly under the control of the FRCs. Consequently, lack of real-time RSTA can lead to unsupported and degraded warfighter functions of “movement and maneuver … intelligence … [and] … protection.”[64]

2. Way Forward

This section discusses the alternative solution for the ISR capability gap of FRCs; proposed FRG Close-range SUAS Employment Chart; drone research and design objectives; and scope and limitations of this study.

a. The Need for an Alternative Solution

The FRG’s current set of SUAS, even with its observed disadvantages and limitations, has shown its own indispensable brand of effectiveness in providing the FRG and FRCs with essential aerial ISR/RSTA in the battlefield. It is not the intention of this study to disregard the effectiveness and capabilities of the Raven RQ-11B Analog and the Mavic Pro. Instead, this study aims to promote the continued employment and sustainment of both drones; take advantage of their benefits and key features; and, at the same time, find other means to compensate for and complement their drawbacks and limitations.

With financial constraints primarily challenging the FRG and its FRCs, these units must make the most of what they currently have and, concurrently, search for an alternative

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[61] U.S. Army UAS Center of Excellence, *Eyes of the Army*, 1.

[62] Win Keller and David Jones, “Developing the Class I Unmanned Aerial System (UAS),” *Army AL & T*, (April 2008): 31, http://search.proquest.com/docview/216592271/.

[63] National Academies of Sciences, *Counter-Unmanned Aircraft System (CUAS) Capability for Battalion-And-Below Operations: Abbreviated Version of a Restricted Report* (Washington, DC: National Academies Press, 2018), 10, https://doi.org/10.17226/24747.

[64] Keller and Jones, 21.

solution to close the gap in its aerial ISR capability. With these in mind, the need for a cheap, fast, and accessible option presents the FRCs with the task of finding a practical and rapid equipage alternative. The alternative, however, should not be simply to acquire more pre-made COTS drones. Instead, this thesis argues that the FRCs should explore the viability of researching and designing their own drone. As a first step in this endeavor, this study integrates the fast-moving commercial drone technology with the vast operational experience of FRCs using the diverse technical skill sets and knowledge that can be learned from academia, specifically, NPS.

b. Proposed Sub-divisions of Close Range

The U.S. Army employs UAS based on echelons. Each echelon is assigned with a dedicated or organic UAS determined through flight range and duration.[65] Army UAS echelons are battalion-level or lower as close range (less than 25 kms), brigade-level as medium-range (less than 125 kms), and division and higher as extended range (200 kms or more).[66] The current SUAS platforms and employment, as well as ISR/RSTA requirements and capabilities, of FRG and the FRCs best fit the battalion-level or lower echelon:

> Battalion-level and lower: close-range (less than 25 kilometers), short duration (one to two hours) missions that operate below the coordinating altitude are thoroughly integrated with ground forces as an organic asset supporting tactical operations.[67]

The current SUAS of the FRG, the Raven RQ-11B Analog and Mavic Pro, as well as the incoming Puma AE RQ-20B, all have close-range, short-duration flights, and are integrated within the FRG as an organic asset supporting tactical operations. There is a need, however, to integrate the FRCs and to tailor their aerial ISR/RSTA requirements to the UAS echelon. Against this backdrop, this study proposes an FRG close-range chart specifically designed according to FRG's organic SUAS, echelons, and tactical operations.

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[65] U.S. Army UAS Center of Excellence, *Eyes of the Army*, 1.

[66] U.S. Army UAS Center of Excellence, 1.

[67] U.S. Army UAS Center of Excellence, 1.

The proposed FRG close-range chart emphasizes the personal range, the range where there is an aerial ISR capability gap caused by the lack of organic SUAS within the FRC-level.

The personal range covers a distance of one kilometer from the ground location of an FRC or its lower echelons to an objective area or point of interest for RSTA. The range may cover, but is not limited to, objective rally point (ORP) to the attack position or limit of advance (LOA); ORP to objective; or contact position to suspected enemy position. Based on the decades of experience of FRCs, undetected distance by a Force Recon Marine from an armed enemy has been recorded as close as less than four meters and an exchange of fire with the enemy ranging from point blank to more or less a kilometer.[68] Figure 7 illustrates the author's proposed FRG Close-range SUAS Employment Chart, with emphasis on the personal range.

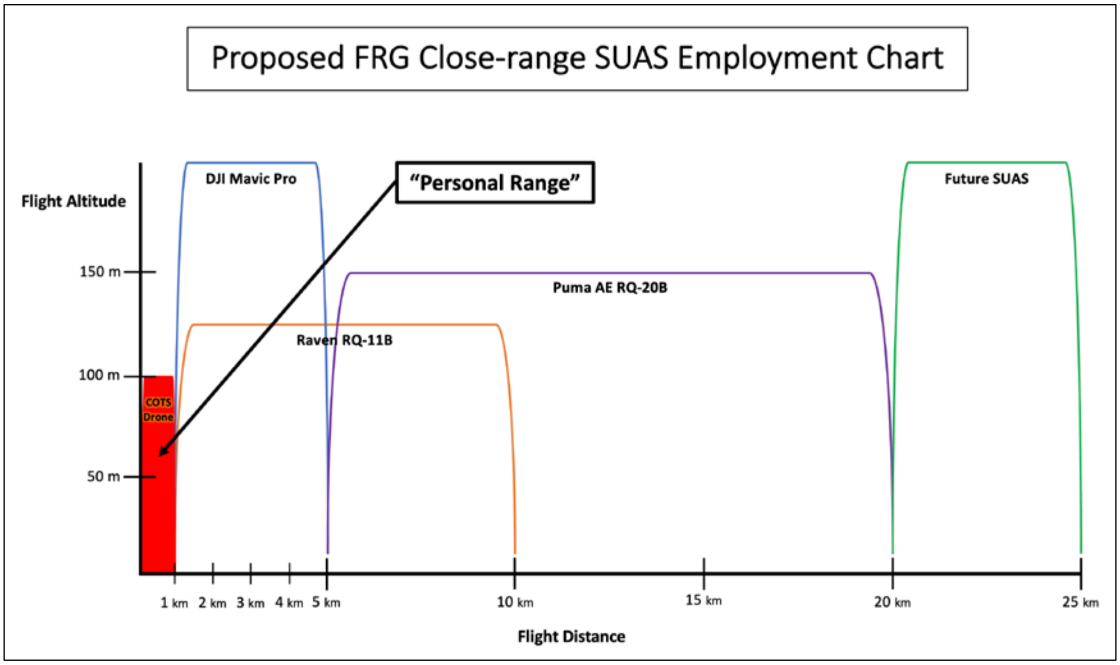

Figure 7. Proposed FRG Close-Range SUAS Employment Chart with Emphasis on the "Personal Range."

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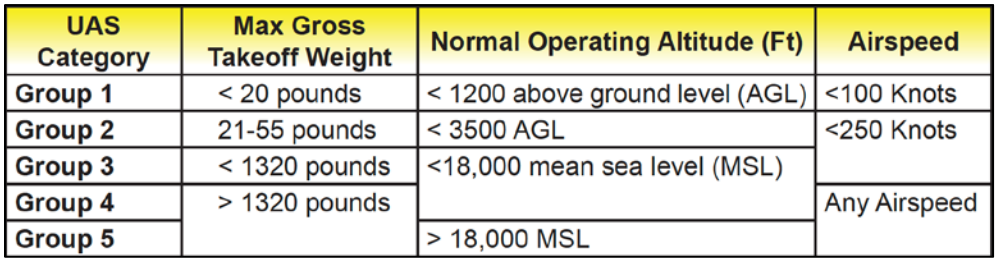
[68] GMA News TV, "AFP to Honor Troops Who Killed Janjalani"; Force Reconnaissance Group, *After Operations Report (Marawi City Crisis)*; Romulo G. Dimayuga II, personal papers, Manila, Philippines, 2019.

c. Objectives

The drone research and design have three objectives. The first objective is focused on exploring for an alternative SUAS design based on these general criteria: low-cost COTS drone components; key features, specifications, limitations, advantages, and disadvantages of the Raven RQ-11B and Mavic Pro; and characteristics of both the U.S. Department of Defense (DOD) UAS Group 1 (Table 8) and the FAA Micro UAS Aviation Rulemaking Committee (ARC) UAS Category 1 (Table 9). The second objective is to build a drone specifically designed for the FRCs. The third objective is to initiate a culture of innovation on small unmanned systems, not just for the FRCs and FRG, but more so for the broader AFP.

Table 8. DOD UAS Category.[69]



UAS Category	Max Gross Takeoff Weight	Normal Operating Altitude (Ft)	Airspeed
Group 1	< 20 pounds	< 1200 above ground level (AGL)	<100 Knots
Group 2	21-55 pounds	< 3500 AGL	<250 Knots
Group 3	< 1320 pounds	<18,000 mean sea level (MSL)	
Group 4	> 1320 pounds		Any Airspeed
Group 5		> 18,000 MSL	

Table 9. FAA Micro UAS ARC Category.[70]

FAA Micro UAS ARC Category		
Category	**Weight**	**Risk of Causing Injury to People**
Category 1	250 g (0.55 lb) or less	Does not need to meet any performance-based standards to fly over people
Category 2	More than 250 g	Presents less than a one-percent risk of causing serious injury to people, given impact
Category 3	unspecified	Presents less than a 30-percent risk of causing serious injury to people, given impact
Category 4	unspecified	Presents less than a 30-percent risk of causing serious injury to people, but that are intended for sustained flight over crowds

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[69] Source: U.S. Army UAS Center of Excellence, *Eyes of the Army*, 12.

[70] Adapted from Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 85.

d. Scope and Limitations

In terms of scope, this study draws on a number of technical disciplines, such as electronics, robotics, and coding, that must be explored and addressed while designing and building a novel SUAS. The author of this thesis attempts to discover how viable an undertaking it is for a person who is not an expert in any of the previously mentioned disciplines to design and build a drone. Next, in order to limit the scope of the organizations involved, the FRCs will serve as the focal organizations for this study. Additionally, a fundamental consideration is the resulting manufacturing cost for the designed drone. The manufacturing cost must be either no more than the price of a DJI Mavic Pro, USD 999.00 and PHP 79,900.00 (USD 1,536.54) in the United States and the Philippines, respectively, or must be within what FRCs are willing to spend, USD 1,000.00 to USD 2,000.00.[71] The drone hardware and software must be COTS, open source, and unclassified. It is important to note, this thesis is enabled by funding from NPS and is required to comply with that institution's rules and government procurement regulations.

G. CONCLUSION

The focal organization of this study provided the basis for the identification of the capability gap: the lack of aerial ISR platform on the company level. With the identification of this gap, the existing drones of the FRG were examined in depth in order to determine their significant features, advantages, and limitations that could help in generating an alternative solution to the identified problem. The same examination results of the drone options together with the organizational data from the FRCs will be further processed in the next chapter, which focuses on methodology. As discussed in that chapter, the FRC COTS SUAS is designed through a systems engineering approach.

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[71] Feist, 12/2/2020 10:54:00 AMDJI Philippines, "Drones"; Force Reconnaissance Group, unpublished data, May 10, 2020.

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III. SYSTEMS ENGINEERING METHODOLOGY

A. INTRODUCTION

The first two chapters uncovered the core issue and identified what needs to be accomplished. In this chapter, the groundwork for the realization of the identified alternative solution is articulated through systems engineering. Systems engineering is an effective and comprehensive approach applied by military organizations and industries in development processes ranging from sophisticated military vessels to small consumer products.[72] According to Mohammad Sadraey, an unmanned aerial vehicle (UAV) system is a prime undertaking for the application of system engineering methodologies due to a drone's full range of design considerations, overall development expenditure considerations, and interrelated risks.[73] The systems engineering's "philosophy of the big picture first" and its focus on the customer's "operational needs"—objectives, requirements, and constraints, among others—make the engineering approach suited for the FRC's COTS drone design methodology.[74] Assessed through capability gaps and organizational challenges, the operational needs of the customer—FRCs—receive the principal emphasis through a systems engineering approach. The method's fundamental attention to components and subsystems makes the approach appropriate for a SUAS design, which in itself is a system of systems of varying components and subsystems.[75]

B. DESIGN PROCESS

The thesis design process adopts Sadraey's "UAV Life-cycle," which is a systems engineering approach to drone design. The system life-cycle involves need identification, conceptual design, preliminary design, detailed design, production and construction,

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[72] Dahai Liu, *Systems Engineering: Design Principles and Models* (Boca Raton, Florida: CRC Press, 2016), 3, https://doi.org/10.1201/9781315273860.

[73] Mohammad Sadraey, *Unmanned Aircraft Design: A Review of Fundamentals* (San Rafael, California: Morgan & Claypool, 2017), 11–12, https://doi.org/10.2200/S00789ED1V01Y201707MEC004.

[74] Liu, *Systems Engineering*, 18–23.

[75] Liu; Sadraey, *Unmanned Aircraft Design*.

utilization and support, and systems phase out and disposal, as shown in Figure 8.[76] Early in the decision-making process, the priorities that can considerably affect the whole or parts of the cycle have to be pre-determined from the ten figures of merit in the UAV design process, as shown in Table 11.[77] Based on the achievability of the top three priorities of this study—cost, period of design, and performance—the FRC COTS Drone design only covers the conceptual and preliminary design phases; however, it aims to enable building a prototype design drone. The limited period of time for this endeavor primarily dictates the limited number of phases that can be covered in this thesis.

