Test Plan, Testing Shifting Payloads on Multi-Rotorcraft

REGULATIONS TO ENSURE eVTOL CONTROL WITH POTENTIAL SHIFTING PAYLOAD

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The Test Plan, Testing Shifting Payloads on Multi-Rotorcraft document presents planned test flights, the key research goals answered by the planned tests, reiterates how the planned tests provide over 2x the required amount of data to answer key research questions with statistical robustness, and discusses key drivers in test planning. Furthermore, the Test Plan, Testing Shifting Payloads on Multi-Rotorcraft document presents the addition of top-priority research areas for analysis including multi-rotorcraft take-off and landing safety and stability with power and thrust issues. Specifically, analysis of the risk areas of multi-rotorcraft take-off and landing with power and thrust issues is presented, key risk areas within this system are defined, and a test plan to answer top-priority research questions in this area is given. Trades against initially planned duplicate and redundant tests regarding standard flight with shifted payloads are made in order to accommodate the expanded research questions without adding scope or cost to the initially planned R&D contract.

Contents

1. TESTS, TEST PLANNING, DATA ACQUISITION & GOALS OF RESEARCH

In order to answer the research questions of the R&D contract, the system of the flight vehicle, shifting payloads, and thrust, power, stability and safety ramifications have been modeled and simulated with variance, to determine the optimal input parameters and sample size for test data. In order to record adequate test data, and to provide robust test data including over 2x margin on the amount of data to be gathered to ensure statistical significance of results, flight test plans have been defined. Flight test plans, justification and context is discussed, and commentary surrounding additional expected tests, data margin, and overall testing is presented. Key quantitative and analysis portions from prior analysis and deliverables are presented for context.

In addition to test plans for examining primary research topics, test plans for examining a recently discovered high-priority research area are presented: examining stability and safety of multi-rotorcraft during take-off and landing when thrust and power issues occur. This system is discussed, types of thrust and power issues that occur with multi-rotorcraft are discussed, typical vehicle responses to power and thrust issues are discussed, and the key tests and most critical components of this system to be examined are defined.

By prescribing flight tests based on statistical simulations of the flight-with-shifting-payload system, and planning flight tests around the most critical areas of potential loss of thrust during take-off and landing, the presented flight tests produce robust data with margin to answer R&D contract research goals and significant into the key risk areas and methods for risk reduction to multi-rotorcraft UAV during take-off and landing.

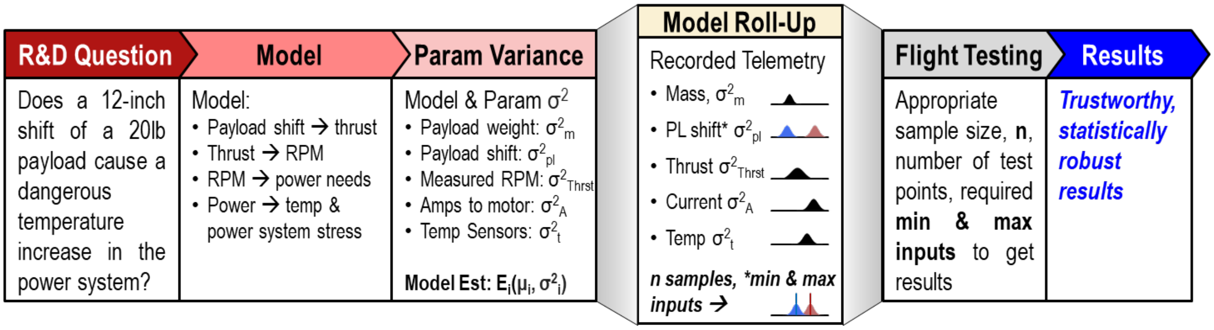
Top Testing Goals

The key research questions that are answered through the flight test plan and resulting analysis include:

- Does a shift in payload require a thrust differential across motors to enable a flight vehicle to remain stable
- Does a thrust differential cause RPM strains on motors producing added thrust
- Does a thrust differential cause power strains on a flight vehicle power system
- Does a vehicle experience instability during flight if a payload CG changes
- What happens if a multi-rotorcraft loses a motor during take-off or landing?
- What happens if a multi-rotorcraft loses partial power to a motor during take-off and landing?
- Do shifting payloads multiply the danger to power and thrust system issues during take-off and landing?

