Old Dominion University
Engineering Management and Systems Engineering Department
23 October 2020
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The Engineering Management Capstone project selected was a technical project to design, build, and test a micro-class (110-mm frame) quadcopter, conducting performance, stability and control, and reliability evaluations. This approach allowed practice of numerous Engineering Management fields to include research, planning, budgeting, scheduling, risk management, data collection, analysis, and reporting. The main focus of the project was to develop and test an empirical model for brushless motor and quadcopter performance with predictive power.

Initial project management and research efforts included development of a time-phased budget, use of Program Evaluation Review Technique (PERT) scheduling tools and creation of a Work Breakdown Structure (WBS), detailed risk analysis, and an in-depth literature review of quadcopter performance theory. An Analysis of Alternatives (AoA) was conducted and one Air Vehicle (AV) and one test stand were selected to design, build, and test. Once the equipment was built, testing was conducted and the data was recorded and analyzed. At project completion, performance and reliability data were analyzed and an empirical multi-rotor performance model was tested against experimental results. These results as well as conclusions for both technical and managerial efforts and areas for further research were incorporated into the final project report.

This submission includes the final project report contained in this document, as well as the student project evaluation and the student program assessment contained in separate documents. The final project report contains an Executive Summary providing an overview of the project and its results, as well as a project background, technical introduction, and the importance of issue resolution. It goes on to define the project focus to include purpose, objectives, and limitations to scope; project significance in local and global terms; the project approach to include design, data collection and analysis procedures, and data results; project management concerns; and project design issues. The project results and their implications are discussed to include an in-depth discussion of each deliverable, and the report concludes with local and global issues, implications, and recommendations for future multi-rotor and Engineering Management work.

This Capstone course has presented an exciting opportunity to practice a broad swathe of Engineering Management methods and techniques on a subject of interest. I developed a greater appreciation for both the nuances of Engineering Management techniques as well as the relationships between Engineering Management disciplines and how they function together to create a cohesive whole. Thank you for the opportunity to take part in this Capstone course and this program.

Respectfully,

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Applications of Technical Management in Multi-rotor Design, Construction, and Test

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EXECUTIVE SUMMARY

This project applied technical management concepts to quadcopter design, construction, and test, making contributions to both the field of quadcopter performance modeling and the field of Engineering Management. This was achieved through a 12-week effort with the purpose to design, build, and test a multi-rotor vehicle and to conduct performance, stability, and reliability evaluations and data analysis to address concerns in multi-rotor vehicle design, multi-rotor performance theory and modeling, and project management methods. The objectives of this project were to select an appropriate vehicle design, conduct project scheduling, risk analysis, and time-phased budgeting, develop a theoretical basis for quadcopter performance, construct a motor test stand and an air vehicle, conduct performance, stability, and control testing, develop an empirical vehicle performance model, briefly analyze vehicle reliability data, and identify considerations for future multi-rotor designs, Engineering Management projects, and areas for further research.

The project was initiated with a schedule, budget, and potential vehicle and test stand designs. The project lead conducted a review of existing multi-rotor performance theory, conducted an Analysis of Alternatives (AoA), and selected one Air Vehicle (AV) and one test stand design to build and test. After finalizing the selected vehicle and test equipment designs, the motor test stand was built, the motor and propeller combination was tested in various conditions, and the data was recorded and analyzed. Next the vehicle was constructed, the Flight Controller (FC) programmed, and vehicle performance and stability testing was conducted on deck and in flight. Performance and reliability data were analyzed and presented in the final report. An empirical multi-

rotor performance model was tested against experimental results, and edited for local optimization. This paper represents the final project report that was written throughout the project and finished after project completion.

Findings from this project point to fairly accurate modeling using relatively simple theoretical equations that have been empirically corrected. Specifically, the propeller thrust model proposed by Gabriel Staples (2014) proved relatively accurate, with only minor changes to the empirical constant k_1 required to reduce net error to zero. The use of predictive tools was instrumental to proper AV design, and although considerable difficulty was encountered relating electrical motor characteristics to propeller performance, the use of predictive performance modeling prior to vehicle construction remained paramount. The importance of proper test stand setup was also emphasized, with significant levels of friction encountered during testing that reduced confidence in test data and required empirical correction. The importance of proper project management throughout the project life cycle was highlighted, however, shortcomings in Risk Management methods and the Program Evaluation Review Technique (PERT) scheduling method were uncovered, which can be addressed with modified models.

Though the theoretical thrust model proved accurate, it is recommended to conduct further testing using different propellers and motors to validate these results and extend their applicability. Further research is required in motor heating mechanisms, voltage decay with increasing power, and RPM drop due to propeller loading to improve simplified models for electrical motor thrust characterization. This paper also recommends modifications to PERT scheduling techniques and Project Management Risk Analysis techniques for future Engineering Management projects.

APPLICATIONS OF TECHNICAL MANAGEMENT IN MULTI-ROTOR DESIGN, CONSTRUCTION, AND TEST

October 2020

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DISCLAIMERS

This report contains theoretical and empirical models developed for small brushless electric motor UAS. Further validation is recommended when applying these results to larger vehicles.

This report has been reviewed and contains no classified information, controlled unclassified information, or personally identifying information.

APPLICATIONS OF TECHNICAL MANAGEMENT IN MULTI-ROTOR DESIGN, CONSTRUCTION, AND TEST

1.0 INTRODUCTION

1.1 Background

1.1.1 General Focus

This project was focused on developing and testing an empirical model for brushless motor and quadcopter performance with predictive power. Unmanned Air Systems (UAS), commonly referred to as drones, have grown in capability and complexity and have become ubiquitous since the turn of the century. UAS are operated by the military, first responders, photographers, utility companies, hobbyists, and enthusiasts, and are being developed to conduct both parcel delivery and passenger ferry in urban environments. As UAS have grown in relevance, so too has the importance of optimizing their performance and efficiency in operations.

1.1.2 Technical Introduction

The development and test of electrically-powered multi-rotor air vehicles is a complex problem with a variety of situational and technical variables which must be balanced in order to achieve a vehicle that has the performance, stability, endurance, and capabilities required for its application. Understanding this problem requires a basic knowledge of multi-rotor air vehicle theory. The most common type of multi-rotor air vehicle is one with four motors each with a single rotor, often called a quadcopter. The four propellers or rotors use a counter-rotating scheme that results in zero net yaw when the angular speeds of all propellers are matched.[1] In-flight static and dynamic

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[1] Grant, P.R. "AER1216: Fundamentals of UAV Performance." Spring 2016.

stability is managed by a Flight Controller (FC) with an onboard inertial sensor and gyro. The FC is able to change the center of thrust and net torque by feeding signals to the Electronic Speed Controller (ESC) of each motor independently at several thousand hertz. Each ESC uses this signal and the power from an on-board battery (usually Lithium-Ion Polymer, "LiPo") to apply torque and change motor RPM. Propellers are usually attached directly to each motor with a 1:1 gearing ratio, and come in a variety of sizes, pitches, and blade designs with differing effects on thrust, drag, and electro-mechanical loading. The thrust generated by each propeller counters both weight and drag, as there is typically no airfoil to provide lift. Ultimate performance is determined not only by thrust, weight, and drag, but also by the electrical and mechanical loading of the motors, ESCs, and the battery. This project seeked to develop a model to predict performance characteristics of micro- (<180mm frame) and mini-(180-300mm frame) class[2] quadcopters, with implications for all battery-powered rotary-wing UAS.

1.1.3 Organizational Personnel

This project focused on the technical rather than managerial aspects of quadcopter performance modeling, and as a result no organization was analyzed. The author had sufficient exposure to multi-rotor aircraft and small UAS as well as aircraft performance modeling to perform all project tasks. Ground tests and test flights were conducted in Ventura, California with the test configurations delineated in Section 3.2, Project Design.

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[2] "Drone (Quadcopter) Frame Sizes – Mini, Micro, Nano." Learning RC.

1.1.4 Importance of Problem Resolution

A sound multi-rotor performance model for miniature and micro class quadcopters is elusive. A review of relevant literature yields discussions of brushless motor electrical characteristics, electrical and thermal loading, or aerodynamic considerations, but falls short of providing a model to predict performance based on quadcopter and motor parameters. While predictive tools do exist and are available for a fee, their inner workings are proprietary and not available for review.[3] As a result, enthusiasts of hobby-grade quadcopters often struggle to meaningfully predict performance prior to purchasing equipment, a problem which can be addressed by a sound empirical performance model. Performance modeling for smaller quadcopters also has far-reaching implications and potential applications for larger UAS and battery-powered multi-rotor aircraft, such as those currently in development for parcel delivery or urban mobility.

2.0 PROJECT DEFINITION

2.1 Definition of the Project Focus

2.1.1 Purpose

The purpose of this project was to design, build, and test a multi-rotor vehicle and to test multi-rotor motors and propellers to address concerns in multi-rotor vehicle design, multi-rotor performance theory and modeling, and project management methods.

2.1.2 Objectives

The objectives of this project were:

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[3] eCalc XCopter calc – Multicopter Calculator. Solution for All Markus Müller.

1. Select appropriate vehicle design(s) to achieve project objectives.
2. Conduct project scheduling, risk analysis, and time-phased budgeting.
3. Develop an in-depth vehicle design to include a component list, power budget, wiring diagram, and performance estimates.
4. Develop a theoretical basis to predict motor performance based on common manufacturer-supplied data, and then to predict vehicle performance based on motor performance and vehicle parameters.
5. Construct a motor test stand and evaluate several types of motors.
6. Fully construct a vehicle from basic components.
7. Program the Flight Controller for positive static and dynamic vehicle stability.
8. Conduct basic vehicle stability and control testing on deck and in flight.
9. Conduct vehicle performance testing on deck and in flight.
10. Develop a vehicle performance model based on empirical flight data and compare it to theoretical expectations.
11. Use an optimization function to find maximized vehicle performance based on empirical and/or theoretical models and subject to certain constraints.
12. Collect and briefly analyze vehicle reliability data.
13. Identify and analyze differences between the initial project schedule and budget and final project schedule and budget.
14. Identify considerations for future multi-rotor vehicle projects.
15. Identify considerations for future Engineering Management projects.
16. Identify areas for further research.