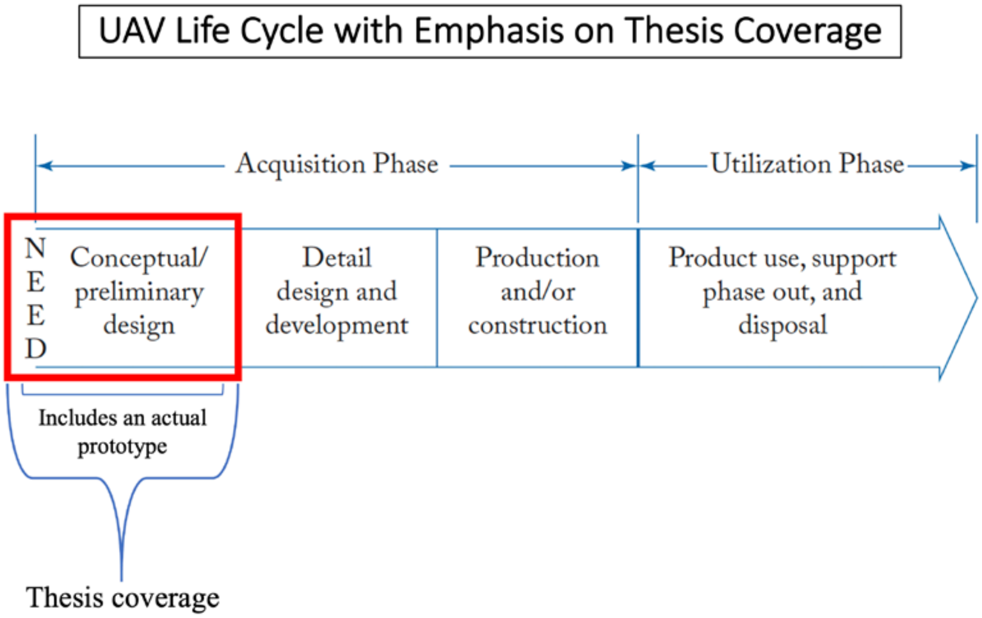

Figure 8. UAV Life Cycle with Emphasis on Areas Covered by This Thesis.[78]

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[76] Sadraey, *Unmanned Aircraft Design*, 11; Liu, *Systems Engineering*, 21.

[77] Sadraey, 7.

[78] Adapted from Sadraey, 11.

C. FRC OPERATIONAL NEEDS AND DESIGN PRIORITIES

The operational needs of FRCs, as elaborated in Table 10, identify the intended purpose and functions of the FRC COTS Drone. These operational needs, which include objectives, requirements, and criteria, are organizational information processed from a variety of sources including 61MC, 62MC, 63MC, 64MC, service company, after battle reports, and assessment reports, among others. The three categories of FRC COTS Drone operational needs depicted in the table are minimum, primary, and secondary operational needs.

Table 10. FRC COTS Drone Operational Needs.[79]

Nr	Objectives	Requirements	Criteria
Minimum Operational Needs			
1	Low-cost	Option 1 - No more than the price of DJI Mavic Pro	- US Price: USD 999.00 - Philippine Price: PHP 79,900.00 or USD 1,536.54
		Option 2 - Price that FRCs are willing to spend	USD 1,000.00 to USD 2,000.00
2	Small size	Smaller than DJI Mavic Pro	Smaller than 7.79 x 3.26 x 3.26 in (198 x 83 x 83mm)
3	Light weight	DOD: UAS Group 1	Less than 20 lbs (9,071.85 g)
		FAA Micro UAS ARC: UAS Category 1	Less than 0.55 lbs (250 g)
4	Remote sensing capable: Set 1	Electro-optical (EO): Visual	Day camera
5	Drone design skills	Non-degree/ Do it yourself (DIY) technical skills	- Electronics - Drone robotics - Soldering - Programming/ Debugging - Computer-aided design (CAD) - 3D Printing
Primary Operational Needs			
6	Remote sensing capable: Set 2	EO: Visual	Night camera
7	Low-noise	More silent than DJI Mavic Pro	Relatively undetectable while flying 12 m above ground level
8	Personal range ISR/ RSTA	Minimum flight distance	One-kilometer flight range
		Minimum flight altitude	100 meters AGL
9	Location tracking capable	Global Positioning System (GPS)	MGRS location format

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[79] Adapted from Force Reconnaissance Group, unpublished data, May 10, 2020.

10	Detect and avoid	Hover/ altitude hold	12 m AGL
		Obstacle avoidance	1 m from front
11	Safety of equipment	Fail safe	Return to launch location upon loss of signal or low battery status
Secondary Operational Needs			
11	Remote sensing capable: Set 3	EO: IR	Thermal camera
12	Autonomy	Semi-autonomous	Mission planning
13	Programmable	Open source programs and codes	Add and remove programs from open sources
14	Extended endurance	High-capacity and extra-compact battery	30 or more mins of flight time

Table 11. Order of Priority for the Design Process.[80]

Order of Priority	Figure of Merit
1	**Cost**
2	**Period of Design**
3	**Performance**
4	Stealth
5	Weight
6	Producibility
7	Maintainability
8	Autonomy
9	Scariness
10	Disposability

D. FRC COTS DRONE DESIGN PHASES

The conceptual and preliminary design phases of the FRC COTS Drone design will be discussed in this section.

1. Conceptual Design Phase

The UAV conceptual design phase is the "UAV design at the concept level … [and the] … first and most important phase of the UAV design and development process."[81]

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[80] Adapted from Sadraey, *Unmanned Aircraft Design*, 7.

[81] Sadraey, 15.

Based on the customer's operational needs and other organizational data gathered from different sources and references as mentioned earlier, the goal of the FRC COTS Drone design process is to design a vertical take-off and landing SUAS—specifically, a micro traditional helicopter—that can provide ISR/RSTA to FRCs within the personal range. Based on organizational data from the FRCs, a traditional helicopter platform was selected for the specific variant of vertical take-off and landing SUAS instead of the much more prevalent multi-copters. Another equally important consideration is that several SUAS articles and practitioners emphasized the practicality and advantage of traditional helicopters. Accordingly, as shown in Table 12, traditional helicopters are arguably more stable, more power efficient, and safer during crashes, although mechanically more complex, than quadcopters.[82]

Table 12. Comparison of Traditional Helicopter and Quadcopter.[83]

Characteristic	**Traditional Helicopter**	**Quadcopter**
Stability	✓	
Efficiency	✓	
Safety	✓	
Mechanical simplicity		✓

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[82] "Drones Different From Quadcopters, Quadcopters Vs Helicopters Vs RC Plane And More," *Grind Drone* (blog), accessed October 31, 2020, https://grinddrone.com/info/drones-different-from-quadcopter; "Are Helicopters Better Than Quadcopters?," *Star Walk Kids* (blog), January 10, 2018, https://www.starwalkkids.com/toys/rc/helicopters-better-quadcopters/; Chris Olson, February 17, 2017, "Heli vs. Multirotor Considerations," *ArduPilot Discourse* (blog), December 17, 2013, https://discuss.ardupilot.org/t/heli-vs-multirotor-considerations/785/17; Oscar Liang, "Quadcopter VS Helicopter - Why Not Scale Up, Full Size Drone," *Oscar Liang* (blog), January 14, 2015, https://oscarliang.com/quadcopter-helicopter-compare-cons-pro/; Quora, "What Makes The Quadcopter Design So Great For Small Drones?" *Forbes*, December 23, 2013, https://www.forbes.com/sites/quora/2013/12/23/what-makes-the-quadcopter-design-so-great-for-small-drones/; Rob Lefebvre, December 17, 2013, comment on StefanG, "Heli vs. Multirotor Considerations," *ArduPilot Discourse* (blog), December 17, 2013, https://discuss.ardupilot.org/t/heli-vs-multirotor-considerations/785/4.

[83] Adapted from Grind Drone; Star Walk Kids; Olson; Liang; Quora; Lefebvre.

Table 13 shows the components of the FRC traditional helicopter UAV, which consist of the air frame, propulsion source, power source and distribution, avionics (command, control, and communication (C3)), and payload, as adapted from the *Small Unmanned Aircraft Systems Guide* by Brent Terwilliger et al.[84] A UAV is the actual aircraft platform itself and should not be confused with a UAS or SUAS, which collectively pertains to the whole system consisting of the UAV, controller, and operator, among others.

Table 13. FRC COTS UAV Components and Functions.[85]

No.	Component	Primary Function
1	Airframe	Primary infrastructure component of the aerial element [or UAV], providing the necessary strength and structural integrity to house, mount, and protect other critical components
2	Propulsion source	A combination of a thrust-generation mechanism and powerplant used to achieve airspeed and lift required for sustained flight.
3	Power storage and distribution	Provides the infrastructure and chemical medium used to store system power [and distribute] (energy)
4	Avionics (C3)	Electronic components used to communicate and process commanded control and telemetry, providing C3 for the aerial element
5	Payload	Portable, remote-sensing apparatus or transported and deployable material (including supporting infrastructure) carried by the aerial element

The FRC COTS Drone Conceptual Design Framework, as shown in Figure 9, illustrates the activities within the design phase. The framework also illustrates the fundamental output of conceptual design phase—an approximate three-view perspective of the UAV configuration.

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[84] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 88−109.

[85] Table created by the author using information/data from Terwilliger et al., 88−109.

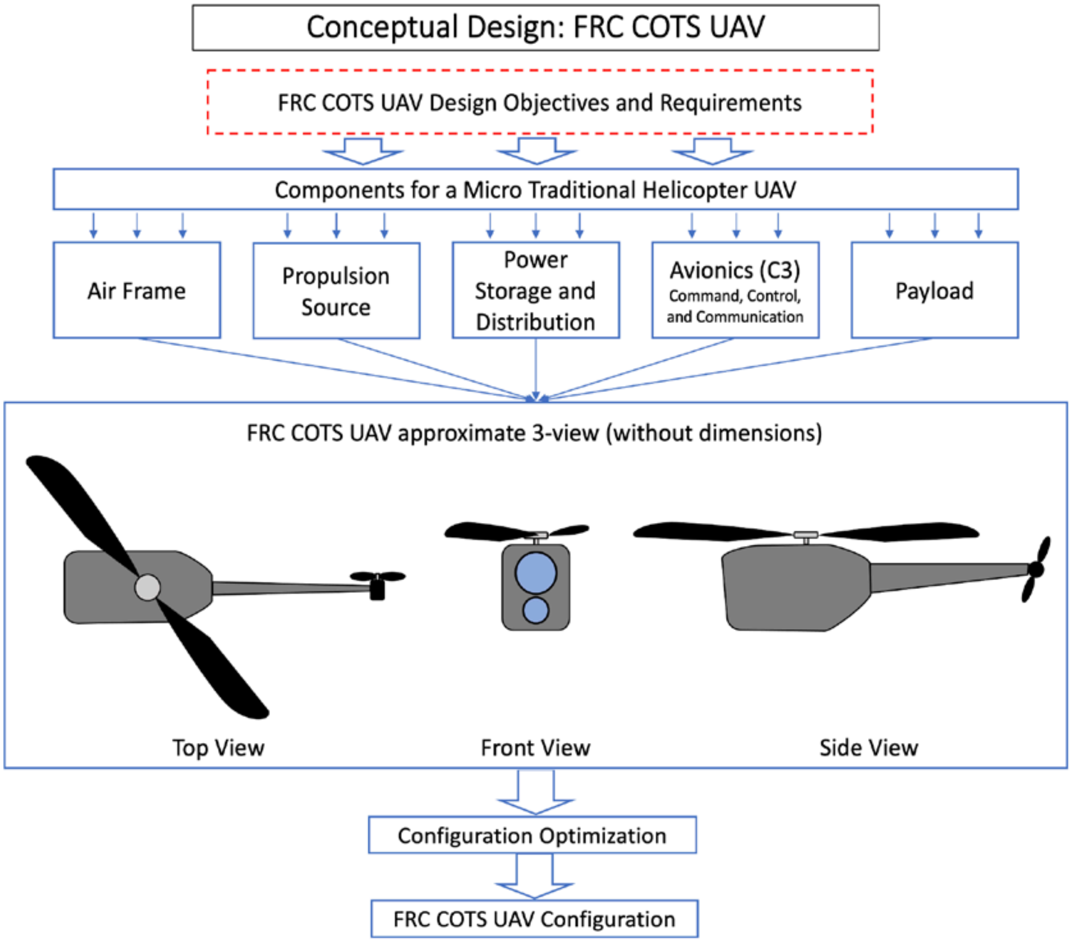

Figure 9. Conceptual Design Framework for FRC COTS UAV.[86]

2. Preliminary Design Phase

The UAV preliminary design phase determines three fundamental UAV design parameters: (1) UAV maximum take-off weight; (2) thrust to weight ratio; and (3) and engine thrust. The identification and computation of these parameters will further dictate the size and manufacturing cost of the drone. Table 17 shows the manufacturing cost. Figure 10 illustrates the steps involved in the preliminary design phase.

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[86] Figure created by the author using information/data from Sadraey, *Unmanned Aircraft Design*, 16; Terwilliger et al., 88−109.