2. METHODOLOGY: INITIALLY PLANNED STABILITY & SAFETY WITH SHIFTING PAYLOADS

As described in Deliverable 3.1 Model and Variable Planning and Analysis and Deliverable 4.1 4.1 Payload Center-of-Mass Detection System Designs, the methodology used to answer the primary and initial research questions is: determine research questions, define system of flight vehicle flying and required measurements to answer research questions, examine variance of inputs and measurements, determine required input parameters from edges of input space and sample size to measure statistically different responses from various inputs to answer research questions. This is accomplished using input parameters for the system, models of expected results, and sampling from inputs and system models using estimated variance in order to determine a set of inputs that result in outputs with different means, that are statistically significant based on their distributions, and distribution comparison p-values to select as inputs for flight tests.



R&D Question

Does a 12-inch shift of a 20lb payload cause a dangerous temperature increase in the power system?

Model

Model:
- Payload shift → thrust
- Thrust → RPM
- RPM → power needs
- Power → temp & power system stress

Param Variance

Model & Param σ^2
- Payload weight: σ^2_m
- Payload shift: σ^2_{pl}
- Measured RPM: σ^2_{Thrst}
- Amps to motor: σ^2_A
- Temp Sensors: σ^2_t

Model Est: $E_i(\mu_i, \sigma^2_i)$

Model Roll-Up

Recorded Telemetry
- Mass, σ^2_m
- PL shift* σ^2_{pl}
- Thrust σ^2_{Thrst}
- Current σ^2_A
- Temp σ^2_t

n samples, *min & max inputs →

Flight Testing

Appropriate sample size, **n**, number of test points, required **min & max inputs** to get results

Results

Trustworthy, statistically robust results

Tracing <u>research questions</u> → <u>models</u> → <u>input data variance, parameter space & sensor variance</u> → <u>required test inputs and sample size</u> ensures that we test the right parameter inputs, get the right number of test data points, and end up with statistically robust results

3. METHODOLOGY: TAKE-OFF & LANDING WITH POWER, THRUST AND PAYLOAD ISSUES

The methodology used to examine take-off and landing with shifting payloads is a little bit different than the methodology planned for analysis and data acquisition for control and stability of the flight vehicle as described in the initial contract. Based on gaining an increased understanding of the research areas of top priority over the past year, in collaboration with and at the direction of R&D contract sponsors, it has been determined that including tests for stability, control and safety during take-off and landing with thrust and power issues, as well as shifting payloads, will be included in the investigative efforts. This is a great topic with far-reaching ramifications pending results, so Rhoman is excited to include this based on test methods and scope-trades as described in the present document.

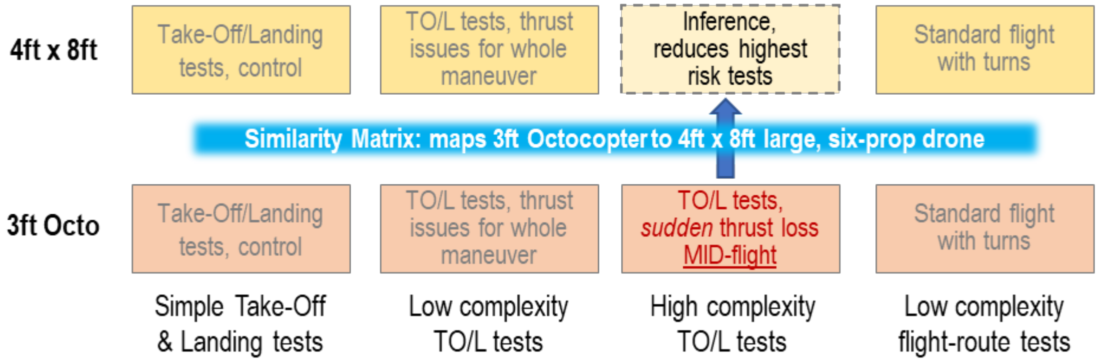
Two main factors dictate a separate methodology for examining this system, 1) the nature of the types of issues that a multi-rotorcraft may face during take-off and landing and 2) the addition of these tests to the initial research scope without their inclusion from the outset. The key driver is the high-risk of flying the main flight test platform close to the ground with intentionally faulty or disabled thrust systems and jeopardizing the flight test vessel for initially planned tests.