2.1.3 Project Scope

The following assumptions and limitations to scope applied to this project:

1. The AHP Multi-Criteria Decision Making (MCDM) model was used for project/design selection based on a limited set of alternatives and factors. This was required due to resource limitations; however, the most important factors were analyzed.
2. Air vehicle components included the frame, motors, propellers, Flight Controller (FC), Electronic Speed Controller (ESC), Lithium Polymer (LiPo) battery, and receiver. Payloads included a video camera and video transmitter.
3. All testing occurred at approximately sea level and the air vehicle did not enter visible moisture. These are typical operating conditions for multi-rotor vehicles.
4. Tests were only performed for quadcopters, not other multi-rotor configurations. The same concepts regarding air vehicle performance can apply to other multi-rotor aircraft, and theoretical models can be adapted to vehicles with more rotors.
5. While the theoretical model still applies, empirical test results and the resulting performance model may not be valid outside the range tested (propeller diameters of 2” to 7” and motor diameters of 8.5mm to 23mm). Non-linear effects of drag, electrical loading, and temperature may cause extrapolation to be inaccurate. The 2” to 7” propeller diameter grouping tested includes the vast majority of hobby and racing quadcopter designs.
6. Vehicle reliability data was limited to a small number of flights and ground operations. Resources were not available to gather statistically significant

numbers of components and operate equipment for the required durations for conclusive reliability results. Available reliability data was analyzed.

2.2 Project Significance

2.2.1 Local Level Impact

This project contributes to multi-rotor performance theory by addressing the lack of predictive quadcopter performance modeling tools and publishing detailed quadcopter performance theory. This is accomplished by aggregating and extending existing multi-rotor performance theory, testing multi-rotor performance against theoretical expectations, and developing an empirical multi-rotor performance model. This model was compared to theoretical and experimental results, and was used in conjunction with published data from component manufacturers to inform multi-rotor design and construction.

2.2.2 Application of Engineering Management Knowledge

Engineering Management knowledge and skills were used in each phase of this project. Project Management applications included a Program Evaluation Review Technique (PERT) chart, Work Breakdown Structure (WBS), Gantt chart, and scheduling baselines. Financial Analysis was applied both with an initial budget and a continuously updated time-phased budget. Risk analysis was applied continuously throughout the project, and Reliability analysis was conducted at completion.

2.2.3 Extension of Project Approach and Findings

This project contributes to Engineering Management through a discussion of shortcomings in existing network scheduling techniques and introduction of a modified network scheduling technique. It will also critique risk evaluation approaches and suggest a modified risk analysis framework.

3.0 PROJECT APPROACH

3.1 Project Design Overview

This project applied technical management concepts to quadcopter design, construction, and test through a 12-week effort to design, build, and test a multi-rotor vehicle and to conduct performance, stability, and reliability evaluations and data analysis. The project was initiated with a schedule, budget, and potential vehicle and test stand designs. The project lead conducted a review of existing multi-rotor performance theory, an Analysis of Alternatives (AoA), and selected two vehicle designs and a test stand design to build and test. The motor test stand was built, several motors and propellers were tested in various conditions, and the data were recorded and analyzed. Next the vehicle was constructed, the Flight Controller (FC) programmed, and vehicle performance and stability testing conducted on deck and in flight. Performance, reliability, and stability data was analyzed and presented in the final report. An empirical multi-rotor performance model was developed and optimized to match experimental findings as closely as possible. The findings of the performance modeling were aggregated for presentation.

3.2 Specific Project Design

3.2.1 Project Approach

a. Project Selection

Project Selection was conducted after an in-depth Analysis of Alternatives, culminating in a Multi-Criteria Decision Making (MCDM) Analytic Hierarchy

Process (AHP) model that informed project selection.[4] Three alternatives were explored – a 90mm frame brushed motor design with a custom FC, a 110mm frame brushless motor design, and a previously assembled 300mm frame brushless motor design. While the cost of the 110mm frame design was highest, its higher value of technical data and relatively low risk out-weighed its higher cost. The aggregate findings of the AHP model are depicted in **Error! Reference source not found.**. Full results of the AHP Project Selection are included in Appendix A, Figure A-5 through Figure A-14.

Table 1: AHP Project Selection Model Findings

Evaluation Criteria	Weight of Criteria	Alternatives: Projects		
		90mm Custom Brushed	110mm Brushless	300mm Brushless
Technical Data	0.64	0.07	0.64	0.28
Project Cost	0.07	0.63	0.07	0.30
Technical Risk	0.28	0.05	0.31	0.64
Total Score		**0.11**	**0.51**	**0.38**

b. Vehicle and Test Equipment Design

Designs for the vehicle and test equipment were finalized after the Project Proposal and an updated schedule, budget, and risk analysis were completed. A literature and performance theory review and logistics handling of high-confidence, high lead-time items was also performed prior to final design completion. While early ordering of some items locked in the design to an extent, it was required to meet the schedule demands. The initial motor

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[4] Landaeta, Rafael. "ENMA 604 Project Management." Old Dominion University. United States, 2014.

test stand design is depicted in Figure 1.[5] The final air vehicle wiring schematics are depicted in Figure 2.

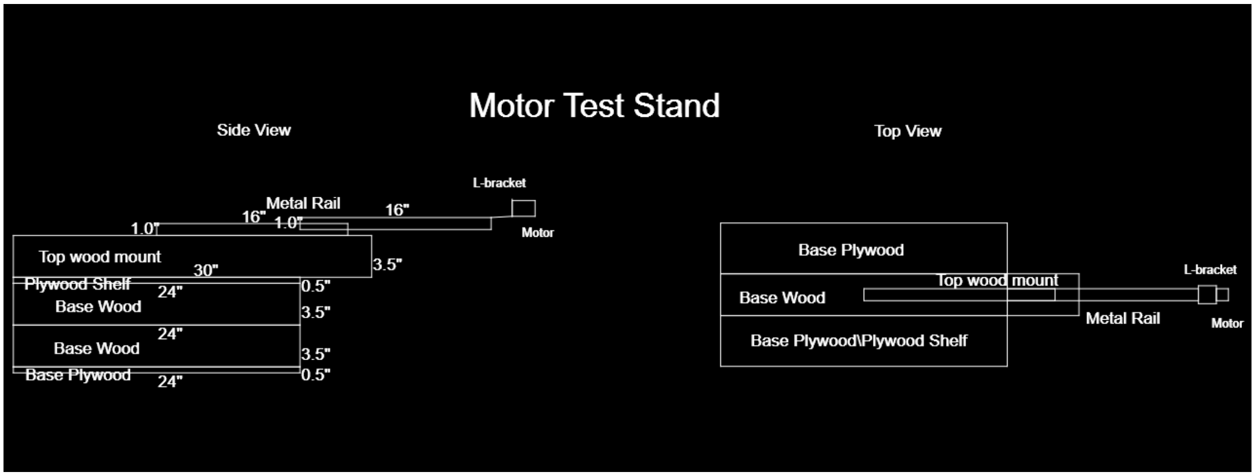

Figure 1: Motor Test Stand Design

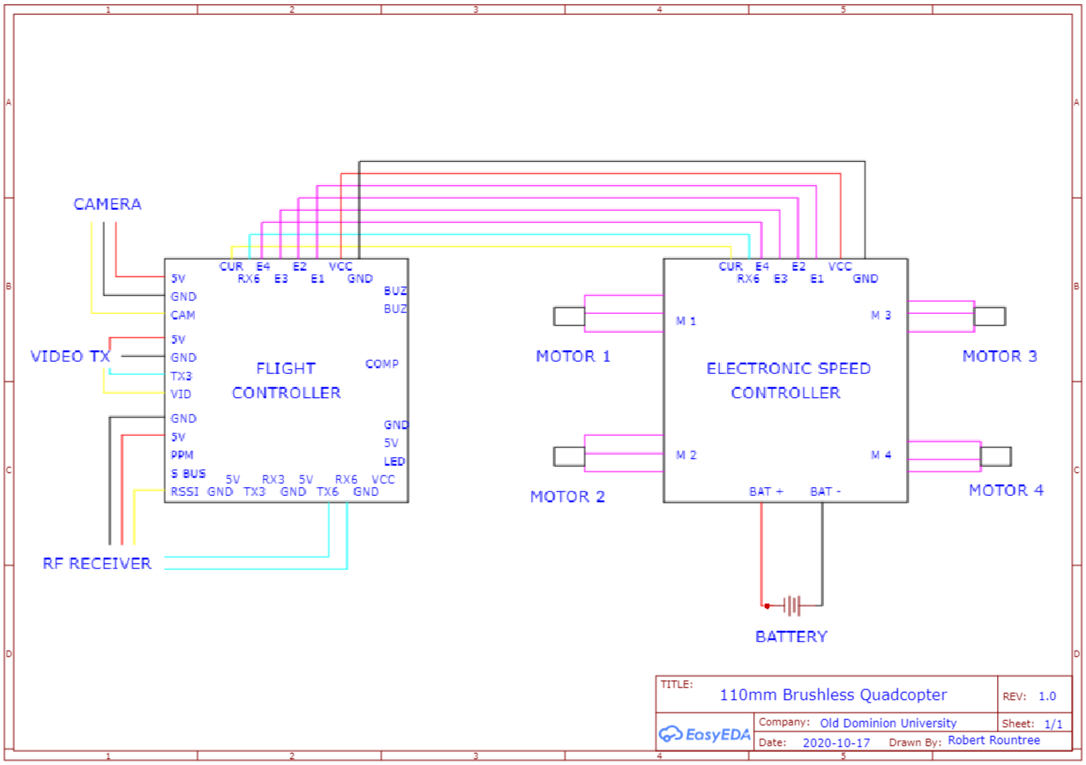

Figure 2: 110 mm Quadcopter Wiring Schematic

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[5] "Engine test stand for brushless motors." RC Test Bench.

c. Construction

Additional equipment was procured as required prior to vehicle and test stand construction. The motor test stand was constructed primarily from wood, with a sliding metal rail designed to minimize friction losses. A scale was used to measure thrust produced by the motor operating on the sliding rail using a tension weight system. The primary air vehicle under test was the 110mm brushless Air Vehicle (AV), constructed from commercially available components, with a design thrust-to-weight ratio (TWR) of approximately 4:1. The FC was programmed using standard gain settings from the resident Betaflight firmware. Components were wired in accordance with the wiring schematic in Figure 2. The full 110mm brushless motor AV configuration is listed in Table 2.