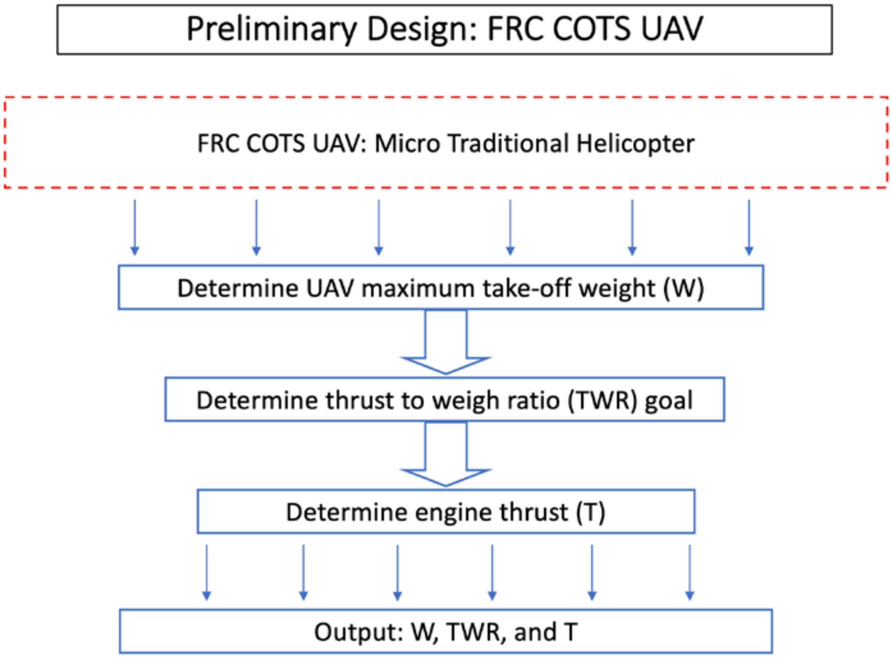

Figure 10. Preliminary Design Framework for FRC COTS UAV.[87]

The three fundamental UAV parameters must be calculated accurately to achieve the desired performance of the micro traditional helicopter and to minimize the procurement of wrong components. The three fundamental UAV parameters are:

- **Total weight (W)**. W is the downward force that the prototype drone must counteract on the opposite direction in order to achieve flight.[88] The W of an object is its mass in kilograms multiplied by the earth's gravity, which is equivalent to 9.81 m/s^2. Resulting W is in Newtons (N). In the civilian or open source drone community, however, drone operators and designers apply a more intuitive approach that assumes the Earth's gravity is constant all over the globe, discards gravity and uses W interchangeably with

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[87] Figure created by the author using information/data from Sadraey, 21; "Build a Linux Based Raspberry Pi Drone," March 29, 2020, posted by Caleb Bergquist, video, 5:30, https://www.udemy.com/course/how-to-build-a-drone/.

Adapted from Sadraey, 21.

[88] Bergquist, "Build a Linux Based Raspberry Pi Drone."

mass.[89] Resulting W is in grams. This design phase will apply the open source done community's intuitive approach of determining W. The W of the FRC COTS Drone is 114.88 g. Table 14 shows the itemized and total weight estimate of the drone COTS components.

Computation:

Given:

- Mass of drone COTS components: 114.88 g
- Earth's gravity: 9.81 m/s^2

Scientific Solution:

W = (mass) (gravity)

W = (.11488 kg) (9.81 m/s2)

W = 1.13 N

Intuitive Approach:

W = mass

W = 114.88 g

Table 14. Weight Estimate of FRC COTS Drone Components.

Drone COTS Components		**Multiplier**	**Unit Weight (g)**	**Sub-total Weight (g)**
Component	**Brand/ Make/ Type**			
Battery	Admiral 2S 250 mAh LiPo	1	19.36	19.36
Battery Eliminator Circuit (BEC)	iFlight 2–8S Micro 5V	1	1	1
BEC	Matek 2–8S Micro 5V	1	1	1

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[89] Bergquist.

Drone COTS Components		**Multiplier**	**Unit Weight (g)**	**Sub-total Weight (g)**
Component	**Brand/ Make/ Type**			
Brushed Electronic speed controller (ESC)	FingerTech tinyESC V2		3.91	3.91
Brushless ESC	Turnigy Multistar BLheli_32 21A ESC 2–4S (OPTO)	1	6.21	6.21
Camera	Run Cam Phoenix II 1000VTL	1	10.17	10.17
Flight controller (FC)	Holybro Kakute F7 Mini	1	6.35	6.35
FPV Goggles	Fat Shark Recon V3 FPV Goggles	1	(not included in UAV weight)	(not included in UAV weight)
FPV Monitor	Aomway HD588 V2 10” HD FPV Monitor	1	(not included in UAV weight)	(not included in UAV weight)
GPS	MATEK Sys GPS and Compass M8Q-5883	1	9.34	9.34
Handheld controller	FrSky Taranis X9D Plus Special Edition 2019	1	(not included in UAV weight)	(not included in UAV weight)
Main motor	1106−11000 KV Brushless Motor	1	7.30	7.30
Main rotor	Master Airscrew 8743F Propellers	1	5.57	5.57
Micro SD	Samsung EVO 128 GB	1	(not included in UAV weight)	(not included in UAV weight)
Range finder	Benewake TFMini	2	6.17	12.34
Receiver	FrSky R-XSR	1	2.74	2.74
Tail propeller	K120 Tail Propeller	1	.22	.22
Video transmitter	Holybro Atlatl Mini 5.8GHz	1	3.58	3.58
Tail motor group	0720 Brushed Motor and Tail	1	25.79 (collective)	25.79 (collective)
Frame set	XK K110 Frame Set	1		
Swashplate group	XK K110 Swashplate	1		
Servo	XK Micro Digital Servo	3		
Total Mass (g)				**114.88**

The FRC COTS Drone components are composed of a unique combination of drone parts based on the research conducted by the author of this thesis.

- **Thrust to weight ratio (TWR)**. TWR is the maximum engine thrust (T) of a drone divided by the W. W and T are forces that cancel out each other and serve as inputs for calculating the TWR goal for the drone design.[90] Assigning a TWR goal that determines the maximum allowable force balance between T and W ensures the best performance of the drone.

  A TWR goal of 1.5:1 is the aim for the drone prototype design. T must be more than the W in order to achieve flight. A 1:1 TWR will only make a drone hover in place.[91] A 1.5:1 TWR is a practical ratio for achieving good performance given that the drone will be equipped with a variety of sensors and payload. Understanding TWR is fundamental to designing drones; moreover, the miscalculation of this parameter will impede drone flight or will make drone components inefficient.[92] Table 15 shows the TWR goal.

Table 15. Thrust to Weight Ratio Goal of the FRC COTS Drone.

TWR Goal	1.5:1
Total Weight (g)	114.88
Required Thrust (g)	172.32

- **Engine thrust (T)**. T is an upward force and is the amount of weight that the motor and rotor can lift into the air.[93] The bench test, as shown in Figure 11, using the 1106–11000 KV Brushless Motor, 8743F propellers, and a 2S LiPo battery, generated a T of 208.84 g. The actual TWR result of 1.82:1 positively exceeded the TWR goal. In concept, with a 1.82:1 TWR, the COTS drone will achieve flight efficiency; will have more than enough

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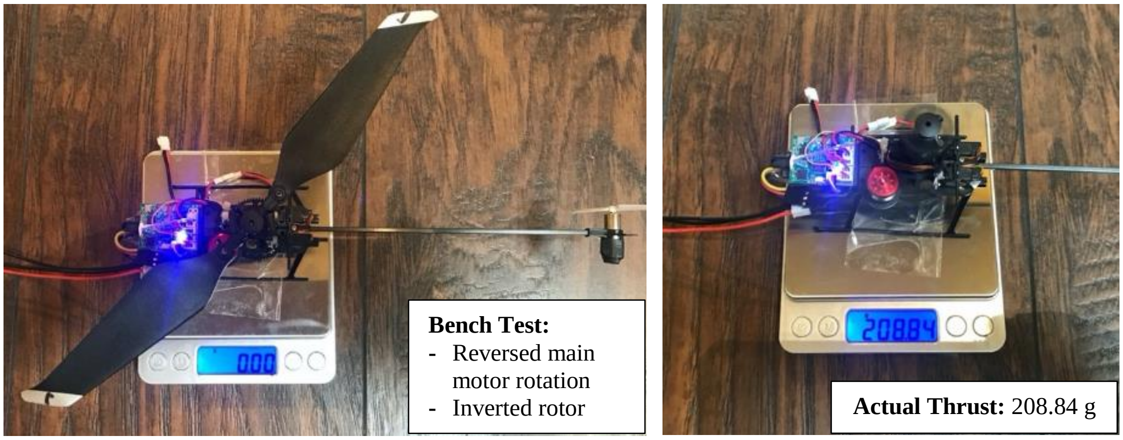
[90] Bergquist.

[91] Bergquist.

[92] Bergquist.

[93] Bergquist.

power; and will be able to accommodate additional hardware component upgrades including bigger batteries for longer endurance in the future. Table 16 shows the three fundamental UAV parameter values, including the actual TWR and required T.



Bench Test:
- Reversed main motor rotation
- Inverted rotor

Actual Thrust: 208.84 g

Bench testing is an intuitive method of measuring the engine thrust of a prospective drone. For this micro traditional helicopter, the main motor rotation was reversed, and the main rotor was inverted in order to generate an upward thrust that will press the drone against the ground. The upward thrust is measured in grams by the weighing scale. This scheme is based on the idea that an upward thrust generates the same force as the normal downward thrust required to achieve lift during actual flight. The motor, rotor, and battery of the actual drone should have the same or better specifications with the motor, rotor, and battery used during the bench testing.

Figure 11. Motor Thrust Bench Testing.

Table 16. Fundamental UAV Parameters List.

No.	Fundamental Parameter	Value
1	**W** or Total Weight	114.88 g
2	**TWR Goal**	1.5:1
	Actual TWR	1.82:1
3	**T** or Actual Thrust	208.84 g
	Required Thrust	172.32 g

Table 17. Manufacturing Cost of FRC COTS Drone.

Drone COTS Components		**Multiplier**	**Unit Price (USD)**	**Sub-Total Price (USD)**
Component	**Brand/ Make/ Type**			
Battery	Admiral 2S 250 mAh LiPo	1	10.59	10.59
BEC	iFlight 2–8S Micro 5V	1	4.78	4.78
BEC	Matek 2–8S Micro 5V	1	8.99	8.99
Brushed ESC	FingerTech tinyESC V2	1	34.46	34.46
Brushless ESC	Turnigy Multistar BLheli_32 21A 2–4S ESC	1	10.99	10.99
Camera	Run Cam Phoenix II 1000VTL	1	29.95	29.95
FC	Holybro Kakute F7 Mini V2	1	33.00	33.00
FPV goggles	Fat Shark Recon V3 FPV Goggles	1	89.00	89.00
FPV monitor	Aomway HD588 V2 10” HD FPV Monitor	1	139.99	139.99
Frame set	XK K110 Frame Set	1	53.57	53.57
GPS	MATEK Sys GPS and Compass M8Q-5883	1	29.99	29.99
Handheld controller	FrSky Taranis X9D Plus Special Edition 2019	1	246.99	246.99
Main motor	1106-11000 KV Brushless Motor	1	15.99	15.99
Main rotor	Master Airscrew 8743F Propellers	1	29.99	29.99
Micro SD card	Samsung EVO 128 GB	1	20.99	20.99
Range finder	Benewake TFMini	2	36.86	73.72
Receiver	FrSky R-XSR	1	20.99	20.99
Servo	XK Micro Digital Servo	3	6.49	19.47
Swashplate group	XK K110 Swashplate	1	20.99	20.99
Tail motor group	0720 Brushed Motor and Tail	1	6.49	6.49
Tail propeller	K120 Tail Propeller	1	2.49	2.49
Video transmitter	Holybro Atlatl Mini 5.8GHz	1	16.99	16.99
Wires and connectors	Assorted	-	9.25	9.25
Total Cost (USD)				**929.66**

E. CONCLUSION

A systems engineering approach to UAV design was used as the design methodology for the FRC COTS Drone. Two phases of the UAV design process were covered in this thesis, the conceptual and preliminary design phases. During the conceptual phase, a vertical take-off and landing SUAS—specifically, a micro traditional drone—was determined as the specific type of drone to be designed based on the operational needs and specific organizational data from the FRCs. During the preliminary phase, the three fundamental parameters W, TWR, and T were determined. These parameters dictate the size and manufacturing cost of the drone. Although this thesis only covers the two initial phases of the drone design process due to the limited time to conduct this study, an actual drone prototype will be constructed. The next chapter elaborates in detail the different elements of the FRC COTS Drone and its components.

IV. FRC COTS DRONE PROTOTYPE DESIGN COMPONENTS

This chapter discusses the components and specifications of the FRC COTS Drone prototype design—a micro traditional helicopter SUAS. A micro helicopter SUAS design addresses the drone operational needs of the FRCs (see Table 10). Among the identified operational needs are low cost, small size, light weight, low-noise, day and night cameras, personal range, obstacle avoidance, altitude-hold, fail safe, and semi-autonomy.

A. WHAT IS A MICRO TRADITIONAL HELICOPTER DRONE?

Although there is very little literature written about this specific type of drone, this chapter attempts to provide a robust discussion of what a micro helicopter drone is by combining military, industry, and hobbyist perspectives.