Examining stability and control despite thrust and power issues, and especially sudden thrust and power issues during take-off and landing doesn't use the same large set of continuously measured data from flight. Examining the take-off and landing system, especially examining sudden thrust and power issues that may arise, generates data points that are partly more qualitative, examining the system as a while during such issues, and also generates more sparse data. When the key data point is how a vehicle responds to a sudden loss of power or thrust during take-off or landing, a single data point is generated during a power drop or cut during a test flight.

By including a 3ft octocopter initially used as an avionics system test bed, and strategically planning tests to show similarities between the two flight test platforms, testing can be performed that robustly answers desired take-off and landing questions while avoiding risk to the 4ft x 8ft flight vehicle and minimizing delays or scope creep.

- Perform standard take-offs and landings with the 3ft UAV and the 4ft x 8ft UAV
- Perform take-offs and landings with known power and thrust issues enacted before take-off and landing with both the 3ft UAV and the 4ft x 8ft UAV
- Establish Similarity Matrix to determine similarities between vehicles and test data response between the 3ft UAV and the 4ft x 8ft UAV
- Perform take-offs and landings with the 3ft UAV with sudden power drops and motor cut-outs during maneuvers
- Make inferences about how the ft x 8ft vehicle would respond with sudden power drops during such maneuvers
- If analysis shows that the same tests can be done with he 4ft x 8ft six-propeller flight vehicle, perform these same tests

Specifically, the same low-risk take-off and landing tests are performed by both the 4ft x 8ft flight vehicle and the 3ft octocopter, similarity mapping is performed, and higher-risk tests are performed with the 3ft octocopter, allowing for trustworthy inference of the behavior of the larger 4ft x 8ft flight vehicle in those same circumstances based on the similarity mapping performed.



By creating a solid basis for comparison between the 3ft octocopter and the 4ft x 8ft six-propeller drone, we can perform highest complexity tests with the 3ft octocopter and make valid inferences about the large 4ft x 8ft six-propeller drone; analysis will determine if higher-complexity tests where power is lost during the middle of an upward-acceleration-while-rotating take-off with the 4ft x 8ft flight vehicle

4. KEY VARIABLES & SYSTEMS FOR INCLUSION IN TAKE-OFF & LANDING TESTS

Key Variables for Consideration with Addition of Take-Off and Landing Tests

Beyond the examination of key input variables and models that describe the research system as presented in prior Deliverables 3.1 Model and Variable Planning and Analysis and 4.1 Payload Center-of-Mass Detection System Designs, a few additional areas for consideration have arisen based on the new inclusion of take-off and landing with thrust and power issues and shifting payload.

Scalability, 4ft x8 ft to 3ft Tarot UAV

Determining and estimating scalability of test results between the 3ft octocopter, 4ft x 8ft six-propeller drone, and beyond to larger vehicles, is built into the test plan. By examining specific maneuvers and the same maneuvers with each platform, at the multiple ends of the mission profile spectrum, we will have a great set of information to use to determine and create the Scalability Matrix that maps how the large and small UAV behave relative to each other in different flight scenarios.

The largest difference is the number of propellers (6 vs. 8) and the shape (rectangular/oblong instead of symmetric) – but by summing up thrusts in a given quadrant of a vehicle, we can actually merge information and are only slightly limited by the different numbers of propellers. Applicability and extrapolation of the Scalability Matrix to larger and heavier vehicles will also be performed.