Table 2: 110mm Brushless Motor Air Vehicle Configuration

Component Type	Component Name	Weight (g)
Frame	TurboBee 111R	33
ESC	Mamba 40A 20mm	7
FC	Mamba F405 20mm	7
Motors	EMAX 1106 6000kV	32
Receiver	FS-iX6B	2
Camera / Video Transmitter	Caddx Firefly 2.1mm	4
Battery	RDQ 550 mAh 3S	45
Total Weight	-	149

d. Testing

Tests were designed to build up in power and risk level from lowest to highest. Ground motor testing was performed first, using the motor test stand. Motor testing featured the EMAX 1106 6000kV motor, which was tested with a single motor soldered to the Mamba 40-Amp ESC. The ESC was connected to the FC per the wiring schematic in Figure 2, and the FC was connected to a laptop via Micro USB. BetaFlight Configurator software was used to drive the pre-determined pulse widths to the motor, resulting in ten test points. After an initial round of testing on the EMAX 1106 6000kV from low power to high power, the battery was recharged and an additional round of testing was performed from high power to low power. This enabled isolation of battery voltage, which drops throughout a round of testing due to depleting battery life.

Flight testing followed ground testing. The vehicle was first tested on the ground using the flight Radio Transmitter, confirming communications between it and the receiver on board the AV, then confirming control of the motors. Next stability and control testing was conducted in a low altitude hover, followed by medium altitude hover and cruise flight, and finally climb performance testing in a climb to 200 feet Above Ground Level (AGL).

e. Data Analysis

i. Objectives. The objectives of ground testing were to collect expected thrust output and electrical draw of the motor at given pulse settings to enable prediction of AV performance airborne. The objective of AV flight testing was to validate theoretical expectations and ground test data using hover data and max-performance climb data.

ii. Data Collection. Data was collected during ground testing with hand-written recordings of test instrumentation indications. Instrumentation included a 150A Watt Meter measuring Amps, Watts and Volts supplied to the ESC, a tension weight scale, and the BetaFlight Configurator software which set pulse modulation from the ESC to the motors. During flight test, the BetaFlight BlackBox (in-flight data recorder) was used to log up to 16MB of flight data at 60Hz. This included all Inertial Measurement Unit (IMU) data including velocity, position, and acceleration, as well as ESC telemetry such as motor RPM and throttle percentage. This data was stored on the FC during flight and downloaded post-flight for analysis.

iii. Analysis. The raw data from the thrust stand was used to create plots of thrust versus RPM, amps, and signal pulse. Test data from two separate runs (low to high and high to low) was averaged to control for battery state. In-flight climb and acceleration data was compared to test and theoretical expectations. Thrust data from ground bench testing was used to improve the observed accuracy of the empirical thrust model.

iv. Expected Results. Based on theoretical modeling, the EMAX 1106 6000kV was expected to generate approximately 150g of thrust at full throttle. In flight with four motors, this would correspond to a TWR of approximately 4.0 and maximum z-axis acceleration of approximately 96 ft/s^2 (29.4 m/s^2).

3.3 Project Management

3.3.1 Schedule

The major project milestones are depicted in Table 3, along with the scheduled due date and actual completion date for each milestone. Of note, motor test data analysis was completed significantly after scheduled, and was not completed until near the end of the project, when it was beginning to be integrated into the paper.

Table 3: Project Milestones

Milestone	Scheduled Due Date	Completion Date
Project Initiation.	27 July 2020	27 July 2020
Project Proposal complete. Initial schedule, risk analysis, and budget complete.	3 August 2020	3 August 2020
Literature review and performance theory complete.	10 August 2020	10 August 2020
Analysis of Alternatives and Project Selection complete. Update schedule, risk analysis, and budget.	17 August 2020	13 August 2020
Vehicle design and test equipment designs complete.	24 August 2020	15 August 2020
Motor test stand construction complete.	31 August 2020	9 September 2020
Motor testing complete.	7 September 2020	12 September 2020
Motor test data analysis complete.	14 September 2020	14 October 2020
Vehicle construction complete.	21 September 2020	15 September 2020
Vehicle Flight Controller programming complete.	28 September 2020	16 September 2020
Vehicle testing complete.	5 October 2020	7 October 2020
Performance, reliability, and stability data analysis complete.	12 October 2020	17 October 2020
Project complete.	16 October 2020	19 October 2020
Project final report completed.	23 October 2020	21 October 2020

A detailed project schedule by activity is depicted in Table 4.

Table 4: Detailed Schedule by Activity

Task	Task Name	Start Date	End Date
1.1.1	Initial Scheduling	Mon, 7/27/20	Mon, 07/27/20
1.1.2	Initial Designs	Tue, 7/28/20	Tue, 07/28/20
1.1.3	Budgeting and Risk Analysis	Wed, 7/29/20	Wed, 07/29/20
1.1.4	Project Proposal	Thu, 7/30/20	Fri, 07/31/20
2.1.1	Literature Review	Mon, 8/3/20	Tue, 08/04/20
2.1.2	Performance Theory	Wed, 8/5/20	Fri, 08/07/20
1.2.1	Analysis of Alternatives	Mon, 8/10/20	Mon, 08/10/20
1.2.2	Project Selection	Tue, 8/11/20	Tue, 08/11/20
1.3.1	Order Equipment	Wed, 8/12/20	Wed, 08/12/20
1.3.2	Equipment Shipping	Thu, 8/13/20	Wed, 09/09/20
1.4.1	Updated Schedule	Thu, 8/13/20	Thu, 08/13/20
1.4.2	Updated Risk Analysis and Budget	Thu, 8/13/20	Thu, 08/13/20
2.2.1	Final Vehicle Design	Fri, 8/14/20	Sat, 08/15/20
2.2.2	Final Test Equipment and Design	Fri, 8/14/20	Sat, 08/15/20
3.1.1	Equipment Procurement	Mon, 8/17/20	Mon, 09/07/20
3.2.1	Motor Test Stand Construction	Tue, 9/8/20	Wed, 09/09/20
4.1.1	Motor Testing	Wed, 9/9/20	Sat, 09/12/20
4.2.1	Motor Test Data Reduction	Sat, 9/12/20	Wed, 10/14/20
3.2.2	Vehicle Construction	Tue, 9/8/20	Tue, 09/15/20
3.3.1	Flight Controller Programming	Tue, 9/15/20	Wed, 09/16/20
4.1.2	Vehicle Testing	Thu, 10/1/20	Wed, 10/07/20
5.1.1	Performance Data Analysis	Wed, 10/7/20	Thu, 10/15/20
5.1.2	Performance Modeling	Thu, 10/15/20	Fri, 10/16/20
5.1.3	Reliability Data Analysis	Fri, 10/16/20	Sat, 10/17/20
5.1.4	Stability Data Analysis	Sat, 10/17/20	Sat, 10/17/20
5.2.1	Final Project Reporting	Mon, 10/12/20	Wed, 10/21/20

3.3.2 Deliverables

The following deliverables were completed for this project:

1. PERT chart, WBS, Gantt chart, and time-phased budget
2. AHP Model justifying project selection
3. Vehicle design documents including schematic, component list, and performance estimates

4. Aggregated multi-rotor performance theory
5. Empirical vehicle performance model
6. Motor and vehicle reliability analysis
7. Considerations for future multi-rotor projects
8. Considerations for future Engineering Management projects
9. Areas for further research

A single deliverable was not completed: An optimization function to find maximized vehicle performance subject to constraints. This deliverable was not completed due to unavoidable complexity and non-linearity found in the underlying performance equations. A more in-depth analysis is conducted in Section 4.2.

3.3.3 Controls

Controls were implemented as needed throughout the project. Every week, the test lead referenced current progress against the baseline schedule for comparison. Any differences were highlighted and a new plan forward was decided. The project Gantt chart, WBS, and PERT chart, available in Appendix A, Figure A-1 through Figure A-4, were used to monitor project schedule and progress and were assessed weekly. A hard cap of 10% over budget was set initially, and any costs that were unbudgeted or over budgeted cost underwent additional review. Test data and theoretical motor calculations were compared to predictive performance tools available for a fee online, in the interest of validating proper theoretical modeling was conducted and test performance data. While budget and timeline prevented achieving statistical significance of all test data, multiple tests of each type were conducted in the interest of improving validity.

3.4 Project Design Issues

The project design was well-suited to accomplish the project overall. The complexity of aerodynamically modelling propellers, even at small scales, turned out to be a major challenge in this project. The final equations utilized were not exactly as originally envisioned, but still provide a simple method for predicting thrust. Any optimization methods proved elusive, limited by the construct of the theoretical equations. The motor test stand as designed was not well-suited for applications with low thrust such as micro-class quadcopters, primarily due to static friction losses. Tests had to be repeated several times, particularly in the mid-throttle region, to achieve accurate static thrust results.

4.0 PROJECT RESULTS AND IMPLICATIONS

4.1 Interpretation of Data

Data measured in the laboratory during ground testing and data measured in flight compared reasonably well to theoretical expectations for the 110mm quadcopter equipped with the EMAX 1106 6000kV motors. Bench test errors in the middle and upper throttle ranges were within 20% of values predicted by the empirical model, with maximum throttle thrust within 5% of predictions. In-flight maximum thrust momentary accelerations matched expectations to within 15%. Overall under the scope of testing conducted, the empirical model developed provided reasonable estimates for observed thrust values. The model is sufficient to serve as a starting point for further research efforts, subject to further testing using different platforms.

4.2 Discussion of Project Deliverables

The following deliverables applied to this project and are presented below or where listed.

1. Project PERT chart, WBS, and Gantt charts. Presented in Appendix A, Figure A-1 through Figure A-4.
2. Risk analysis. Risks were assessed as part of the Analysis of Alternatives initially, and risk mitigation procedures were conducted for the risks identified for the selected project. The Overall Project Risk Factor[6] of the chosen platform (the 110mm brushless performance model) was 0.6, representing a moderate-high overall project risk. The overall project risk factor for the 110mm brushless motor AV is depicted in Table 5. Summary reports of the generic project risks, platform-specific risks, and overall risk factor of each possible project/platform is included in Figure A-15 through Figure A-17.

Table 5: Overall Project Risk, 110mm

Overall Project Risk (110mm)	
Probability of occurrence	0.46
Risk impact	0.27
Overall Risk Factor	**0.60**

Schedule and technical risks were re-assessed at each weekly review and the plan was updated as needed. Hazards were assessed before each testing evolution and controls implemented to mitigate risk of injury or property damage. An example hazard assessment for ground static thrust motor testing and for flight testing is depicted in Table 6.

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[6] Landaeta, Rafael.