A micro traditional helicopter drone, like its bigger variants, is an unmanned aircraft lifted and propelled by a single horizontal rotor blade rotating around a mast.[94] It utilizes a main motor and rotor to generate thrust and a tail rotor and propeller to compensate the resulting torque from the main motor and rotor.[95] A micro-sized traditional helicopter is usually between 150 mm to 375 mm in length and falls under the weight categories of DOD UAS Group 1 and FAA Micro UAS ARC: UAS Category 1.[96] Due to the size of this micro drone, no internal combustion engines exist in this class of drones. This type of drone is designed to fly and maneuver in all three axes of rotation (roll, pitch,

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[94] Federal Aviation Administration, *Helicopter Flying Handbook*, FAA-H-8083-21B (Oklahoma City: Federal Aviation Administration, 2019), 1–1, https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/helicopter_flying_handbook/media/helicopter_flying_handbook.pdf

[95] “Microduino-Quadcopter Tutorial,” Microduino Wiki, October 4, 2018, https://wiki.microduinoinc.com/Microduino-Quadcopter_Tutorial.

[96] Paul Lawrence, *RC Helicopters: The Pilot’s Essentials* (San Bernardino, California: CreateSpace Independent Publishing Platform, 2020), 22; U.S. Army UAS Center of Excellence, *Eyes of the Army*, 12; Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 85.

and yaw) and in six directions (forward, backward, left, right, up, and down).[97] A drone operator controls the flight and maneuvers of the SUAS through a radio transmitter.[98] In addition to the characteristics of stability, power efficiency, and safety, as mentioned in Chapter III, a micro helicopter is more resistant to crashes due to its small size and weight; and is easier and more inexpensive to repair compared to bigger types of drones.[99]

B. WHY DESIGN A MICRO TRADITIONAL HELICOPTER DRONE?

Aside from addressing the ISR capability gap of FRCs, another significant motivation of this thesis is starting a culture of innovation in small unmanned systems and technology within the AFP. A contributing factor to this motivation is the potential of a micro traditional helicopter for future development of an aerial ISR platform that is smaller and stealthier, due to miniaturization. Miniaturization of drone components is continuously made possible by the fast-paced advancement of COTS technology. The evolving trends in the micro helicopter drone arena show great potential for innovation and technological advancement, as seen with the FLIR Black Hornet III, a nano helicopter UAV and "the world's smallest operational ISR platform."[100] While the prototype drone of this thesis is in no way comparable to the USD 85,000.00 FLIR Black Hornet III, the potential of micro traditional helicopter SUAS such as the FRC COTS Drone is evidenced by the Black Hornet's success today as a global leader in nano-UAV as compared to quadcopters. Micro and nano drones share the same size category and are basically the same type of drones.[101]

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[97] "Three Axes of Rotation and Stability," Flight Literacy, January 22, 2020, https://www.flightliteracy.com/three-axes-of-rotation-and-stability/; Dany2345, "Flying a 3 Channel RC (Gyro) Helicopter," *Instructables Circuits* (blog), accessed September 22, 2020, https://www.instructables.com/id/Flying-a-3-channel-RC-gyro-Helicopter/; Lawrence, *RC Helicopters*, 10.

[98] Lawrence, 10.

[99] Lawrence, 22.

[100] "Black Hornet Airborne Personal Reconnaissance System," FLIR, accessed September 22, 2020, https://www.flir.ca/products/black-hornet-prs/.

[101] "Mini Drones and Nano Drones - The Smaller the Better [Updated 2020]," Dronethusiast, July 7, 2020, https://www.dronethusiast.com/best-micro-mini-nano-drones/.

C. FRC COTS DRONE COMPONENTS AND SPECIFICATIONS

This section provides a detailed discussion of the major elements and individual components of the FRC COTS Drone.

1. Platform Type: Vertical Takeoff and Landing

The FRC COTS Drone is a Vertical Takeoff and Landing (VTOL) SUAS. VTOL SUAS are drones with rotary-wing mechanisms capable of hovering and both longitudinal and lateral flight movements.[102] The upward thrust generated by the main motor and rotor together with its mechanical controls counteract the downward pull of gravity and manipulate the drone's vector.[103] The benefits and advantages of VTOL SUAS are that it requires a "small launch/recovery area (no runway), [is] rapidly deployable, and capable of translational flight (slow, fast, lateral, longitudinal, and hover; [and offers] better low-speed maneuverability)," which address the aerial ISR capability requirements and the operational needs of the FRCs.[104]

a. Lift Generation and Control Type: Cyclic/Collective Pitch Mixing (CCPM or Collective Rotor)

This mechanical lift and control components consist of rotor blades mounted to a rotor hub on top of a shaft, a powerplant or the motor, and a swashplate.[105] The combination of a spinning rotor and three servos that manipulate the swashplate's pitch, roll, and height collectively provides control to the magnitude and direction of thrust.[106] Figure 12 illustrates the movement of a swashplate.

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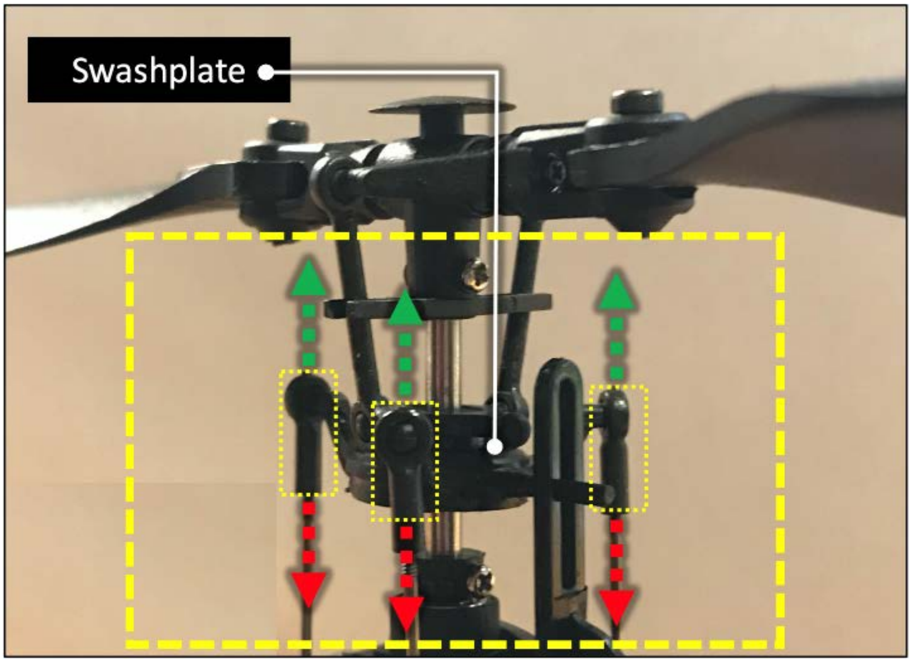
[102] Terwilliger et al., Small Unmanned Aircraft Systems Guide, 68.

[103] Terwilliger et al., 68.

[104] Force Reconnaissance Group, unpublished data, May 10, 2020; Terwilliger et al., 68.

[105] Terwilliger et al., 69.

[106] Terwilliger et al., 69.



The swashplate, manipulated by the combination of upward and downward movements of actuating servos of a traditional helicopter, is the mechanism that makes this particular type of drone more mechanically complex than a quadcopter, as mentioned in Chapter III.

Figure 12. Swashplate Movements.

b. Rotary-Wing Propulsion Configuration: Traditional Helicopter

The main distinguishing features of a traditional helicopter are a single rotor in high-speed rotation on top of a mast and a tail propeller that counterbalances the rotational torque.[107] The manipulation of the swashplate provides control to the longitudinal and lateral movements of the drone.[108] Figure 13 illustrates the rotation of the main rotor and the counteraction of the tail propeller.

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[107] Terwilliger et al., 71.

[108] Terwilliger et al., 72.

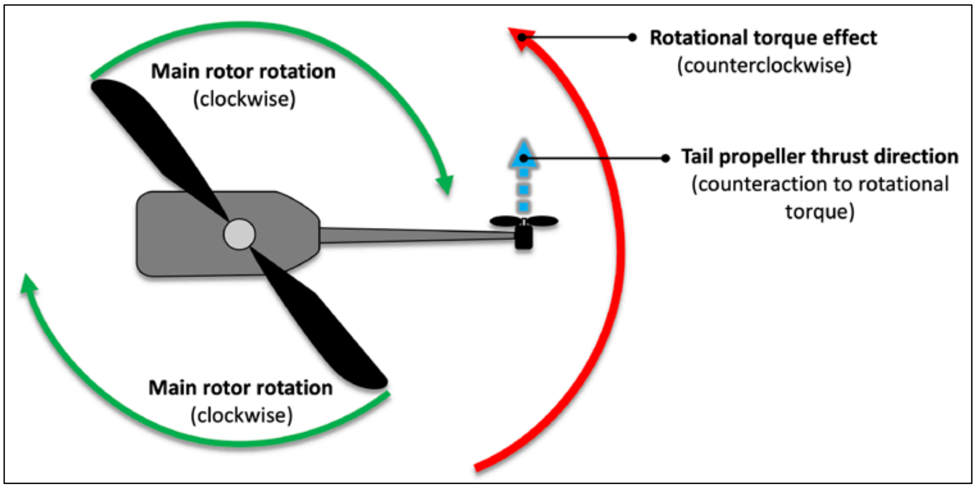

Figure 13. Rotational Torque and Tail Propeller Counteraction.[109]

2. Categories and Designation

The FRC COTS Drone belongs to both DOD UAS Group 1 and FAA Micro UAS ARC Category 1.

a. DOD Classification: Group 1

The FRC COTS Drone belongs to Group 1 of the DOD's UAS category. The COTS drone weighs less than 9,071.85 g or 20 lbs. Table 8 shows the DOD UAS categories.

b. Industry and Regulatory: Micro UAS Category 1

In terms of industry standards, the FRC COTS Drone falls under Category 1 of the Micro UAS ARC Category. The COTS drone weighs under 250 g or 0.55 lb, which does not pose a serious risk of injury when flying over people. Table 9 shows the FAA Micro UAS ARC categories.

3. Major Elements of the FRC COTS Drone

The system composition of the FRC COTS Drone adopts Terwilliger's SUAS architecture that follows the hierarchy of larger UAS with the following major elements, such as the aerial element, payload, C3, and human element, but excluding support

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[109] Adapted from Terwilliger et al., 71.

equipment.[110] The FRC COTS Drone is designed to be compact and to be operated by a single operator; hence, it does not require bulky support equipment during operations. Table 18 and Figure 14 show the major elements of the FRC COTS Drone:

Table 18. Major Elements of the FRC COTS Drone.[111]

Aerial Element	This consists of the micro traditional UAV minus the handheld controller and the operator. It is remotely operated and is designed to perform the ISR/RSTA functions required by the FRCs.
Payload	This comprises the day and night visual remote-sensing apparatus, or camera, transported by the aerial element.
C3	This consists of both ground-based and airborne-based C3 components and systems used to transmit and translate information between the operator and the aerial element.
Human Element	This is the operator responsible for the operation and maintenance of the overall drone system.

The major elements or subsystems of the FRC COTS Drone are based on Terwilliger et al.'s SUAS Guide and modified to conform to the micro traditional helicopter drone's intended design.

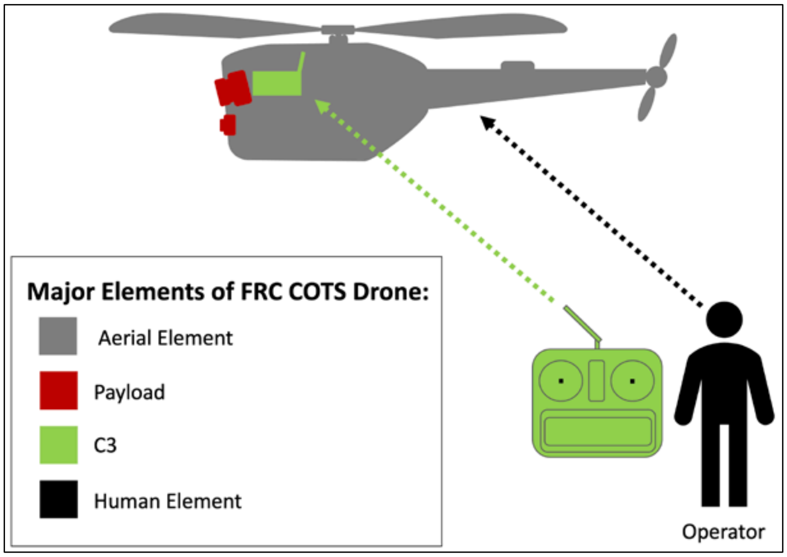

Figure 14. Major Elements or Subsystems of the FRC COTS Drone.[112]

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[110] Terwilliger et al., 87.

[111] Table created by the author using information/data from Terwilliger et al., 88–109.

[112] Adapted from Terwilliger et al., 87.

a. Aerial Element

The aerial element is the basic UAV itself, which is the airborne element of the SUAS.[113] The primary components of the aerial element are shown in Figure 15.