Representative Take-Off and Landing Flight Paths

A take-off and landing flight path not just up and down, but typically, a VTOL take-off at the start of a flight mission would including rising up vertically while beginning to travel in a specific direct. In order to mimic an expected ideal take-off trajectory, we anticipate a rise of 5 to 15 feet, a horizontal movement of 2 to 10 feet, and a rotation of 30 to 60 degrees. A spiral-ascent may also be used in testing as an ideal example take-off.

Landing trajectories would include starting with horizontal flight, slowing, and lowering the ground. It is expected that in typical landing maneuvers, a vehicle is less likely to rotate. Landing test flights are expected to include flying in a forward direction 5 to 15 feet above the ground, slowing, and descending at a rate of approximately 2 feet down for every 1 foot forward.

How Power and Thrust Can Face Issues and How UAV May Respond

In order to examine control, stability and any dangerous issues for multi-rotorcraft during take-off and landing with shifted, non-centered, or shifting payloads, a proper method of reducing power or thrust to a motor must be used. One of the key notes to be aware of when performing tests to examine the loss of power or thrust to a motor during take-off and landing is the variable nature of the methods that vehicle may use to account for motor issues, as well as the variable nature of thrust issues that may arise. There are multiple options for accomplishing this:

Partial Motor Cutoff/Thrust Impediment

- Reduce amount of power that flows through wires to motor
- Set a software switch in the code to scale down the percent of thrust sent to a given motor
- Use a smaller propeller on the motor without updating thrust and RPM curves

Complete Motor Cutoff/Thrust Impediment

- Disconnect power wires to motor
- Set a software switch in the code to stop all signal to the motor
- Remove the propeller from the designated propeller

System Knowledge of Motor Loss

Additionally, a key area to address is whether or not a controller knows that the motor has failed or is degraded. If a system does not know that a motor has failed versus if it is aware that it has lost a motor, it may respond and recover differently.

Various pieces of a Rhoman control system developed outside the scope of the present R&D contract includes live determination of number of motors of a flight vehicle and adapting the controller to this potentially variable number of motors. Typical and generally available multi-rotorcraft control systems don't adapt to variable numbers of motors or detect the loss of a motor. Test to examine this system may be included. Additionally, it may be possible to include tests to investigate what happens if the controller thinks that a motor is bad, when it is in fact a bad sensor reading. This would be equivalent to seeing how the drone flies when it thinks it only has 5/6 or 7/8 motors when in fact it has all of its motors.

Asymmetric Flight Vehicles

If the vehicle is asymmetric in some way (either due to different rotor sizes or due to rotor placement), which rotor fails will make a difference. Incorporating this concept into tests would be wise, and can be included by disengaging certain propellers of the flight vehicles. For the octocopter, this would entail disabling a motor while in a symmetric arm position, and disabling a motor while in an asymmetric arm position. For the 6x8, this would entail disabling either a side thruster or a front/rear thruster. Theoretically, the octocopter can still land with 5/8 motors disabled, while the 6x8 can land with 3/6 disabled, assuming it is the right combination for each of those. Tests to examine the results of asymmetric layouts by disengaging multiple and specific rotors will be added based on programmatic judgement and technical expertise regarding their utility in adding to test data and feasibility for the aircrafts.