Table 6: Test Hazard Assessment

Hazard	Risk Level (1-9)	Mitigation	Residual Risk (1-9)
Propeller assembly undergoes Rapid Unscheduled Disassembly (RUD) during bench propeller testing	5	All personnel at the test bench will wear safety goggles. RPM will build from low to high.	3
Test bench undergoes Rapid Unscheduled Disassembly (RUD) during bench propeller testing	2	Personnel will stand back from test bench. Bench integrity will be checked prior to test.	1
AV injures personnel during flight test	5	AV will be tested in open area and will stay clear of personnel by 100 ft.	3
AV damages property during flight test	3	AV will be tested in open area and will stay clear of property and buildings by 20 ft.	1

3. Time-Phased Budget.

The finalized project budget is depicted in Table 7 with the actual and budgeted cost for each line item. The actual cost was \$306.64, 15% below the budgeted cost of \$358.91. Individual equipment costs generally matched actual costs, with two items that were purchased that were not accounted for in the original budget.

Table 7: Project Budget

Equipment	Budgeted Cost	Actual Cost	Actual (% of Budgeted)
110mm AV			
iFlight TurboBee 111R	$21.99	$23.12	105%
Mamba F405 Mini Mk2 Stack	$37.99	$39.06	103%
4x EMAX Eco 1106 6000KV	$39.96	$44.12	110%
FS A8S	-	$9.99	-
Caddx Firefly 1/3" 2.1mm, 5.3-5.9 Ghz	-	$18.99	-
EMAX Avan Babyhawk 2.3" 12x	$3.99	$4.03	101%
3S 550 mAh 70C Battery	$9.24	$9.24	100%
SunnySky 2305 2300kV Motors	$50.00	$41.99	84%
Motor Test Stand			
60A Single ESC	$30.00	$25.00	83%
Hyperion eMeter	$30.00	$23.00	77%
Tension Scale	$13.00	$13.00	100%
Test Stand Hardware	$30.00	$32.20	107%
Support Hardware			
Servo Tester	$8.00	$9.99	125%
XT-30 connectors	$4.96	$4.99	101%
Smoke Stopper	$8.00	$7.92	99%
Total budget	$287.13	$306.64	107%
Total budget with 25% overhead	$358.91		85%

The time-phased budget is depicted in Figure 3 below. Actual cost expenditures generally lagged planned expenditures, largely due to the longer anticipated planning and purchasing cycle. This was caused by many items requiring considerable research prior to purchase. The delayed construction phase, as previously shown in Table 4, contributed to the budgeted cost expenditures not being complete until mid-September 2020.

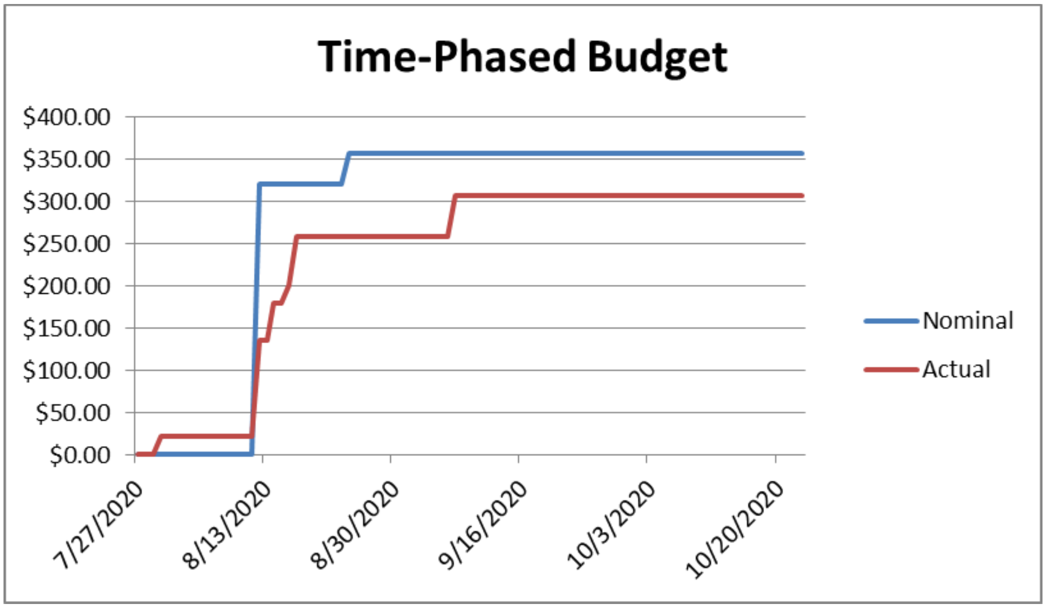

Figure 3: Project Time-Phased Budget

4. <u>AHP model justifying vehicle design selection.</u> Presented in Table 1, page 16. In-depth findings are presented in Appendix A, Figure A-5 through Figure A-14.
5. <u>Vehicle design documents.</u> Schematics (Figure 1), wiring diagram (Figure 2), and component list (Table 2). A summary of initial performance estimates are presented below in Table 8. Performance calculations and performance test data will be expressed in deliverables six through eight below.

Table 8: Initial AV Performance Estimates[7]

Aircraft Weight (g)	150
Motor Thrust (g)	150
Total Thrust (g)	600
TWR	4.0

6. <u>Aggregated multi-rotor performance theory.</u>

Multi-rotor performance theory is rooted in basic physical mechanics and Newton's Laws, but can become extremely complicated when taking into account

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[7] "Drone Motor Fundamentals – How Brushless Motor Works."

air density, compressibility, differing airflow through different sections of the propeller, electric motor heat limiting, and RPM limiting due to propeller drag. However, these complexities can be either ignored or estimated for rough calculations, and can be corrected later with empirically-derived constants. A simplified model of thrust allows it to be expressed by determining the mass flow rate of air through a propeller. This model has been adapted from work originally published by Gabriel Staples in 2014.[8]

Starting with Newton's second law:

$$F = \frac{d(mv)}{dt}$$

Equation 1

If we consider the velocity of air exiting the propeller to be constant for a given power setting, we can modify this equation to:

$$F = v\frac{dm}{dt}$$

Equation 2

This v will be expressed as Ve, propeller exit velocity. This equation works for a static AV, but for a moving AV the air velocity of the AV subtracts from the exit velocity as such:

$$F = \frac{dm}{dt}(Ve - Vac)$$

Equation 3

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[8] Staples, Gabriel. "Propeller Static & Dynamic Thrust Calculation Part 2 of 2 – How did I Come Up With This Equation?" 4 May 2014.

The mass flow rate of air through the propeller is equal to the air density times the cross-sectional area of the propeller times the velocity at which the air is flowing through the propeller.

$$F = \rho A Ve(Ve - Vac)$$

Equation 4

Air density is ρ, A is the cross-sectional area of the propeller, and the air moves through the propeller at speed Ve. The propeller cross-sectional area is equal to the propeller radius squared times pi:

$$F = \rho(\pi r^2)Ve(Ve - Vac) = \rho\left(\frac{\pi d^2}{4}\right)Ve(Ve - Vac)$$

Equation 5

To get Ve, we assume that Ve is equal to the pitch speed of the propeller, that is, the theoretical distance a propeller would move forward when moved one rotation. Pitch speed is dependent on propeller RPM and propeller pitch:

$$Ve = Np * Pp$$

Equation 6

Where Np is propeller RPM and Pp is propeller pitch. If we insert equation 6 into equation 5, we get:

$$F = \rho\left(\frac{\pi d^2}{4}\right)(NpPp)(NpPp - Vac)$$

Equation 7

Simplifying for static thrust (non-moving aircraft), we can remove the Vac term since Vac will be equal to zero.

$$F = \rho\left(\frac{\pi d^2}{4}\right)(NpPp)^2$$

Equation 8

This is our baseline static thrust equation.

7. Empirical vehicle performance model.

Empirical correction constants postulated by Gabriel Staples in 2014[9] propose a correction factor to account for higher efficiency of high-diameter, low-pitch propellers. The finalized static thrust equation with these correction factors is depicted in Equation 9, where the first-order constant k_1 = 3.29546, and the higher-order constant k_2 = 1.5.

$$F = \rho\left(\frac{\pi d^2}{4}\right)(NpPp)^2\left(\frac{d}{3.29546Pp}\right)^{1.5}$$

Equation 9

Assuming standard air density, this allows calculation of thrust with knowledge of only three variables: RPM, propeller pitch, and propeller diameter. This can be used in conjunction with a common brushless motor electrical equation:[10]

$$Np = Kv(v - iR_m)$$

Equation 10

Where v is the line voltage seen at the motor, i is the line-peak current, and Rm is the motor winding resistance. This combined equation is presented in Equation 11, and provides a link between thrust, propeller parameters, and electrical parameters.

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[9] Staples, Gabriel.

[10] Lanteigne, Eric and Muzar, Dominic. "Experimental Characterization of Brushless DC Motors and Propellers for Flight Application." Proceedings of the Canadian Society for Mechanical Engineering International Congress 2016. June 26-29, 2016, Kelowna, BC, Canada.

$$F = \rho\left(\frac{\pi d^2}{4}\right)(Kv(v - iR_m)Pp)^2\left(\frac{d}{3.29546Pp}\right)^{1.5}$$

Equation 11

Next, we compare findings from Equation 9 and 11 to our own test performance data, and determine if any corrections to these equations are required. Results from static thrust testing of the EMAX 1106 6000kV motor on the ground using the motor test stand are summarized in Table 9. Full results from all rounds of ground testing are presented in Figure A-18 through Figure A- 20. As evident from analysis of Table 9, error tended to become smaller as thrust increased. This is expected to be due to measurement error, specifically residual static friction, rather than a true indication of theoretical model accuracy. Average results at all values above 40% throttle produced experimental data within 14% of theoretical predictions from the models presented in Equations 9 and 11. All test data (Figure A-18 and Figure A-19) above 40% throttle was within 18% of predicted values. Note that pulse width in μs is shown as to throttle % in Table 9 for ease of interpretation.

Table 9: Static Thrust Test Results Summary

Throttle %	Measured RPM	Measured Thrust (g)	Predicted Thrust (g)	Error %
10%	7150	0	4	100%
20%	11100	8	15	49%
30%	15450	25	31	19%
40%	19700	45	49	8%
50%	24850	58	65	12%
60%	28800	73	85	14%
70%	31950	93	101	8%
80%	34750	120	133	10%
90%	40900	155	165	6%
100%	46300	175	193	9%

Measured and predicted thrust are plotted against RPM in Figure 4. Thrust is plotted against pulse in Figure A-21 and measured thrust is plotted against amps in Figure A-22.