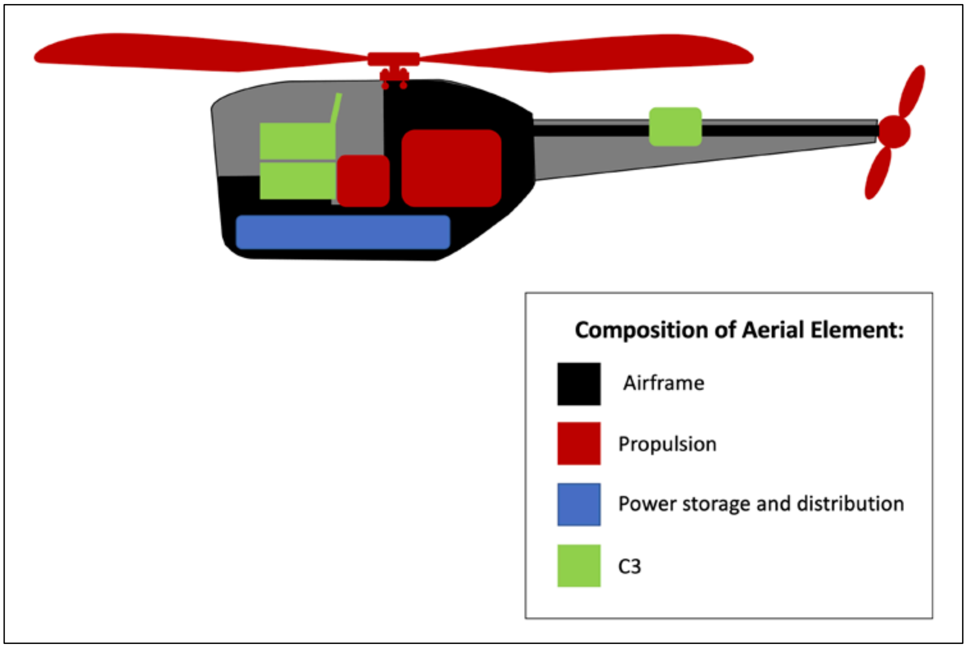

Figure 15. Components of the FRC COTS Drone Aerial Element.[114]

1. **Airframe.** This is the base infrastructure of the aerial element where all other hardware components are mounted and housed.[115] The FRC COTS Drone utilizes the XK Innovations K110 main frame as its airframe, as shown in Figure 16. It is made of light but durable plastic and measures 9.3 x 2.3 x 2.2 cm. This frame can be modified to accommodate electronics and sensors.

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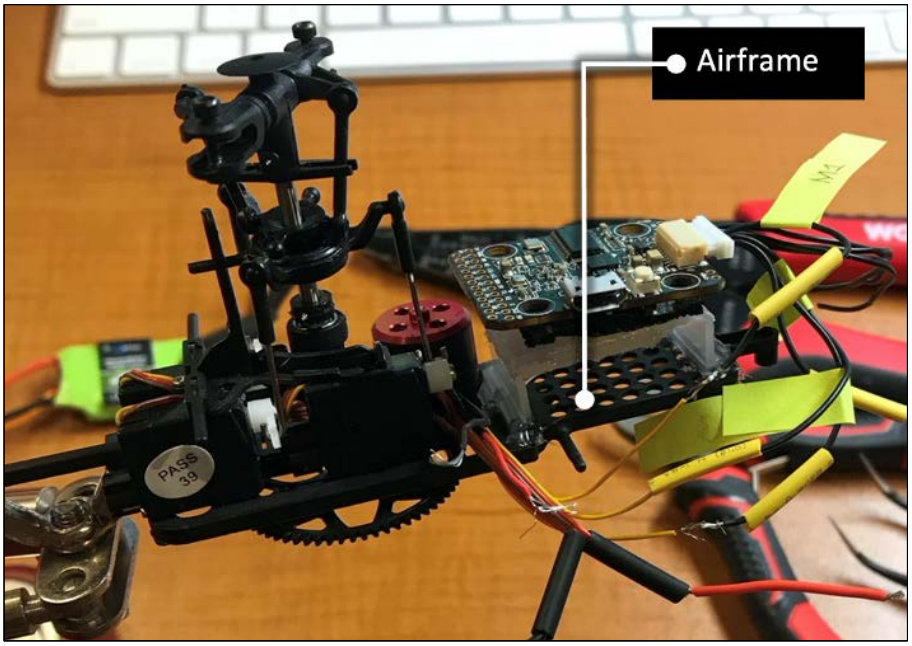
[113] Terwilliger et al., 88.

[114] Adapted from Terwilliger et al., 88.

[115] Terwilliger et al., 88.



This illustration shows a modification made to the original helicopter frame to increase the mounting capacity for electronics, sensors, and other components.

Figure 16. XK Innovations K110 Helicopter Main Frame.

2. **Propulsion Source.** This consists of the main motor and rotor that generate thrust for lift and airspeed essential for sustained flight.[116] Due to a micro helicopter drone having a separate tail thrust-generation mechanism, this section includes the tail motor and propeller. These elements for thrust generation, along with the powerplant, are described in the following paragraphs.

The **Main Rotor** consists of a "series of hub-mounted, rotating blades attached to a powerplant."[117] The main rotor of the FRC COTS Drone is a Master Airscrew Stealth 8743F Propeller designed to provide low-noise flight, improved efficiency, and extended flight time for quadcopters;

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[116] Terwilliger et al., 88.

[117] Terwilliger et al., 90.

however, it was customized as a helicopter rotor for the purpose of this thesis.[118]

The **Tail Propeller** of the FRC COTS Drone is a XK K120 helicopter tail propeller. It is compact, efficient, and low-noise. The main rotor and tail propeller of the FRC COTS Drone are shown in Figure 17 and Figure 18, respectively.

This picture shows the original propeller before it was modified as a micro helicopter drone main rotor.

Figure 17. Master Airscrew Stealth 8743F Propeller.

Figure 18. XK Innovations K120 Helicopter Tail Propeller.

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[118] "DJI Mavic 2 STEALTH Upgrade Propellers," Master Airscrew, accessed September 22, 2020, https://www.masterairscrew.com/products/dji-mavic-2-stealth-upgrade-propellers-x4-black.

The **Powerplant** converts stored energy into a rotational motion that turns the drive shaft connected to the rotor and propeller.[119] The FRC COTS Drone uses a 1106–11,000 KV brushless-electric outrunner motor as the main powerplant. A 0720 brushed motor is utilized as the tail motor. Figures 19 and Figure 20 show the main motor and tail motor, respectively

Figure 19. XK Innovation 1106–11,000 KV Brushless Motor (Main Motor).

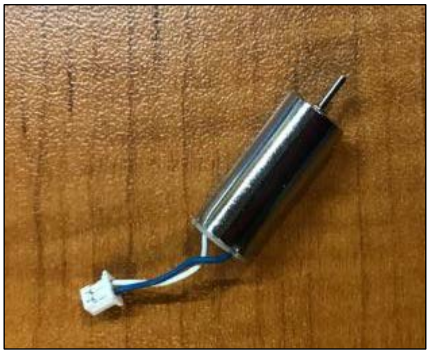

Figure 20. XK Innovation 0720 Brushed Motor (Tail Motor).

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[119] Terwilliger et al., 92.

3. **Power Storage and Distribution.** “The power for operation of the aerial element must be self-contained (stored) and distributed to the powerplant, actuated components, and electronics (electricity and/or fuel) in the proper format and range.”[120] The following paragraphs describe these elements of the FRC COTS Drone.

Power Storage is supplied by a “storage medium [that] consists of a series of rechargeable, electrochemical voltaic cells that produce an electric current through an electrochemical reaction; recharging reverses the reaction.” [121] The FRC COTS Drone uses a Lithium-based battery, specifically, a 2S 30C Lithium-polymer (LiPo) battery, to power its thrust-generating mechanisms, electronics, and other components. It should be noted that LiPo batteries require careful and specific handling, charging, discharging, and storage procedures to avoid damage and accidental combustion.[122] Figure 21 shows the main LiPo battery of the FRC COTS Drone.

Figure 21. Admiral 250 mAh 2S 30C LiPo Battery.

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[120] Terwilliger et al., 96.

[121] Terwilliger et al., 96.

[122] OSPrey, “Drone Battery Safety: Charging and Storing LiPo Batteries,” *GetFPV Learn* (blog), May 1, 2019, https://www.getfpv.com/learn/fpv-essentials/drone-battery-safety/.

Distribution and Control on the FRC COTS Drone are provided by a brushless ESC and brushed ESC to regulate the flow of electricity to its main and tail motors, respectively. These ESCs are micro-sized, programmable to a variety of settings, flashed with the latest firmware, and designed to actively protect the motors from voltage issues. Additionally, battery elimination circuits (BEC) are used to ensure sustained and regulated voltage distribution to the servos and sensors. Figures 22, 23, 24, and 25 show the ESCs and BECs.

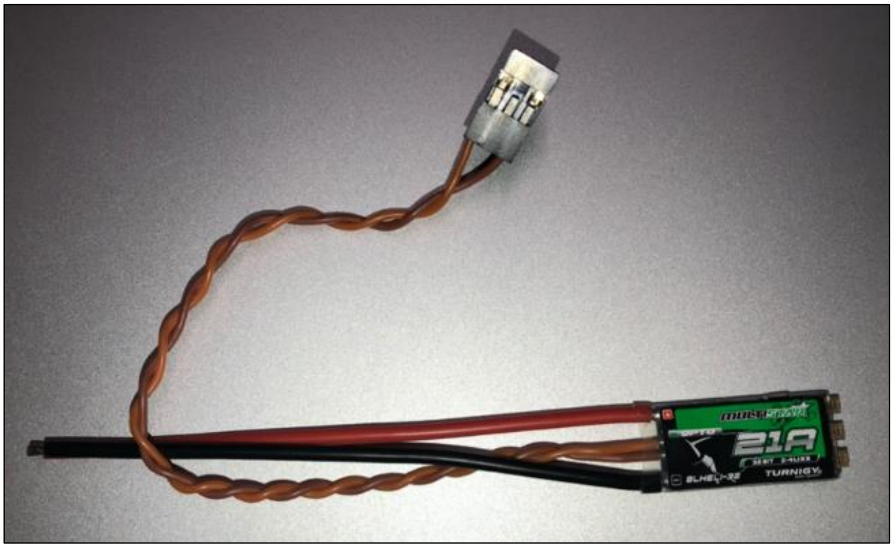

Figure 22. Turnigy Multistar BLheli_32 21A ESC 2–4S (OPTO) ESC (for the Main Motor).

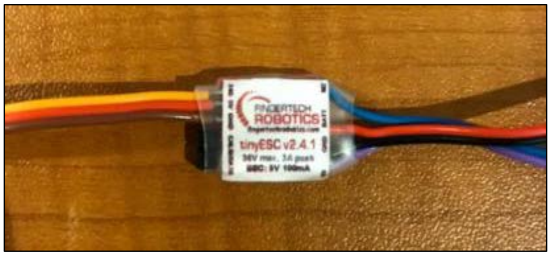

Figure 23. FingerTech tinyESC V2 (for the Tail Motor).

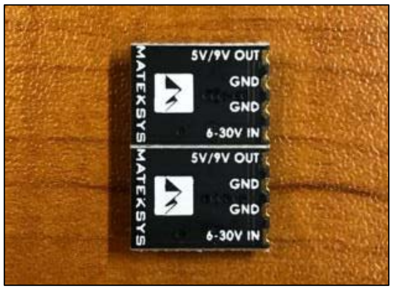

Figure 24. iFlight 2–8S Micro 5V/12V BEC.

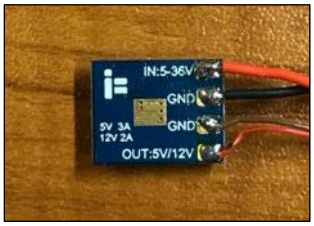

Figure 25. Matek 2–8S Micro 5V BEC.

Avionics are the "electronic components used to communicate and process commanded control and telemetry, providing C3 for the Aerial Element." [123] Commands from the ground-based operator are transmitted to the UAV through a discrete radio frequency and thereafter interpreted and executed by the system into appropriate responses.[124]

4.1. **Communications.** The communication between the operator and the FRC COTS Drone is bi-directional: uplink and downlink. Uplink is "commanded control … sent from the ground control station (GCS) up to the Aerial Element for execution" while the downlink communicates "telemetry and captured payload data back to the GCS" from the aerial element.[125] The FRC COTS Drone uses the 2.4 GHz frequency band for control commands.

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[123] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 99.

[124] Terwilliger et al. 99.

[125] Terwilliger et al., 99.

The **Receiver (RX)** is a "mono-directional, electronic communication device designed to wirelessly capture signals broadcast by a transmitter (TX) emitting a signal on the same frequency."[126] The FRC COTS Drone utilizes a FrSky R-XSR 2.4 GHz 16 Channel ACCST micro receiver, shown in Figure 26. The R-XSR is an ultra mini receiver that has an effective receiving range that can reach up to 3.3 kms and is compatible with other FrSky Taranis handheld controller models.[127]

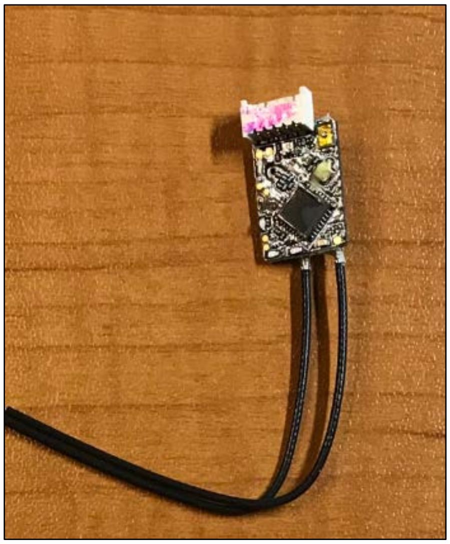

Figure 26. FrSky R-XSR 2.4 GHz 16 Channel ACCST Micro Receiver.