Dealing with thrust issues:

- Increase RPM: if a multi-rotorcraft doesn't respond as desired based on motor not delivering the desired thrust, a system may automatically keep increasing power and RPM to a motor; this is most likely to occur when a system uses a blind-thrust-feedback loop, ie, where the system is designed using a simple PID controller when increases thrust or power to a given motor while the vehicle's measured state is not in the desired state
- Shut-off motor: if a multi-rotorcraft determines that one motor is not working properly, it may shutoff that motor, and switch to an n-1 control system, where it enacts a new control system designed to account for a motor issue; most multi-rotorcraft can still fly if one motor goes out
- System adaptation: if a motor partially fails, and delivers only a partial thrust, it would be possible for a system to detect the partial thrust of the motor, and update tuning parameters or a control system to still use that reduced capability motor; this is the least common solution and requires more advanced methods

Thrust and power issues that may arise:

- Lost propeller: if a propeller breaks off of it's mounting, the axis could still spin, but there would be no thrust
- Partially broken propeller: if a propeller breaks during use, it may still provide some thrust, it may create an uneven torque and wobble on the flight vehicle, or it may create an unintentional negative thrust
- Wiring disconnects or breaks: if wiring breaks, a motor may stop working entirely, either from loss of signal or loss of power; this may occur between the power source and the speed controllers for the motor or between the speed controllers for the motor and the motor
- Wiring partial separations: these may result in intermittent motor failure, or stuttering, of a motor
- Thrust issues may arise before or during a take-off or landing maneuver, ie, the issue may arise during the action or before the action; this would require the system to adjust *during* a take-off and landing, as opposed to enacting the take-off and landing with a known n-1 set of motors and capability

Highest Risk Scenarios

Based on discussion of how power and thrust may fail for a multi-rotorcraft motor, and possible expected vehicle responses, the most dangerous situation is when power is reduced or lost, as a surprise, midway through a take-off or landing. Loss of thrust is a encompasses loss in power to motors, as well as other issues that could reduce or eliminate thrust.

Thrust Reduction Before Take-Off/Landing

Most multi-rotorcraft can fly missing a propeller, and flight with reduced thrust to a given propeller is also generally very doable – from an engineering perspective if the flight vehicle has control systems in-place to account for the different motor thrust curves, along with the knowledge of what the reduced thrust may be, and adequate power to supply additional RPMs to the engine.

If the vehicle knows about the thrust issue prior to attempting a take-off or landing, it is likely a very surmountable issue. Assuming that the vehicle knows about the issue prior to flight, it is a low risk test. Tests will be performed using reduced power (50%) power, throughout an entire take-off and landing test.

Thrust Total-Loss Before Take-Off/Landing

Likewise, if a multi-rotorcraft knows that it is missing a motor, it can generally still fly. Provided that the flight vehicle has control systems programmed into it that work with n-1 motors, and that it knows that a motor fails, it would be able to accomplish a flight in this diminished capacity. Each remaining motor would function in a less power-optimal space based on the initial design and selection of the motors, but provided that the vehicle had the right control system onboard, it would still be able to avoid a crash.

Thrust Reduction or Loss DURING Take-Off/Landing

If a motor or thrust system fails due to power or other issues *during* a take-off or landing maneuver, this is where the highest danger occurs.

A drone may take a few moments to determine that is has experienced a loss of thrust, and to account for such an issue – there may not be time for the drone to make such a recognition, and recover adequately, if such a scenario occurs while close to the ground or other obstacles. Furthermore, there may be larger torques, torque differentials, or jerking motions due to the sudden loss of propeller that may cause the drone to fly erratically until it can re-stabilize – again, this is most dangerous when near to the ground or other obstacles.

The most dangerous part of taking-off and landing when a thrust or power system issue arises is the drone not being aware of such an issue, and continuing to send command signals to its motors as if there was no issue, especially when there is little time to restabilizing due to nearby obstacles.

This is how we determine the most essential piece of this system to examine: the moment when a multi-rotorcraft drone suddenly and surprisingly experiences a power or thrust reduction during vertical and lateral acceleration movement, likely with rotation – a take-off and landing. This is the prime driver in setting up the planned tests: generating context through tests with thrust issues thorught an entire take-off and landing, and including specific tests, once background context has been established, to examine the moment that power or thrust is lost or diminished.

Additional tests beyond the presented test set may be added or substituted in order to examine the effects of a control system that can adapt to variable numbers of motors on the stability and safety of the control system.