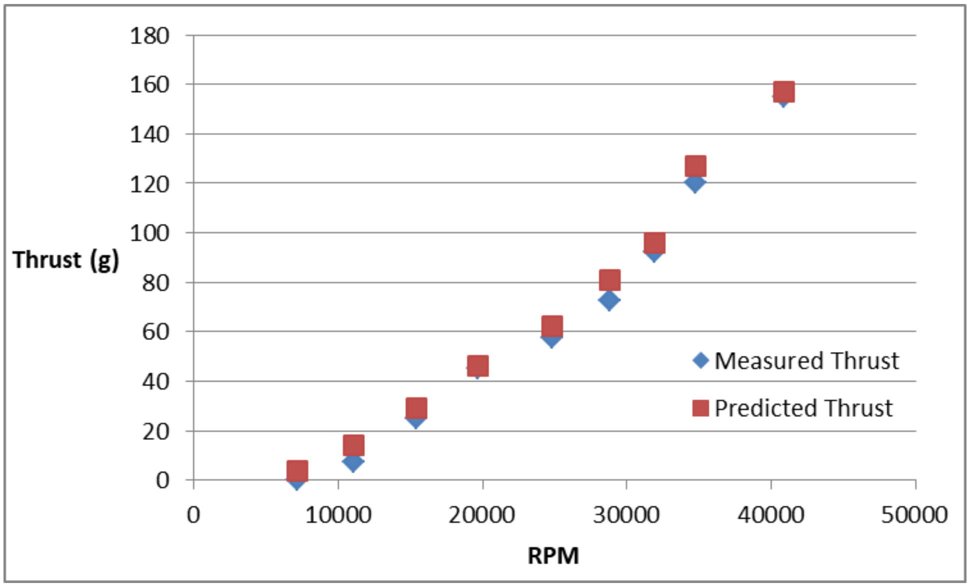

Figure 4: Static Thrust versus RPM

The difference between measured and predicted thrust for each throttle setting was evaluated, and 5 grams of difference was contributed to friction. The difference between the measured and experimental values is given the letter δ. Table 10 depicts the error and friction-free error at each throttle setting.

Table 10: Delta between Measured and Experimental Thrust

Measured Thrust (g)	Predicted Thrust (g)	Error %	δ	δ less Friction
0	4	100%	4	-1
8	15	49%	7	2
25	31	19%	6	1
45	49	8%	4	-1
58	65	12%	8	3
73	85	14%	12	7
93	101	8%	8	3
120	133	10%	13	8
155	165	6%	10	5
175	193	9%	18	13

The two empirical constants from the equation, k_1 and k_2, can be altered to minimize the differences between measured and experimental thrust after taking friction into account, giving a more accurate solution for the range tested. Experimentation found that $k_2 = 1.5$ and $k_1 = 3.403$ minimized theoretical and experimental data differences. Thus we obtain Equation 12, our modified empirical thrust equation.

$$F = \rho\left(\frac{\pi d^2}{4}\right)(NpPp)^2\left(\frac{d}{3.403Pp}\right)^{1.5}$$

Equation 12

Correcting for friction and using the new empirical Equation 12, average errors were reduced to 8% or less at 40% throttle or higher. A comparison between the new predicted thrust values and actual test data is depicted in Table 11.

Table 11: Corrected Thrust Predictions

Throttle %	Measured RPM	Measured Thrust (g)	Predicted Thrust (g)	δ	δ less Friction	Residual Error %
10%	7150	0.0	3.7	4	-1	-36%
20%	11100	7.5	14.0	6	1	11%
30%	15450	25.0	29.3	4	-1	-2%
40%	19700	45.0	46.4	1	-4	-8%
50%	24850	57.5	62.3	5	0	0%
60%	28800	72.5	80.7	8	3	4%
70%	31950	92.5	95.9	3	-2	-2%
80%	34750	120.0	127.0	7	2	2%
90%	40900	155.0	156.9	2	-3	-2%
100%	46300	175.0	183.6	9	4	2%

8. An optimization function to find maximized vehicle performance subject to constraints. Numerous interrelationships between variables resulted in non-linearity that prevented creation of a linear thrust optimization function using AV parameters under reasonable constraints. Additional variables such as temperature, thermal overload, and propeller drag with increasing RPM were not accounted for and present additional constraints on electric motor and AV performance that put an optimization function of this nature out of reach.
9. Brief vehicle and motor reliability analysis. No reliability issues were encountered with the air vehicle or the motor in testing performed. Faulty solder connections required additional battery connector maintenance prior to ground testing, but this was a construction flaw as opposed to a reliability issue. Hardening procedures such as gluing solder connections likely enhanced AV reliability. AV flight and motor test times and reliability data from each period are depicted in Table 12.

Table 12: Test Events and Reliability Issues

Event	AV	Configuration	Flight/motor time	Maintenance Required	Notes
Ground static thrust test 1	N/A	Motor Only - EMAX 1106 6000kV	11:36	Failed connector prior to test	Low to high throttle
Ground static thrust test 2	N/A	Motor Only - EMAX 1106 6000kV	10:23	None	High to low throttle
Flight test 1	110mm Brushless	Standard (no video)	8:12	None	Basic hover
Flight test 2	110mm Brushless	Standard	6:47	None	Medium altitude hover
Flight test 3	110mm Brushless	Standard	4:05	None	Cruise flight and climb testing

10. Considerations for future multi-rotor vehicle projects. Future multi-rotor vehicle projects should focus on test stand accuracy and pre-construction performance analysis. Detailed findings are presented in Section 4.3.
11. Considerations for future Engineering Management projects. Presented in Section 4.3.
12. Areas for further research. Areas for further research include gathering additional empirical data using different propeller and motor combinations, as well as research in motor loading and heating and electrical decay. Additional findings are presented in Section 4.3.

4.3 Recommendations / Project Results

4.3.1 Local-Level Implications/Recommendations.

Findings from this project point to fairly accurate modeling using equations with a theoretical basis that have been empirically corrected. The empirically derived constants k_1 and k_2 were found to be reasonably accurate, although for this implementation k_1 was found to be closer to 3.4 than 3.29. It is recommended to conduct further testing using different propeller and motor combinations to validate these results and extend their applicability.

Based on the testing performed, the platform under test does not have significant reliability issues. Further testing is required for a statistically significant reliability analysis.

AV construction methods utilized in this test were sound. Previous experience ensured Receiver/Transmitter compatibility and minimized soldering issues. The use of online paid predictive tools was instrumental to proper AV design, highlighting the importance of performance analysis and prediction prior to construction.

4.3.2 Local Level Issues Identified as a Result of the Project

Considerable difficulty was encountered relating electrical motor characteristics to propeller performance in a meaningful way. This will require further research in motor heating mechanisms, voltage decay with increasing power, and RPM drop due to propeller loading.

The presence of significant friction in the test stand points to the importance of a friction-free environment for future motor testing. Even in a system optimized to minimize friction, significant levels of friction (5-10g) were encountered, reducing confidence in the test data and requiring an empirical correction. Small friction losses are less important in applications for larger motors, but may still be significant. Test stand redesign should be considered to maximize accuracy.

4.3.3 Project Implications / Issues Beyond the Local Level

This project validated the importance of proper project management throughout the project life cycle. Project Management methods to include planning, scheduling, budgeting facilitated straightforward and progress-based periodic project reviews during the completion of this project. However, this project also highlighted shortcomings in Risk Management methods and PERT scheduling techniques. These shortcomings can be addressed with slightly modified models.

The Risk Management method presented in this paper and often taught by Engineering Management Project Management courses involves finding the hazards or risks that are possible, along with the probability of occurrence and the severity of each. Probability of occurrence (P) and severity (S) is then averaged, and the overall risk factor of a project is determined as Risk Factor = (P+S)-(PS).

The major problem with this method of calculating a project Risk Factor is that it does not account for the number of risks a project has. For example, if a project has a Risk Factor of 0.72, and an additional risk of probability 0.1 and severity 0.1 is added, the overall Risk Factor number will drop, despite the fact that the addition of this new risk makes the project slightly riskier overall. This method of Risk Analysis allows for a general discussion of how risky a project is, but does not lend itself to comparative discussions regarding multiple projects with greatly different numbers of risks. A far better (but more complex) method to analyze risk would be to characterize each risk probabilistically with a distribution of likelihood and severity, then to add risks individually to determine total risk profile.

The Program Evaluation Review Technique (PERT) Chart method also witnessed significant shortcomings in this project. The main problem is that it cannot account for a “need by” date, and instead assigns resources and activities to the next available time slot, when in reality there may be conflicts or resource leveling constraints that make execution of the PERT as written impossible. This is encountered in the PERT chart for this project, depicted in Figure A-4. Because there is a several-day break in the schedule (for instance, 2 days of slack between activity 4.2.1 and 3.2.2), the critical path which should have zero slack ends up having slack. While it is possible that there is slack there, it is also possible that alternative activities result in 5 days being the fastest possible time in which to accomplish 3 days of work, due to resource leveling constraints. The PERT should differentiate between the number of days it takes to complete a task and the number of days that will elapse between activities.

In addition to providing insights for Engineering Management, this project provided insights regarding quadcopter and general electric rotary vehicle design and test. The simple empirical thrust model developed was reasonably accurate for hobby or enthusiast use and would be useful for initial order-of-magnitude estimates in industry or defense applications, though the model requires subsequent validation with larger rotors. The initial relationships made between thrust, the velocity constant, and electrical characteristics of motors will be beneficial to any students of brushless DC electric multi-rotor aircraft. This project also highlighted the need for continued study into simplified models for electrical motor thrust characterization.