The **Transmitter (TX)** is an "electronic communication device, paired with an RX … on the same frequency, [which is] required to complete a mono-directional link, … and is typically used on the Aerial Element to broadcast telemetry and payload data (downlink) to an RX."[128] The FRC COTS Drone utilizes a video TX for transmitting payload data to the GCS and

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[126] Terwilliger et al., 101.

[127] "R-XSR," FrSky, accessed October 10, 2020, https://www.frsky-rc.com/product/r-xsr/; "Frsky Archer M+ Review and Comparison to R-Xsr with Range Tests," June 24, 2020, TweetFPV, video, 11:55, https://www.youtube.com/watch?v=sxZlPLUzK1c.

[128] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 101.

operator. Figure 27 shows the Holybro Atlatl Mini 5.8GHz Video Transmitter.

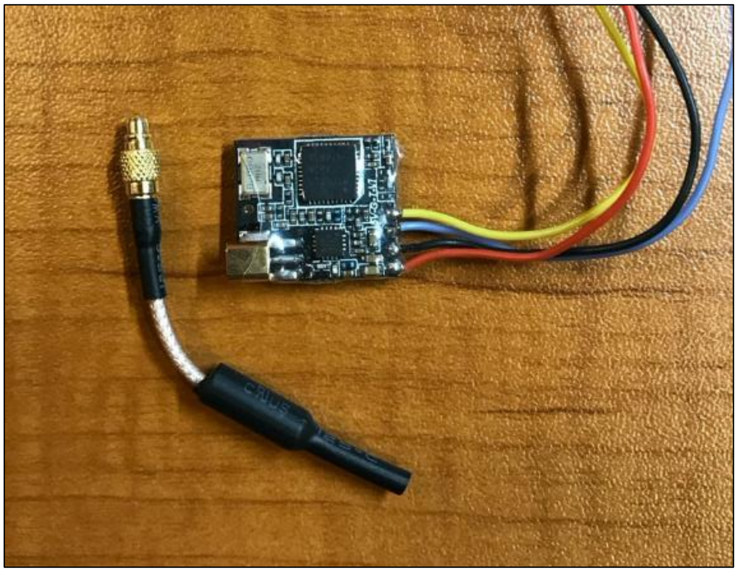

Figure 27. Holybro Atlatl Mini 5.8GHz Video Transmitter.

4.2. **Processing.** "Commanded control parameters are typically communicated in a digital format that must be interpreted by a controller and conveyed to a specific component (actuation, internal sensor, or payload)." [129]

The **Flight Controller (FC)** is a specialized component designed to receive and process input signals into appropriate digital or analog outputs that are then sent to mechanical components for execution.[130] In simple terms, the FC is the brain of the drone.[131] The FRC COTS Drone utilizes a Holybro Kakute F7 Mini V2, which is a miniaturized model of a high-quality FC. It is compatible with open source firmware; has a built-in gyroscope,

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[129] Terwilliger et al., 102.

[130] "How to Choose a Flight Controller for FPV Quadcopter," Drone Nodes, accessed September 23, 2020, https://dronenodes.com/drone-flight-controller-fpv/; Terwilliger et al., 103.

[131] Drone Nodes.

accelerometer, and barometer; and is recommended by micro drone designers.[132] Figure 28 shows the Holybro Kakute F7 Mini V2.

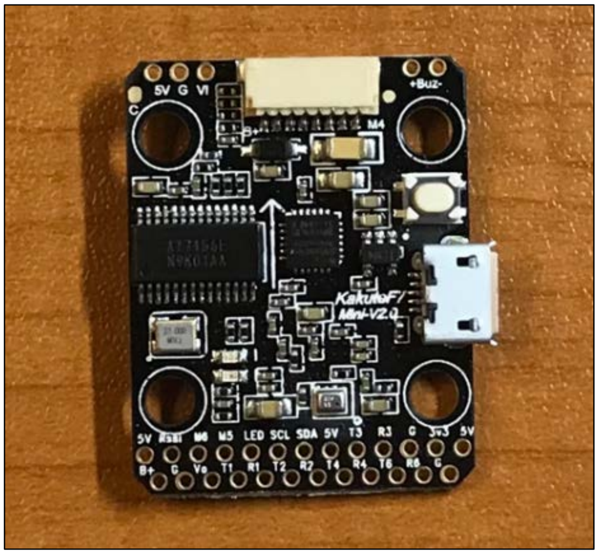

Figure 28. Holybro Kakute F7 Mini V2.

Software consists of the “logical programming developed and installed onto computational hardware, such as a microcontroller or PC, to provide functionality and support for the intended operation of the device.”[133] The FRC COTS Drone’s primary software is the Ardupilot, an open source firmware that serves as the operating system (OS) of the UAV. ArduPilot can be downloaded for free and is the leading open source autopilot system

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[132] “Holybro Kakute F7 Mini,” ArduPilot, accessed September 23, 2020, https://ardupilot.org/copter/docs/common-holybro-kakutef7mini.html; Huaji JHX, “Micro Traditional Helicopter with Optical Flow, RPM Sensors, LiDAR Rangefinder,” *ArduCopter* (blog), ArduPilot, March 21, 2020, https://discuss.ardupilot.org/t/micro-traditional-helicopter-with-optical-flow-rpm-sensors-lidar-rangefinder/53871; Zhangsir Zhangpeng, “The Smallest ArduHeli Comes from the K120 & Kakute F7 Mini with a DDFP Hollow-Cup Tail,” *ArduCopter* (blog), ArduPilot, November 16, 2019, https://discuss.ardupilot.org/t/the-smallest-arduheli-comes-from-the-k120-kakutef7mini-with-a-ddfp-hollow-cup-tail/49312.

[133] Terwilliger et al., 104.

for a variety of unmanned systems.[134] The brushed ESC that controls the main motor of the FRC COTS Drone runs with the BLHELI_32, a third-generation firmware for ESCs.[135]

4.3. **Actuation.** This is the mechanical process of moving a drone's hardware component such as manipulating the swashplate to change the direction or increase the throttle.[136] The FRC COTS Drone uses three micro rotational servos to collectively manipulate the swashplate, which makes changes to the aileron, roll, pitch, throttle, and yaw of the drone. Figure 29 shows the micro servo.

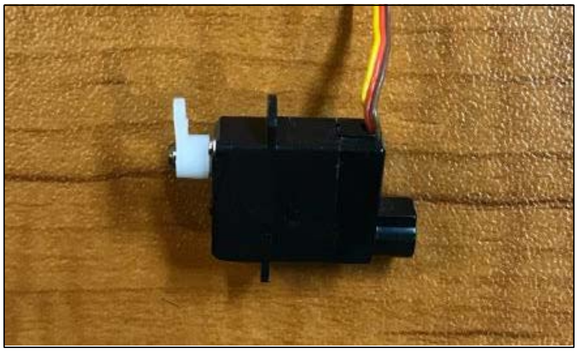

Figure 29. Micro Servo.

4.4. **Telemetry.** This is the "data used to determine critical operational parameters of the Aerial Element, captured from sensors mounted throughout the airframe and within components." [137]

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[134] "Welcome to the ArduPilot Development Site," ArduPilot, accessed September 23, 2020, https://ardupilot.org/dev/.

[135] "BLHeli_32 ESC Firmware Overview," *Oscar Liang* (blog), April 7, 2017, https://oscarliang.com/blheli-32-overview/.

[136] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 106.

[137] Terwilliger et al., 106.

4.4.1. **Proprioceptive.** These are sensors that "measure the internal status and orientation of the Aerial Element and its components to determine the state of the system." [138] The FRC COTS Drone has the following proprioceptive sensors:

The **Gyroscope** measures a UAV's orientation, "rate of rotation, degree of tilt, angular velocity,"[139] and is an essential sensor for maintaining flight stability and avoiding crashes. The FC of the FRC COTS Drone has a built-in gyroscope (see Figure 28).

The **Accelerometer** is a sensor that determines a UAV's linear movements along any axis; maintains a stable hover; and works with the gyroscope to track changes in movement and position of a UAV.[140] The FC of the FRC COTS Drone has a built-in accelerometer (see Figure 28).

The **Voltage Sensor** detects the amount of voltage being supplied by the power source to avoid over and under voltage conditions that can damage the FC and other electrical components.[141] The FC of the FRC COTS Drone has a built-in voltage sensor (see Figure 28).

The **Magnetometer (compass)** is a sensor that measures the direction and strength of a magnetic field, which enables a drone to identify the magnetic North and make corrections to its trajectory.[142] The FRC COTS Drone uses an external compass with a built-in GPS module, as shown in Figure 30.

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[138] Terwilliger et al., 107.

[139] Joseph Flynt, "What Sensors Do Drones Use?" *3D Insider* (blog), April 18, 2019, https://3dinsider.com/drone-sensors/.

[140] Flynt.

[141] Christopher Marchman, "Thrust Sensing for Small UAVs" (master's thesis, Missouri University of Science and Technology, 2016),19, https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=8560&context=masters_theses.

[142] ArduPilot, "Holybro Kakute F7 Mini"; Flynt, "What Sensors Do Drones Use?"

Figure 30. Mateksys M8Q-5883 GPS Module w/Compass.

The **GPS** receiver triangulates the relative position of a drone from the signals it captures from GPS satellites and compares the actual position of the drone with the targeted position to enable the FC to determine in which direction to move.[143] A GPS receiver is essential for autonomous missions.[144] The FRC COTS Drone uses an external GPS module with built-in external compass, as shown in Figure 30.

4.4.2. **Exteroceptive.** These are sensors that measure the external proximity of the UAV to the ground terrain features.[145] The FRC COTS Drone has the following exteroceptive sensors:

A **Range (distance) sensor** uses sonar technology to measure the UAV's altitude from the ground and distance from other surfaces.[146] The FRC COTS Drone utilizes Benewake TFMini range finders for altitude hold and obstacle avoidance, as shown in Figure 31.

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[143] Flynt.

[144] Flynt.

[145] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 108.

[146] Flynt, "What Sensors Do Drones Use?"

Figure 31. Benewake TF Mini.

The **Barometer** measures air pressure to determine the altitude of the drone.[147] The FC of the FRC COTS Drone has a built-in barometer (see Figure 28).

b. Payload

Payload is a "critical component of the Aerial Element."[148] Operation and transport of payloads such as cameras, radars, light detection and ranging (LiDAR), and cargo delivery, is one of the primary functions of a drone.[149]

Electro-optical (EO) Remote Sensing. EO visual imaging sensors "are used to capture various emitted, absorbed, or reflected energy across the electromagnetic spectrum … [specifically,] red, green, and blue (RGB) light in the visual range." [150] The FRC COTS Drone utilizes the Lumenier Run Cam Phoenix II 1000VTL FPV Camera, a daylight and low light first person view (FPV) camera capable of capturing pictures and videos during

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[147] Flynt.

[148] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 109.

[149] Terwilliger et al., 109.

[150] Terwilliger et al., 109.

both day and limited visibility flight missions.[151] Figure 32 shows the Lumenier Run Cam Phoenix II Camera.

Figure 32. Lumenier Run Cam Phoenix II 1000VTL FPV.

c. Ground-based C3

Ground-based C3 provides the "critical interface that support [s] and maintain [s] [the interaction with the operator and the drone and provides] the infrastructure necessary to accept commanded control instructions … and location information; depict processed payload data … and convey important feedback to influence the remote pilot's future control commands." [152]

> The **GCS Receiver** receives proprioceptive data, exteroceptive data, and payload data from the UAV.[153] The FPV monitor of the FRC COTS Drone has a built-in dual 40 channel receiver, as shown in Figure 35.

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[151] "Runcam Phoenix 2 1000TVL FPV Camera - Lumenier Edition (White)," GetFPV, accessed October 10, 2020, https://www.getfpv.com/runcam-phoenix-2-1000tvl-fpv-camera-lumenier-edition-white.html.

[152] Terwilliger et al., 114.

[153] Terwilliger et al.

The **GCS Transmitter** is "used to broadcast the commanded control instructions processed and executed by the Aerial Element (via uplink)."[154] The FRC COTS Drone utilizes a conventional handheld controller, the FrSky Taranis X9D Plus Special Edition (SE) 2019 transmitter, as shown in Figure 33. The Taranis X9D Plus SE is the latest model on the Taranis series, which features an upgradable operating system, upgraded communication protocol, increased computing capability, SD card storage, upgraded switches, and a high-speed module digital interface, among others.[155]

Figure 33. FrSky Taranis X9D Plus Special Edition 2019.

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[154] Terwilliger et al., 114.

[155] "Taranis X9D Plus SE 2019," FrSky, accessed October 10, 2020, https://www.frsky-rc.com/product/taranis-x9d-plus-se-2019/.

FPV enhances situational awareness by providing real-time visual display and feedback to the operator as viewed from the UAV perspective through its EO visual imaging sensors.[156] The FRC COTS Drone provides the operator with dual options to view the FPV footage, either through the Fat Shark Recon V3 FPV Goggle or through the Aomway HD588 FPV Monitor, as shown in Figures 34 and 35, respectively. Both FPV devices can be used simultaneously for multiple viewing of the same FPV footage from the drone, with one device for the operator and the other device for a second observer.