Unhinged Motor without Proper Valid Feedback

One of the actual worst case scenarios would be if an ESC (not a motor) is both malfunctioning and not communicating, meaning it is generating totally random thrusts or spinning backwards at max speed or something tremendously erroneous like this. This would be an expansion of the case where a thrust change happened suddenly and by surprise/without knowledge to the flight vehicle, as it assumes that this scenario would be short-lived before some other monitoring system figures out what is going on and kills power to or restarts that ESC. Tests to investigate such a scenario may be included, but are not the prime focus of testing.

Key Telemetry and System Data for Measurement

When investigating safety and stability during take-off and landing, generally the same telemetry is available as during flight, but various other pieces of system information become more relevant

- Power sent to each motor
- Power used by each motor
- RPMs of each propeller
- When the motor stops working (if it stops working at a point during the test versus before the test)
- The angle and state of the vehicle at points during take-off and landing
- Vibration, oscillations, wiggle, wobble, or other vehicle characteristics during take-off and landing
- Wind, as take-off and landing are shorter events, and occur closer to the ground, wind and environmental factors play a larger role, and have less of an opportunity to balance out or average out over long flights

Combining potential issues, typical vehicle responses, key research goals on the matter, and a feasible test campaign, we determine that examining flight vehicle response during take-off and landing with standard power, with half power, with cut power, and following these results with power lost midway through a take-off or landing, would be most beneficial. Additional details are provided below in Flight Tests section.

Research	Stratification & Analysis	Results
Examining flight vehicle response during take-off and landing:	I. Standard power II. Half power III. 100% cut power **IV. Power lost <u>midway through</u> a take-off or landing**	Insights into key safety ramifications of loss of power and or thrust during take-off and landing maneuvers

5. TEST ADDITIONS AND SCOPE CHANGE, TRADING NEW AND REDUNDANT TESTS

In order to include an adequate number of tests to examine take-off and landing with thrust and power issues, as well as shifted and shifting payloads, various trades were made against previously planned backup and redundant tests. We are not able to increase the scope of the initially planned R&D contract, and it has been communicated to not increase the scope or take on and additional research that creates and cost or schedule delays while answering the added research questions, so to this end, strategic project trades are made.

Because an ideal way to examine take-off and landing with power and thrust issues along with shifting payloads entails using Rhoman's 3ft avionics test-bed drone, it means that multiple tests can be added that in sum, take the same time as a smaller number of flight tests with the large 4ft x 8ft six-propeller flight vehicle, we are able to accommodate the added research questions and goals without a net-positive increase to R&D contract cost.

Additions	Subtractions
• Add multiple take-off and landing tests with 3ft octocopter initially planned for avionics system testing • Add select set of take-off and landing tests with 4ft x 8ft six-propeller flight vehicle • Add power-reduction hardware, software or system for select motors on both the 3ft UAV • Add power-reduction hardware, software or system for select motors on both the 4ft x 8ft vehicle • Add ground-cover UAV protection system for take-off and landing tests • Add payload shift sensors to the 3ft octocopter (or pre-planning PL-CG system and mounting)	• Select one PL-CM system as a 'main' system • Do not repeat each test with each PL-CM system, instead perform one test with all PL-CM system to verify that they behave similarly, then primary testing routine is done with the main PL-System, not each of them • Remove *requirement* of frame flex tests, focus on stability and power system ramifications of tests

6. FLIGHT TESTS: TAKE-OFF AND LANDING TESTS

Based on the addition of key research questions into take-off and landing of UAV with power and thrust system issues, tests have been planned that leverage an existing Rhoman Aerospace 3ft octocopter asset, as well as the 4ft x 8ft six-propeller flight vehicle as initially planned for the R&D contract. Tests are designed to ascertain safety, stability, control, and power system issues that may arise during take-off and landing when partial or complete thrust and power system issues disrupt a motor and it's thrust.