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ACRONYMS AND ABBREVIATIONS

AGL...................Above Ground Level

AHP...................Analytic Hierarchy Process

AoA ....Analysis of Alternatives

AV ....Air Vehicle

ESC...................Electronic Speed Controller

FC ....Flight Controller

GPS...................Global Positioning System

IMU....................Inertial Measurement Unit

LiPo...................Lithium-Ion Polymer

MCDM ....Multi-Criteria Decision Making

MEM..................Master’s of Engineering Management

NLT ....No Later Than

OR.....................Operations Research

PERT.................Program Evaluation Review Technique

PID ....Proportional, Integral, Derivative

RUD ....Rapid Unscheduled Disassembly

TWR ....Thrust-to Weight Ratio

UAS...................Unmanned Aircraft System

WBS ....Work Breakdown Structure

APPENDIX A: FIGURES

Table of Contents

Applications of Technical Management in Multi-Rotor Design, Construction, and Test
Old Dominion University - ENMA 605
Robert Rountree

Project Start: Monday, 7/27/2020

#	Task	Start	End	Work Days
1.0	Initial Concept Development	Mon, 7/27/20	Wed, 9/9/20	33
1.1	Project Proposal	Mon, 7/27/20	Fri, 7/31/20	5
1.1.1	Initial Scheduling	Mon, 7/27/20	Mon, 7/27/20	1
1.1.2	Initial Designs	Tue, 7/28/20	Tue, 7/28/20	1
1.1.3	Budgeting and Risk Analysis	Wed, 7/29/20	Wed, 7/29/20	1
1.1.4	Project Proposal	Thu, 7/30/20	Fri, 7/31/20	2
1.2	Project Selection	Mon, 8/10/20	Wed, 8/12/20	3
1.2.1	Analysis of Alternatives	Mon, 8/10/20	Tue, 8/11/20	2
1.2.2	Project Selection	Wed, 8/12/20	Wed, 8/12/20	1
1.3	Logistics	Wed, 8/12/20	Wed, 9/9/20	21
1.3.1	Order Equipment	Wed, 8/12/20	Wed, 8/12/20	1
1.3.2	Equipment Shipping	Thu, 8/13/20	Wed, 9/9/20	20
1.4	Project Updates	Thu, 8/13/20	Fri, 8/14/20	2
1.4.1	Updated Schedule	Thu, 8/13/20	Thu, 8/13/20	1
1.4.2	Updated Risk Analysis and Budget	Fri, 8/14/20	Fri, 8/14/20	1
2.0	Research and Development	Mon, 8/3/20	Fri, 8/21/20	15
2.1	Research	Mon, 8/3/20	Fri, 8/7/20	5
2.1.1	Literature Review	Mon, 8/3/20	Tue, 8/4/20	2
2.1.2	Performance Theory	Wed, 8/5/20	Fri, 8/7/20	3
2.2	Design	Mon, 8/17/20	Fri, 8/21/20	5
2.2.1	Final Vehicle Design	Mon, 8/17/20	Wed, 8/19/20	3
2.2.2	Final Test Equipment and Design	Thu, 8/20/20	Fri, 8/21/20	2
3.0	Construction	Mon, 8/24/20	Fri, 9/25/20	25
3.1	Procurement	Mon, 8/24/20	Mon, 8/24/20	1
3.1.1	Equipment Procurement	Mon, 8/24/20	Mon, 8/24/20	1
3.2	Hardware	Tue, 8/25/20	Fri, 9/18/20	19
3.2.1	Motor Test Stand Construction	Tue, 8/25/20	Thu, 8/27/20	3
3.2.2	Vehicle Construction	Mon, 9/14/20	Fri, 9/18/20	5
3.3	Software	Mon, 9/21/20	Fri, 9/25/20	5
3.3.1	Flight Controller Programming	Mon, 9/21/20	Fri, 9/25/20	5
4.0	Test and Evaluation	Mon, 8/31/20	Thu, 10/1/20	24
4.1	Testing	Mon, 8/31/20	Thu, 10/1/20	24
4.1.1	Motor Testing	Mon, 8/31/20	Wed, 9/2/20	3
4.1.2	Vehicle Testing	Mon, 9/28/20	Thu, 10/1/20	4
4.2	Data Analysis	Mon, 9/7/20	Wed, 9/9/20	3
4.2.1	Motor Test Data Reduction	Mon, 9/7/20	Wed, 9/9/20	3
5.0	Data Analysis and Reporting	Mon, 10/5/20	Fri, 10/16/20	10
5.1	Data Analysis	Mon, 10/5/20	Fri, 10/9/20	5
5.1.1	Performance Data Analysis	Mon, 10/5/20	Mon, 10/5/20	1
5.1.2	Performance Modeling	Tue, 10/6/20	Wed, 10/7/20	2
5.1.3	Reliability Data Analysis	Thu, 10/8/20	Thu, 10/8/20	1
5.1.4	Stability Data Analysis	Fri, 10/9/20	Fri, 10/9/20	1
5.2	Reporting	Mon, 10/12/20	Fri, 10/16/20	5
5.2.1	Final Project Reporting	Mon, 10/12/20	Fri, 10/16/20	5

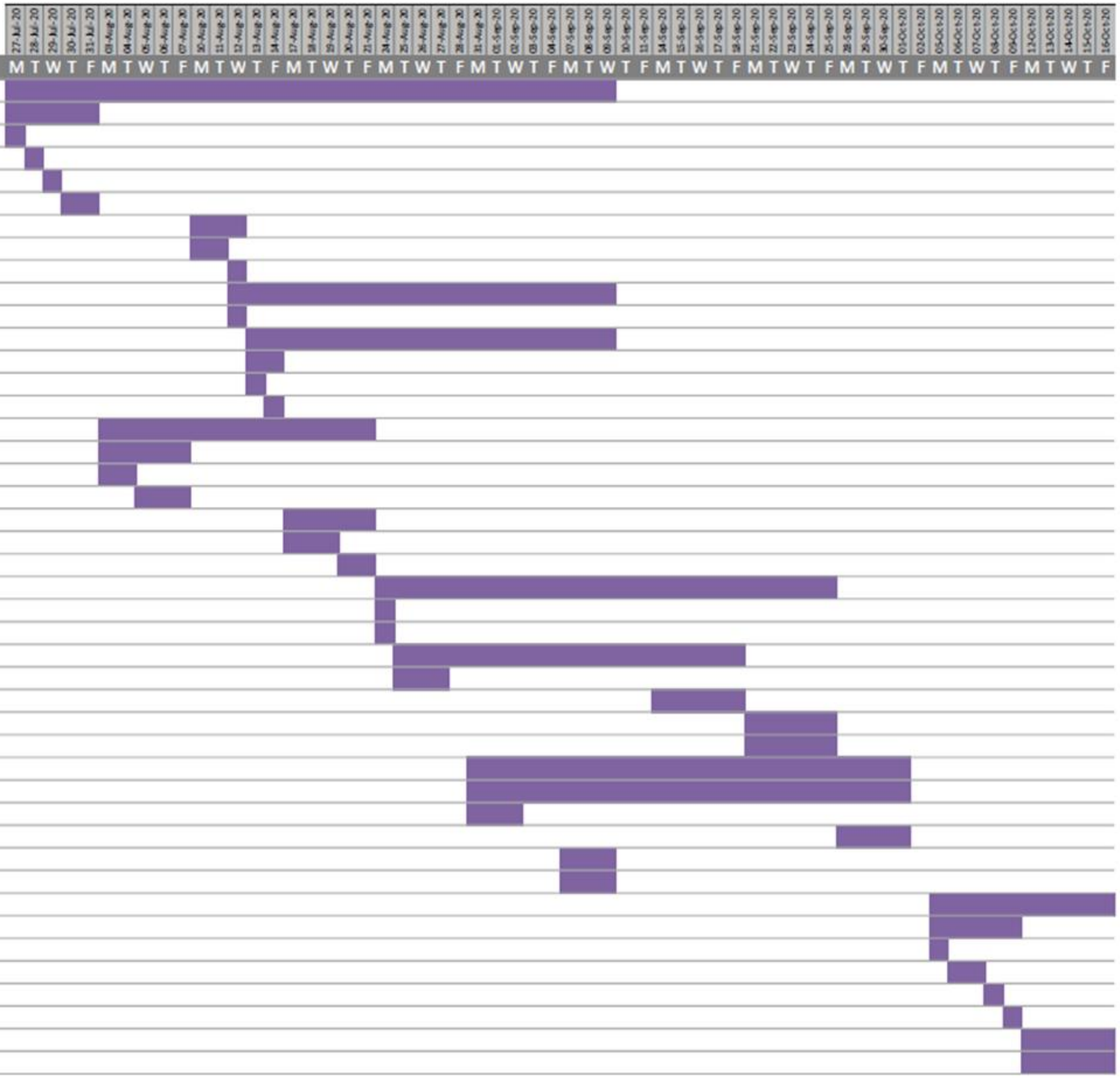

Figure A-1: Project Gantt Chart and WBS

Figure A-2: Project Work Breakdown Structure

#	Activity	Start	End	Resources
1.0	**Initial Concept Development**			
1.1	Project Proposal	-	-	-
1.1.1	Initial Scheduling	Mon, 7/27/20	Mon, 7/27/20	Project lead
1.1.2	Initial Designs	Tue, 7/28/20	Tue, 7/28/20	Project lead
1.1.3	Budgeting and Risk Analysis	Wed, 7/29/20	Wed, 7/29/20	Project lead
1.1.4	Project Proposal	Thu, 7/30/20	Fri, 7/31/20	Project lead
1.2	Project Selection	-	-	-
1.2.1	Analysis of Alternatives	Mon, 8/10/20	Tue, 8/11/20	Project lead
1.2.2	Project Selection	Wed, 8/12/20	Wed, 8/12/20	Project lead
1.3	Logistics	-	-	-
1.3.1	Order Equipment	Wed, 8/12/20	Wed, 8/12/20	Project lead
1.3.2	Equipment Shipping	Thu, 8/13/20	Wed, 9/9/20	None
1.4	Project Updates	-	-	-
1.4.1	Updated Schedule	Thu, 8/13/20	Thu, 8/13/20	Project lead
1.4.2	Updated Risk Analysis and Budget	Fri, 8/14/20	Fri, 8/14/20	Project lead
2.0	**Research and Development**			
2.1	Research	-	-	-
2.1.1	Literature Review	Mon, 8/3/20	Tue, 8/4/20	Project lead
2.1.2	Performance Theory	Wed, 8/5/20	Fri, 8/7/20	Project lead
2.2	Design	-	-	-
2.2.1	Final Vehicle Design	Mon, 8/17/20	Wed, 8/19/20	Project lead
2.2.2	Final Test Equipment and Design	Thu, 8/20/20	Fri, 8/21/20	Project lead
3.0	**Construction**			
3.1	Procurement	-	-	-
3.1.1	Equipment Procurement	Mon, 8/24/20	Mon, 8/24/20	Project lead
3.2	Hardware	-	-	-
3.2.1	Motor Test Stand Construction	Tue, 8/25/20	Thu, 8/27/20	Project lead, Test stand materials
3.2.2	Vehicle Construction	Mon, 9/14/20	Fri, 9/18/20	Project lead, Air vehicle materials
3.3	Software	-	-	-
3.3.1	Flight Controller Programming	Mon, 9/21/20	Fri, 9/25/20	Project lead
4.0	**Test and Evaluation**			
4.1	Testing	-	-	-
4.1.1	Motor Testing	Mon, 8/31/20	Wed, 9/2/20	Project lead
4.1.2	Vehicle Testing	Mon, 9/28/20	Thu, 10/1/20	Project lead
4.2	Data Analysis	-	-	-
4.2.1	Motor Test Data Reduction	Mon, 9/7/20	Wed, 9/9/20	Project lead
5.0	**Data Analysis and Reporting**			
5.1	Data Analysis	-	-	-
5.1.1	Performance Data Analysis	Mon, 10/5/20	Mon, 10/5/20	Project lead
5.1.2	Performance Modeling	Tue, 10/6/20	Wed, 10/7/20	Project lead
5.1.3	Reliability Data Analysis	Thu, 10/8/20	Thu, 10/8/20	Project lead
5.1.4	Stability Data Analysis	Fri, 10/9/20	Fri, 10/9/20	Project lead
5.2	Reporting	-	-	-
5.2.1	Final Project Reporting	Mon, 10/12/20	Fri, 10/16/20	Project lead