The Fat Shark Recon V3 FPV Goggle provides an "ultra-immersive [field of view] FOV," which significantly enhances the operator's situational awareness, as seen from the perspective of the drone.[157] This box-style goggle has a 4.3-in display and built-in digital video recorder (DVR) for real-time recording. On the other hand, the Aomway HD588 FPV Monitor has a screen large enough to display the unfolding situation but small enough to be carried inside the backpack of the operator. It has a high definition (HD) display and an integrated DVR for real-time recording.[158]

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[156] Terwilliger et al., 118.

[157] "Recon V3 FPV Drone Racing Goggles," Fat Shark, accessed October 21, 2020, https://www.fatshark.com/product/recon-v3/.

[158] "HD588: 10.1" 5.8GHz 40CH HD Diversity FPV Monitor," Aomway, accessed October 10, 2020, https://www.aomway.com/en/product/10-1%ef%bc%82hd-diversity-fpv-monitor/.

Figure 34. Fat Shark Recon V3 FPV Goggle.

Figure 35. Aomway HD588 V2 10” HD FPV Monitor.

d. Human Element

Finally, personnel “plays an essential part [in] the successful operation [, management] and configuration” of a SUAS.[159] The human element has the responsibility for piloting the SUAS and overseeing the operational and logistical requirements of the SUAS.[160] The human element of the FRC COTS Drone is the operator.

The **Operator** is the primary pilot of the drone. The recommended qualifications, duties, and responsibilities of an FRC COTS Drone operator are to complete the FRG/FRC in-house drone operator certification course; serve as the designated pilot of a specific unit of the FRC COTS Drone; perform routine inspection of the overall system of systems of the FRC COTS Drone; and in coordination with concerned personnel, to oversee and maintain the operational readiness of the FRC COTS Drone. Additionally, the operator collects SUAS operational data and submits after-flight reports, and maintains active contact with the SUAS innovation team.

D. CONCLUSION

In this chapter, a micro traditional helicopter drone was described based on the combined perspectives of the military, industry, and hobbyist sectors. These perspectives primarily differ in the way they utilize and develop drones. The military utilizes drones mainly for intelligence-gathering, surveillance, target acquisition and combat missions, while industry utilizes drones in various sectors such as agriculture, construction, surveying, and entertainment, among others. The hobbyist sector, on the other hand, uses drones for recreation, racing, and custom design. Although military-grade drones are undoubtedly more highly sophisticated, the unclassified nature and almost unrestricted and ready usage of COTS components of drones for both the industry and hobbyist sectors allows them to develop drone technology rapidly. Between the industry and hobbyist sectors, the hobbyist sector has the more active and widespread community for sharing, enhancing, and applying open source drone technologies. The hobbyist sector continuously

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[159] Terwilliger et al., *Small Unmanned Aircraft Systems Guide*, 120.

[160] Terwilliger et al.

challenges the current drone technology that enables sustained development and advancement. With these attributes, the industry and hobbyist sectors present the military with a huge potential for alternative and practical solutions for drone technology on an ongoing basis.

This chapter provided a discussion of the elements of the FRC COTS Drone and a detailed illustration of the itemized hardware and software components of the drone, as well as the “peopleware” involved in the system. The next chapter discusses the prototype FRC COTS Drone generated through this study.

V. THE PROTOTYPE

This chapter discusses the actual prototype generated from the conceptual and preliminary design processes of a systems engineering approach to UAV design. The FRC COTS Drone is a micro traditional helicopter SUAS that caters to the operational needs of the FRCs. This drone is designed to be low-cost; micro-sized; equipped with day and low-visibility camera; equipped with range-finder sensors for obstacle avoidance and altitude-hold; and deployable within the personal range. The FRC COTS Drone is an alternative solution that addresses the aerial ISR capability gap of the FRCs. Although this study only required the two initial phases of the UAV design process, this thesis endeavored to generate an actual prototype. Despite the limited amount of time permitted for this research and accompanying challenges, the FRC COTS Drone prototype achieved substantial success.

A. A PERSONAL RANGE RECONNAISSANCE DRONE FOR FORCE RECON MARINES

The FRC COTS Drone prototype is a personal range reconnaissance drone (PRRD) that aims to equip the Philippine Force Recon Marines with a team-level organic ISR/RSTA platform. The drone is designed to close the ISR gap within the personal range, 1 km radius and 100 m AGL from the operator, which is inadequately covered by FRG's existing SUAS. The FRC COTS Drone is equipped with a "day/night"[161] camera that provides an enhanced situational awareness during both day light and low visibility missions. The drone is designed to detect and avoid obstacles in front of it, is enabled with altitude-hold mode that is essential for staring at targets from a fixed position from above, and is programmed to return to its previous location upon encountering poor radio signal or low battery. The FRC COTS Drone is capable of transmitting live-stream HD video and HD pictures back to the end-users. The drone is designed to be operated by a single person and is intended for tactical employment within the attack range where the actual contact, lethal or non-lethal, happens.

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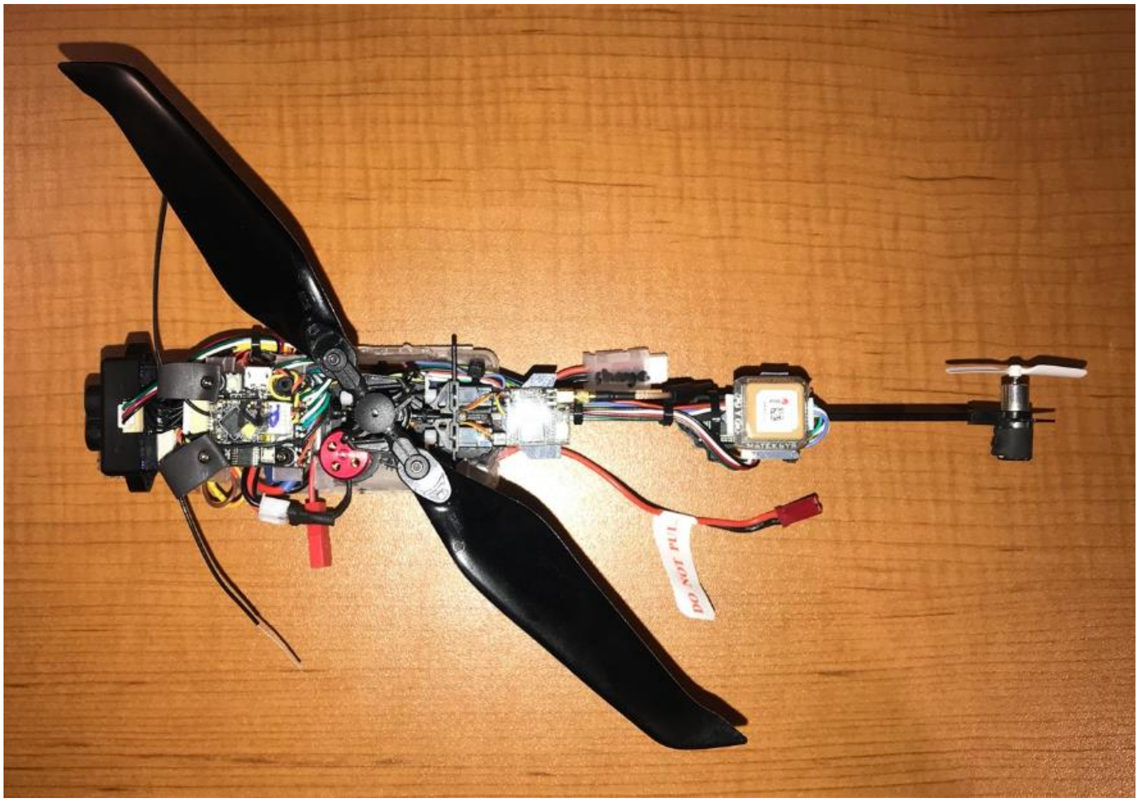
[161] GetFPV, "Runcam Phoenix 2 1000TVL FPV Camera - Lumenier Edition (White)."

B. COTS COMPONENTS ENSURE UP-TO-DATE TECHNOLOGY

The FRC COTS Drone is built from the latest COTS drone hardware and is run with the most up-to-date COTS drone software. The low-cost but competitive physical components and the free but advanced operating systems allow the COTS drone to maintain a low price of less than USD 1,000.00, which can be sustained by an FRC. The COTS hardware and software are compatible with a wide range of product alternatives available from the global commercial market. Both COTS hardware and software are upgradable and replaceable, ensuring that the FRC COTS Drone is future-proof—able to accommodate the rapidly evolving COTS technology and to avoid becoming obsolete in the future.

C. FOUR-PART RECONNAISSANCE KIT

The FRC COTS Drone consists of a four-part reconnaissance kit designed to be carried with minimal effort by an individual soldier during actual missions. The whole system can fit inside a single backpack. The first part is the micro helicopter itself; its dimensions are 15.4 x 4.5 x 8 cm, and it weighs 114.88 g. The second part is the handheld controller that measures 18 x 19 x 9 cm and weighs 796 g. The third part is the FPV goggle, measuring 15 x 12 x 7.5 cm and weighing 371.39 g. The fourth part is the HD FPV tablet monitor, which measures 24.6 x 17.2 x 20 cm and weighs 900 g. Figures 36, 37, 38, and 39 show the FRC COTS Drone Prototype. Figure 40 shows the four-part PRRD Kit.



Pending a 3D printed drone fuselage, Figures 37 to 39 illustrate the FRC COTS Drone prototype's mounting of camera, sensors, electronics, and other components; wire lengths and layout, and airframe extra and temporary modifications.

Figure 36. FRC COTS Drone Prototype (Top View).

Figure 37. FRC COTS Drone Prototype (Side View).

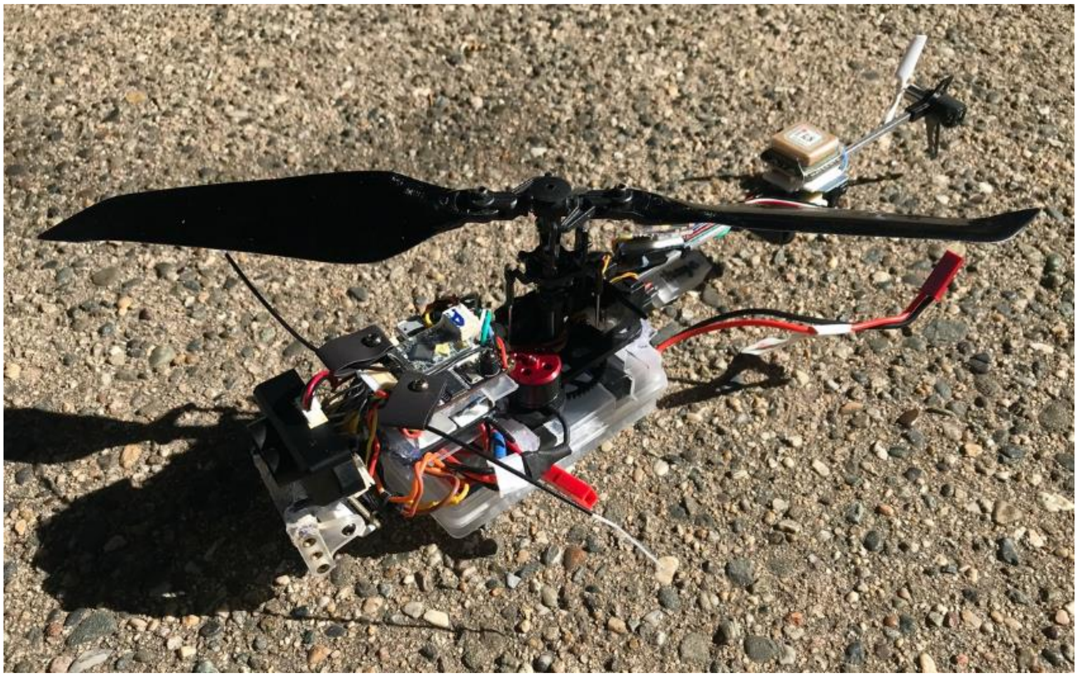


Figure 38. FRC COTS Drone Prototype (Side Angle View).

Figure 39. FRC COTS Drone Prototype (Front-Corner View).

The four-part PRRD kit is composed of the (1) FRC COTS UAV, (2) FrSky Taranis X9D Plus SE 2019 handheld controller, (3) Fat Shark Recon V3 FPV Goggles, and (4) Aomway HD588 V2 HD FPV Monitor.

Figure 40. Four-part PRRD Kit.

D. MILESTONE CHART

The milestone chart shows the tasks accomplished in connection with the drone prototype design and build efforts. This chart allows the drone designer to keep track of his or her progress in developing the prototype FRC COTS Drone. The chart also includes the means taken advantage of by the author to learn the requisite introductory skills related to designing and building a drone at the time of this thesis. The indicated tasks overlapped with each other and were repeated until considerable progress was achieved.

Table 19. Milestone Chart.