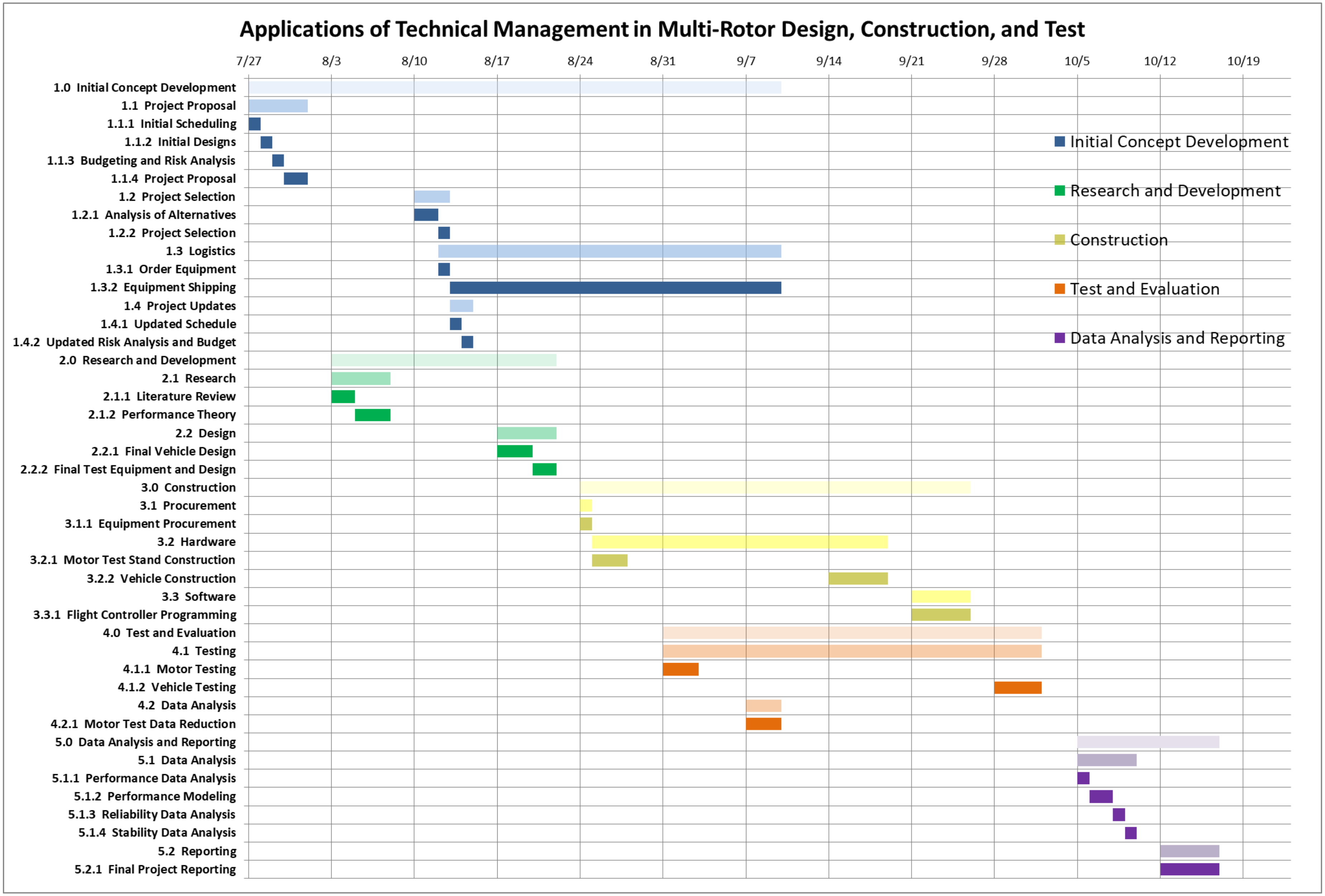

Figure A-3: Project Gantt Chart

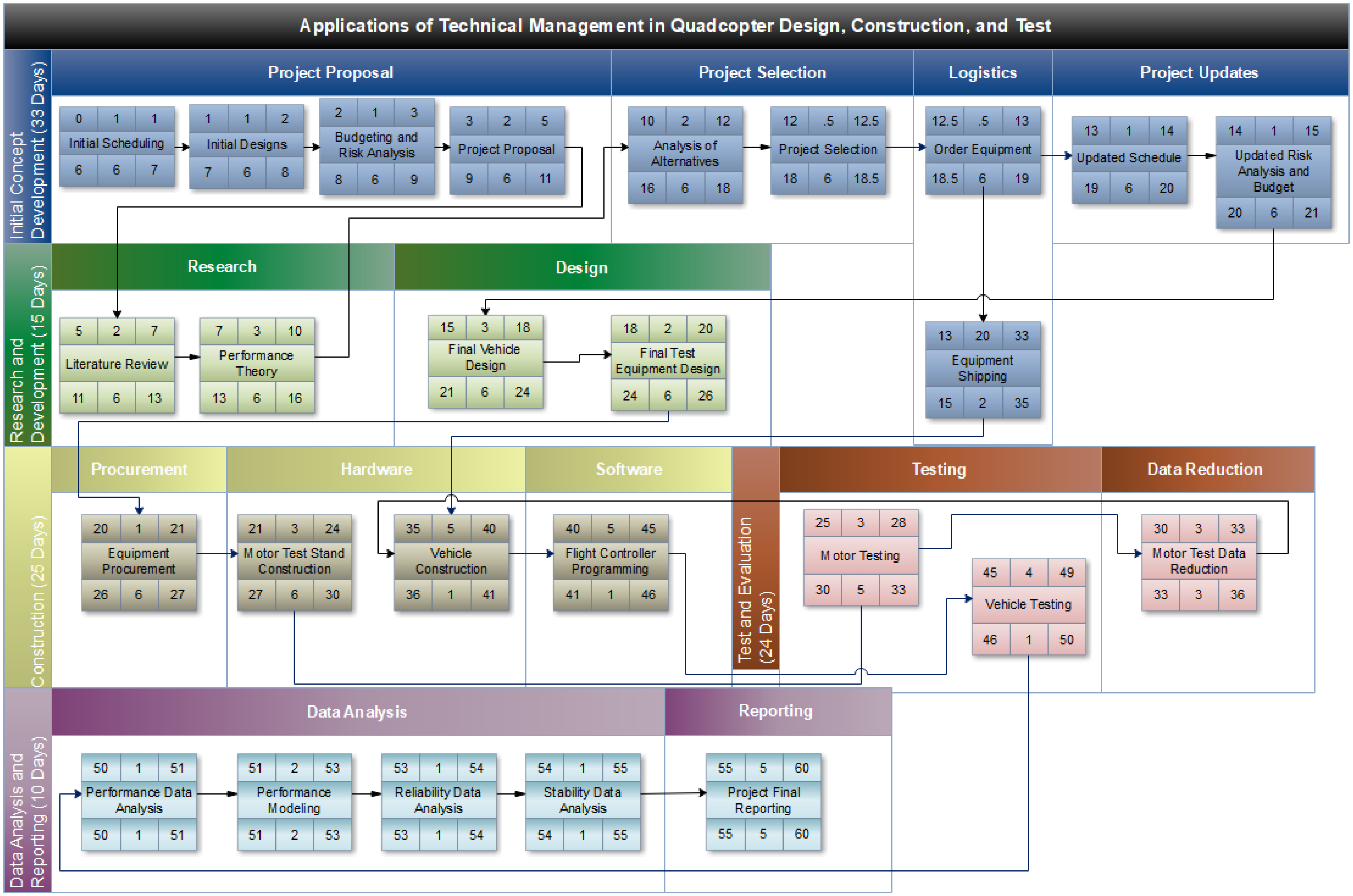

Figure A-4: Project PERT Chart

Figure A-5: Project Selection AHP Initial Valuations

Alternative Projects	Evaluation Criteria		
	Value of Technical Data	Project Cost	Technical Risk
90mm Custom Brushed	3	$42.00	9
110mm Brushless	8	$116.00	4
300mm Brushless	5	$55.00	2

Figure A-6: Project Selection AHP Pairwise Comparisons

	Value of Technical Data	Project Cost	Technical Risk
Value of Technical Data	1	7	3
Project Cost	0.14	1	0.2
Technical Risk	0.33	5	1

Figure A-7: Project Selection AHP Normalized Pairwise Comparisons and Weights

	Value of Technical Data	Project Cost	Technical Risk	Weight
Value of Technical Data	0.67	0.53	0.71	0.64
Project Cost	0.096	0.076	0.04	0.073
Technical Risk	0.22	0.38	0.23	0.28

Figure A-8: Project Selection AHP Technical Data Pairwise Comparisons

Criterion: Value of Technical Data			
	90mm Custom Brushed	110mm Brushless	300mm Brushless
90mm Custom Brushed	1	0.14	0.2
110mm Brushless	7	1	3
300mm Brushless	5	0.33	1