No.	**Task Name**	**Progress**
Learning Introductory Technical Knowledge and Skills		**Completed**
1	Learn from Ardupilot, other drone communities, forums, discussions, blogs, articles, and videos	Completed
2	Attend introductory Soldering Workshop (RoboDojo, NPS)	Completed
3	Attend introductory 3D Printing Workshop (RoboDojo)	Completed
4	Attend introductory 3D Modeling: Fusion 360 Workshop (RoboDojo)	Completed
5	Attend introductory Raspberry Pi Workshop (RoboDojo)	Completed
6	Attend introductory Coding: Python for Non-programmers Workshop (RoboDojo)	Completed
7	Attend introductory Ant Weight Battle Bots Workshop (RoboDojo)	Completed
8	Complete Build a Linux-based Raspberry Pi Drone (quadcopter) Course (Udemy)	Completed
9	Complete Make an Open Source Drone (quadcopter) Course (Udemy)	Completed
Drone Type Research		**Completed**
10	Platform type research	Completed
11	Lift generation and control type research	Completed
12	Rotary-wing propulsion configuration research	Completed
UAV Research		**Completed**
13	Airframe	Completed
14	Main rotor	Completed
15	Main motor	Completed
16	Tail motor	Completed
17	Tail propeller	Completed
18	Servos	Completed
19	Battery	Completed
20	Main motor ESC	Completed
21	Tail motor ESC	Completed
22	Servo BEC	Completed
23	Sensor BEC	Completed
24	Receiver	Completed
25	Video transmitter	Completed
26	Flight controller	Completed
27	Gyroscope	Completed
28	Accelerometer	Completed

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29	Voltage sensor	Completed
30	Compass	Completed
31	GPS	Completed
32	Range finder	Completed
33	Barometer	Completed
	Payload Research	**Completed**
34	FPV camera	Completed
35	Day camera	Completed
36	Night camera	Completed
37	Thermal camera	Completed
Ground-based C3 Research		**Completed**
38	GCS receiver	Completed
39	GCS transmitter	Completed
40	FPV monitor	Completed
GCS Research		**Completed**
41	Mission Planner	Completed
42	QGroundControl	Completed
Software Research		**Completed**
43	Ardupilot/ Arducopter	Completed
44	BLHeli_16	Completed
45	BLHeli_32	Completed
Procurement Process		**Completed**
46	Determining COTS components for procurement based on research	Completed
47	Submission of requested items	Completed
48	Modification of request due to unavailability of fast-moving items	Completed
49	Delivery of requested items	Completed
Build Process		**Completed**
50	Determine W, TWR, and T	Completed
51	Design wiring diagram	Completed
52	Install GCS	Completed
53	Install flight controller software	Completed
54	Flash ESC firmware	Completed
55	Modify airframe	Completed
56	Assemble frame set	Completed

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57	Assemble swashplate	Completed
58	Modify main rotor	Completed
59	Solder wirings	Completed
60	Solder and install electronics	Completed
61	Solder and install motors	Completed
62	Solder and install servos	Completed
63	Solder and install camera	Completed
64	Solder and install range finders	Completed
65	Set up servo outputs	Completed
66	Set up receiver channels	Completed
67	Connect and calibrate through GCS	Completed
68	Determine helicopter setup	Completed
69	Calibrate remote control transmitter	Completed
70	Calibrate compass	Completed
71	Calibrate accelerometer	Completed
72	Set up servo output	Completed
73	Calibrate ESC	Completed
74	Set up flight modes	Completed
75	Set up Fail safe	Completed
76	Arm drone	Completed
Functionality Testing		**In progress**
77	Test main motor	Completed
78	Test tail motor	Completed
79	Test servos	Completed
80	Test swashplate	In progress
81	Troubleshoot helicopter parameters and settings	In progress

E. CONCLUSION

The FRC COTS Drone is an alternative solution to the FRCs’ capability gap in aerial ISR. A fully operational FRC COTS Drone will provide Force Recon Marines with enhanced situational awareness through real-time RSTA at a minimal price that their companies are willing and are able to spend. With its carefully selected COTS components, the FRC COTS Drone is future-proof, ensuring its long-lasting operational and technological survivability in the many years to come.

The last chapter outlines the overall content, relevance, and effort related to this study. Recommended future works will be offered and, at the same time, the challenges experienced in pursuing this thesis are mentioned.

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VI. CONCLUSION, RECOMMENDATIONS, AND CHALLENGES

A. CONCLUSION

As established, a feasible solution to the FRCs' aerial ISR capability gap is a unit-inspired low-cost drone made of COTS hardware and software—a SUAS designed and built by a Force Recon Marine for the Force Recon Marines. Despite being a pioneer unit in the employment of military-grade and commercial drones, the FRG has not maximized and has not fully developed its aerial ISR capability due to severely limited drone platforms and similarly limited resources to sustain the capability. The cheap, fast, and accessible option—COTS technology—offers a rapid and effective solution for FRG's capability gap. The global availability of COTS components and the unprecedented pace of advancement in this technology not only provides FRCs with an alternative low-cost solution, but more so, offers the first steps towards their very own drone technology research, design, and development. Indeed, with this thesis, the seeds of the culture of innovation in small unmanned systems and technology in the AFP have been planted. With this thesis, the innovation process has begun.

The FRC COTS Drone design mirrors the advantages and compensates for the limitations of FRG's existing drones, the Raven RQ-11B Analog and the DJI Mavic Pro. In the same manner, this study supports the position of FRG to sustain the employment of its existing drones because of the indispensable advantages that they bring to the FRCs. The FRC COTS Drone fills the ISR/RSTA vacuum within the personal range of individual Force Recon Marines, which has been caused by the lack of organic SUAS within the company level. Collectively, the FRC COTS Drone together with the Raven, the Mavic Pro, and the incoming Puma, cover the broader close-range ISR/RSTA requirements of FRCs. The FRC COTS Drone is expected to enhance the FRCs' effectiveness and lethality on the battlefield which should help them sustain their indisputable contributions to the counterinsurgency and counterterrorism efforts of the Philippines.

The FRC COTS Drone design is modeled from a systems engineering approach to drone design applied by militaries and industries. As driven by the top priorities of the design process—cost, period of design, and performance—this thesis covered the conceptual and preliminary design phases of the UAV design process. Although not an official part of the two phases, an extensive effort was generated to build the prototype design drone. The primary considerations for the design process are the drone operational needs of the customers—in this case, the FRCs. These operational needs resulted in a requirement for a rare SUAS design—a micro traditional helicopter SUAS. A micro helicopter drone presents a significant potential for success within the micro/nano UAV class of drones.

In this thesis, the author demonstrated the viability of designing and building a drone by a user who has neither experience nor education in any technical disciplines associated with drones. The open source information on drones from the internet; introductory workshops hosted by the RoboDojo, an innovation space of NPS for robotics; and funding from the Defense Analysis Department of NPS were all indispensable to the success achieved by this thesis. Even with the compounding limitations presented by the COVID-19 pandemic, limited time to finish the thesis, and the author's limited technical skills, the outcome reached desired expectations.

This thesis shows that a solution to a chronic issue that may seem beyond the means of an organization need not be expensive and overly complex. The solution might be inexpensive and driven from the bottom-up, such is the case of the FRC COTS Drone. It is an alternative solution driven by Force Recon Marines themselves for their own companies. The FRC COTS Drone presents an achievable alternative that FRCs can learn, construct, and maintain within their means. Not only did the FRCs find a solution to their problem, but more importantly, their solution can trickle-up to the broader military organization. From the bottom, this process of innovation should move upwards, starting from companies, to the group, to the PMC, and so on until it reaches the AFP level. This thesis also shows that an innovative idea will remain just an idea unless someone takes on the challenge and offers a commitment to start the innovation process.

The FRC COTS Drone itself might be micro in size, but its implications can be applied on a macro level. The tactical and strategic implications of this thesis can be replicated in other parts of the world where the military is faced with the same challenges as the FRCs. Tactically, aside from addressing capability gaps, end-users of externally made technologies may find ways to transition to being actual developers of their own technology. Strategically, more capable countries can use this as a model for security cooperation. Capable countries can help their partner countries to be self-sustaining in terms of technological development while advancing mutual interests in the region.

Indeed, three distinct fields achieved synergy on this study. The integration of the Philippine experience, the technical knowledge and resources of NPS, and the global commercial market resulted in a distinct outcome that addresses a specific problem.

B. CHALLENGES ENCOUNTERED

The author encountered two primary challenges in pursuing his research and development of the prototype described in this thesis. Due to the pandemic caused by the COVID-19 outbreak, right after the thesis proposal received approval on March 2020, Monterey County imposed shelter-in-place directives for all persons and NPS accordingly shifted to online classes and minimum face-to-face contact for all students and faculty. This situation affected the overall thesis process; severely restricted the opportunity for interaction with technical experts from NPS; and restricted access to the Robo Dojo, which hosts introductory workshops on soldering, 3D printing, and coding, among other activities necessary for the production of the prototype drone.[162]

The second challenge was presented by the procurement process and bureaucracy. Due to the procurement process, it typically took an average of three months before the author received the requested items to produce the prototype. This span of time becomes an obstacle especially during follow-up and re-procurement of items. The pandemic also affected the rate of delivery of the drone parts.

C. RECOMMENDATIONS

The author recommends two areas for future work to enhance the FRC COTS Drone and two real-world applications in connection with this thesis.

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[162] “Welcome to RoboDojo Community website,” Naval Postgraduate School, accessed September 21, 2020, https://nps.edu/web/robodojo.

1. Future Work

Two areas for future research should center on enhancing the functionality and competitiveness of the FRC COTS Drone. This recommendation involves both the SUAS and the drone designer. For the SUAS, future work should focus on updating, upgrading, and simplifying the micro helicopter drone.

Specifically, updates will be needed to the software for the electronics, especially the FC, ESC, and GCS. The multiple software packages that run and provide the special attributes of these components are free-of-charge open source software that are constantly being validated, challenged, and improved by subject matter experts linked to a global network of drone specialists and enthusiasts. Periodic and planned updates happen within weeks to months to rectify bugs and enhance features.

Upgrade refers to the enhancement of the hardware components of the SUAS. In particular, miniaturization is the future of this drone. The direction of the FRC COTS Drone in terms of hardware should be geared towards becoming smaller in size and lighter in weight while increasing in functionality. Advances in the COTS market should be able to satisfy this direction in tandem with active in-house efforts on modification and manufacturing.

Simplifying addresses one of the drawbacks of micro helicopters, which is the drone's mechanical complexity. In June 2020, for example, a drone designer invented a prototype swashplate-less helicopter.[163] By eliminating the mechanical swashplate, the designer's breakthrough removed the mechanical complexity of the helicopter. This technology, when finally available in the market, should be incorporated to the FRC COTS Drone.

When updating, upgrading, and simplifying the drone in the future, researchers must not overlook the cost-sensitive criterion of the FRC COTS Drone users. Overall, the unprecedented pace of advancements in COTS technology is real; hence, the FRC COTS

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[163] "Drone Helicopter Hybrid," June 24, 2020, Tom Stanton, video, 9:00, https://www.youtube.com/watch?v=d80oXSCcHTk.

Drone, which is fundamentally COTS in nature, is relatively ensured of not becoming an obsolete piece of equipment in the near future.

Finally, drone designers and operators should enhance their technical skills and form a design team. While the intent of the author of this thesis is to demonstrate that designing a drone is possible even without technical skills, the further development and innovation part of the process can benefit from the input of technically proficient individuals. Gaining technical proficiency may range from participating in workshops, online courses, or formal education. Another endeavor that will benefit the development of the FRC COTS Drone and the broader culture of innovation in small unmanned systems is building a drone design team. A drone design team with diverse technical expertise and field experience can provide in-depth enhancement of the FRC COTS Drone and later, its upgraded versions and other future drone projects.

2. Real-World Application

The author recommends the creation of innovation centers in the AFP and the feasibility of conducting United States-Philippines security cooperation modeled from this thesis as real-world applications.

a. Innovation Centers in the AFP

This study, with its stated objective of providing a low-cost, out-of-the box solution to chronic capability gaps, can be particularly attractive to military organizations with limited financial resources such as the AFP. The FRC COTS Drone, as well as other applicable research and design projects, can be supported and sustained by the AFP through innovation centers that are purposely activated to cater to innovation projects. These innovation centers need not necessarily have the technical expertise or resources required to support and sustain innovation projects. Instead, the role of these centers is to facilitate a sustained linkage of the innovation teams to internal and external networks that can contribute to the innovation projects. Internal networks are units within the AFP while external networks can range from other government agencies, industries, relevant civilian communities and foreign organizations, among others. Innovation centers can offer a huge potential in facilitating favorable conditions essential to the success of the innovation process.

b. A Model for United States-Philippines Security Cooperation

This study can serve as a model for security cooperation between the armed forces of the United States and the Philippines. As previously mentioned, three fields were integrated in this thesis—the Philippine FRG and FRC experience, the NPS knowledge base and resources, and the global commercial market. As a model for a United States-Philippines security cooperation, the Philippine experience, aside from the FRG and FRCs, can be provided or represented by a different organization in the Philippine military, in collaboration with the previously recommended innovation centers in the AFP. The role of NPS, on the other hand, as the provider of technical expertise and resources, should be assumed by the U.S. military. U.S. special operations forces (SOF) are in a position to spearhead the U.S. military's role, while being augmented by other U.S. active, reserve, or civilian subject matter experts (SME). To further extend the pool of technical experts, other stakeholders such as universities and industries in the Philippines should be encouraged to participate as key actors. Importantly, the U.S. military can set up maker spaces or innovation spaces in the Philippines, like the RoboDojo of NPS, to serve the security cooperation's purpose. Lastly, the global commercial market, accessed from either the United States or the Philippines, should remain as a fundamental field in this security cooperation model. While this thesis focused on unmanned systems, specifically SUAS, there is a vast selection of other innovation projects that can be pursued using the FRC COTS Drone thesis model.

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