Figure A-9: Project Selection AHP Technical Data Normalized Pairwise Comparisons

Criterion: Value of Technical Data				
	90mm Custom Brushed	110mm Brushless	300mm Brushless	Average
90mm Custom Brushed	0.08	0.10	0.05	0.07
110mm Brushless	0.54	0.68	0.71	0.64
300mm Brushless	0.38	0.23	0.24	0.28

Figure A-10: Project Selection AHP Project Cost Pairwise Comparisons

Criterion: Project Cost			
	90mm Custom Brushed	110mm Brushless	300mm Brushless
90mm Custom Brushed	1	7	3
110mm Brushless	0.142857143	1	0.1666667
300mm Brushless	0.333333333	6	1

Figure A-11: Project Selection AHP Project Cost Normalized Pairwise Comparisons

Criterion: Project Cost				
	90mm Custom Brushed	110mm Brushless	300mm Brushless	Average
90mm Custom Brushed	0.68	0.50	0.72	0.63
110mm Brushless	0.10	0.07	0.04	0.07
300mm Brushless	0.23	0.43	0.24	0.30

Figure A-12: Project Selection AHP Technical Risk Pairwise Comparisons

Criterion: Technical Risk			
	90mm Custom Brushed	110mm Brushless	300mm Brushless
90mm Custom Brushed	1	0.125	0.1111111
110mm Brushless	8	1	0.3333333
300mm Brushless	9	3	1

Figure A-13: Project Selection AHP Technical Risk Normalized Pairwise Comparisons

Criterion: Technical Risk				
	90mm Custom Brushed	110mm Brushless	300mm Brushless	Average
90mm Custom Brushed	0.06	0.03	0.08	0.05
110mm Brushless	0.44	0.24	0.23	0.31
300mm Brushless	0.50	0.73	0.69	0.64

Figure A-14: Project Selection AHP Results Summary

Evaluation Criteria	Weight of Criteria	Alternatives: Projects		
		90mm Custom Brushed	110mm Brushless	300mm Brushless
Technical Data	0.64	0.07	0.64	0.28
Project Cost	0.07	0.63	0.07	0.30
Technical Risk	0.28	0.05	0.31	0.64
Total Score		0.10947003	0.5055837	0.384946

Figure A-15: Generic Project Risks

Generic Project Risks	
Probability of occurrence	0.5
Risk impact	0.3
Overall Risk Factor	**0.65**
Moderate-Risk Project overall (Mod-high)	

Figure A-16: Platform-specific Risks

Platform-Specific Risks						
	90mm Custom	110mm Performance	250mm Performance	330mm Performance	90mm Brushed	1m Performance
Probability of occurrence	0.54	0.40	0.40	0.37	0.43	0.50
Risk impact	0.39	0.23	0.23	0.30	0.38	0.52
Overall Risk Factor	0.72	**0.54**	0.54	0.56	0.64	0.76

Figure A-17: Overall Project Risk by Platform

Overall Project Risk by Platform						
	90mm Custom	110mm Performance	250mm Performance	330mm Performance	90mm Brushed	1m Performance
Probability of occurrence	0.53	0.46	0.46	0.44	0.46	0.50
Risk impact	0.36	0.27	0.27	0.30	0.34	0.45
Overall Risk Factor	0.70	**0.60**	0.60	0.61	0.64	0.73

Figure A-18: Run 1 Static Thrust Test Data

Pulse (us)	V	A	W	kV	Measured RPM	Measured Thrust (g)	Predicted Thrust (g)	Error %
1100	12.39	0.27	3.5	6000	7500	0	4	100%
1200	12.26	1.29	17.1	6000	11800	5	15	67%
1300	12.11	3.28	30.7	6000	15300	30	31	4%
1400	11.9	6.03	73.5	6000	20000	50	49	3%
1500	11.67	8.61	81.9	6000	24500	55	66	17%
1600	11.25	10	120	6000	28300	70	83	15%
1700	10.9	11.6	127	6000	32000	90	98	8%
1800	10.74	10	100	6000	36100	115	132	13%
1900	10.48	9	107	6000	39600	140	164	15%
2000	10.39	10	110	6000	44100	160	190	16%

Figure A-19: Run 2 Static Thrust Test Data

Pulse (us)	V	A	W	kV	Measured RPM	Measured Thrust (g)	Predicted Thrust (g)	Error %
1100	11.9	0.3	4.1	6000	6800	0	4	100%
1200	11.9	1.4	16.6	6000	10400	10	14	29%
1300	11.9	3.1	36.9	6000	15600	20	30	34%
1400	11.9	5.8	68.7	6000	19400	40	49	18%
1500	11.5	8.2	94.0	6000	25200	60	65	7%
1600	11.5	10.4	119.9	6000	29300	75	86	13%
1700	11.0	10.9	120.3	6000	31900	95	104	8%
1800	11.1	11.4	126.8	6000	33400	125	135	7%

1900	11.0	11.7	129.1	6000	42200	170	165	3%
2000	11.0	12.4	136.2	6000	48500	190	196	3%

Figure A- 20: Average Static Thrust Test Data

Pulse (us)	V	A	W	kV	Measured RPM	Measured Thrust (g)	Predicted Thrust (g)	Error %
1100	12.2	0.3	3.8	6000	7150	0	4	100%
1200	12.1	1.3	16.9	6000	11100	8	15	49%
1300	12.0	3.2	33.8	6000	15450	25	31	19%
1400	11.9	5.9	71.1	6000	19700	45	49	8%
1500	11.6	8.4	87.9	6000	24850	58	65	12%
1600	11.4	10.2	120.0	6000	28800	73	85	14%
1700	11.0	11.2	123.7	6000	31950	93	101	8%
1800	10.9	10.7	113.4	6000	34750	120	133	10%
1900	10.8	10.4	118.0	6000	40900	155	165	6%
2000	10.7	11.2	123.1	6000	46300	175	193	9%

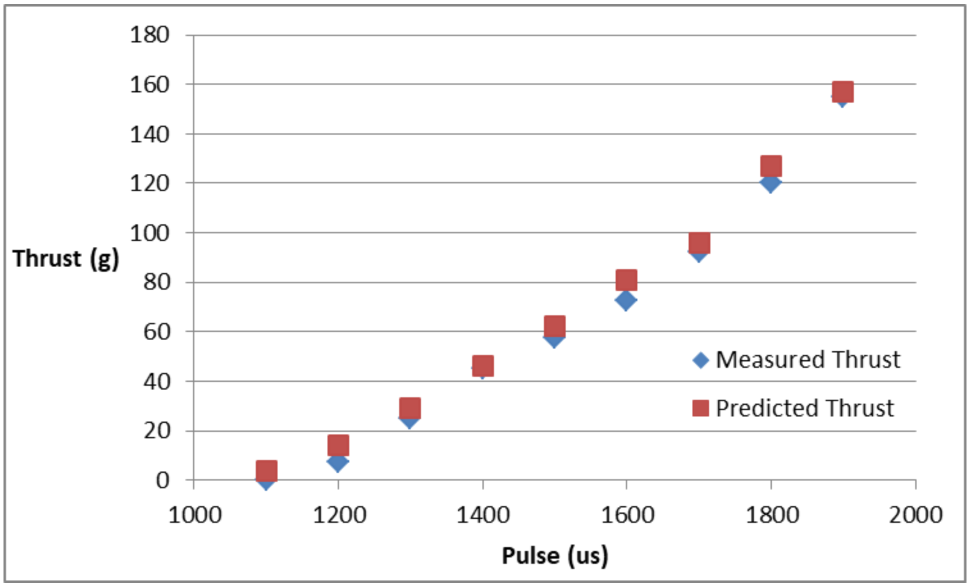

Figure A-21: Thrust (g) versus Pulse (µs)

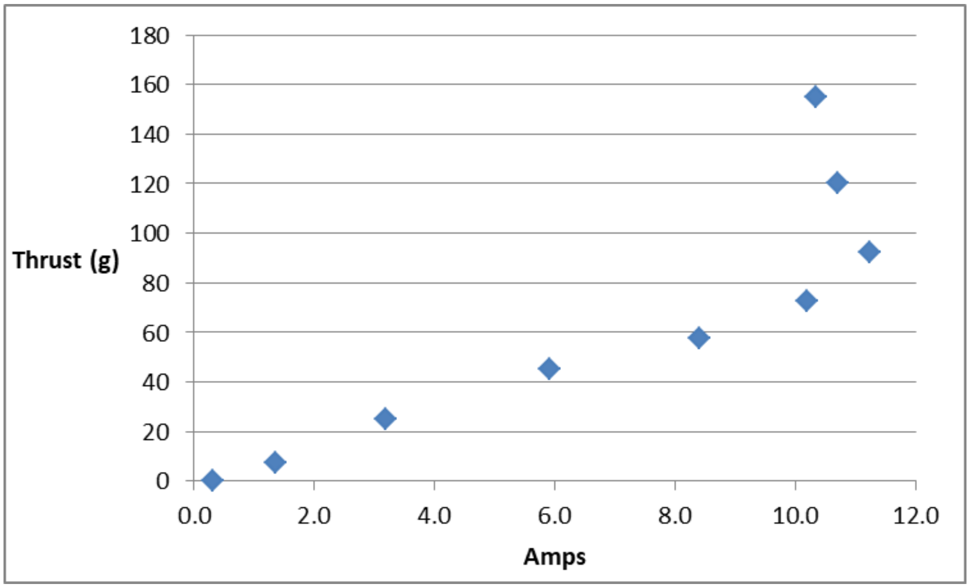

Figure A-22: Measured Thrust versus Amps

Author Biography

LT Robert Rountree grew up in Atlanta, GA, where he attended Tucker High School and was a member of the swim team and a sailing instructor. Rob graduated from the United States Naval Academy in Annapolis, MD in 2012 with a Bachelor's of Science in Economics, and commissioned as an Ensign in the U.S. Navy. He trained as a Naval Flight Officer (NFO) under instruction for two years before earning his wings in August 2014. He flew the E-2C Hawkeye for three years at VAW-116 in California before transferring to VX-30 in 2017, where he flew the P-3C Orion and RQ-23A TigerShark Unmanned Aircraft System. He was selected to attend the U.S. Naval Test Pilot School as a member of Class 157 and graduated as a Test NFO in June 2020. He then returned to VX-30 in Point Mugu, where he tests the E-2D Hawkeye and RQ-23A TigerShark. He lives in Ventura, CA, with his beloved wife and daughter.