Goals of Tests

The main focus of the added tests is to determine: what are the issues regarding safety, stability, avoiding a crash, and power system ramifications when a multi-rotorcraft is taking-off or landing with thrust or thrust-affecting power system issues. The top priority is to examine safety issues when a craft experiences a sudden loss of thrust to a motor during a take-off or landing maneuver, an additional key focus, albeit secondary, is the aforementioned system with a live-shifting payload.

- Take-off and landing are the most dangerous parts of any flight mission, during such maneuvers, including upward or downward acceleration in combination with lateral movement and possible rotation, how does the full or partial loss of power or thrust affect a multi-rotorcraft?
- What happens if a multi-rotorcraft loses a motor during take-off or landing?
- What happens if a multi-rotorcraft loses partial power to a motor during take-off and landing?
- Do shifting payloads multiply the danger to power and thrust system issues during take-off and landing?

Flight Tests Answer Research Questions

Research Question	Quantifiable System to Test	Test Input Determination	Parameter Space Inputs	Flight Tests
During take-off and landing, how does the full or partial loss of power or thrust affect a multi-rotorcraft?	How much does the UAV tilt when there is a power or thrust issue? What qualitative issues are visible, and when?	Take-off and landing with partial power or thrust reduction and complete power or thrust reduction	Amount of power or thrust loss Power or thrust loss before flight Power of thrust loss during flight Flight vehicle control system knowledge of power/thrust issues Flight vehicle telemetry and trajectory, weather, wind	Flight tests as described that create a baseline, examine the system with thrust issues, then test key error point: Determination of flight vehicle performance during take-off and landing Determination of flight vehicle performance and response to thrust and power issues prior to complete maneuver Flight vehicle response characterization of response with loss of thurst/power midway through maneuver Shifting and off-center payloads
What happens if a multi-rotorcraft loses a motor during take-off or landing?	Is there a sudden jerk and one key moment of instability? Can the UAV recover? How much altitude does a UAV lose during a loss or reduction in power? Is there a directional loss of control, beyond elevation loss?	Take-off and landing with partial power/thrust reduction that occurs midway through maneuver		
What happens if a multi-rotorcraft loses partial power to a motor during take-off and landing?				
What type of power and thrust issues are most dangerous to a multi-rotorcraft during take-off and landing?	- Different thrust and power issue inputs - Vehicle responses, including motor power strains, RPM, and stability, sudden tilts of Vehicle	Partial, complete, and surprise power/thrust loss before and during maneuver		
Do shifting payloads multiply the danger to power and thrust system issues during take-off and landing?	If a payload is off center by x-inces, is there a discernable difference in vehicle response of y-RPM or power to certain motors?	Live-shifting and off-center payloads during power/thrust issue take-off and landing	Above along with off-center and live-shifting payload	

Driving Factors of Test Set Definition

- Tests are performed in 'pairs' – a take-off test is followed by a short flight to setup a landing test, and a landing test is performed with the same setup as take-off test
- Tests are performed in two directions at once, to account for wind direction both with and against the flight vehicle; a vehicle performs a take-off test facing a direction, goes into forward flight to prepare for a landing test, lands, and then repeats the same take-off test, flight, and landing, in the opposite direction, landing in the initial take-off location
- It is assumed that tests won't be performed in constant, strong wind, but average random wind gusts that occur during testing are acceptable and expected
- There are various pieces of the take-off and landing system to investigate, but based on analysis presented in the document, the most important piece of the system to examine is when a motor loses partial or complete thrust or power midway through a take-off or landing

Flight Tests to be Performed

Minimum Tests to be Performed

In order to setup tests that answer key research questions and are broadly feasible in the scope of the R&D contract, a minimum set of tests has been designed that will be performed on a best-effort basis. The set of tests aims to study issues that arise during a sudden partial or complete loss of power during a take-off or landing, and builds up to this through essential context from data from take-offs and landings with partial or full motor outages beginning before take-offs and landings.

Take-off and landing tests are 'coupled' – ie, when a certain vehicle setup is created for a take-off test, a landing test is planned using the same setup. This allows for maximum efficiency when testing, and also allows for the examination of take-off and landing with consistent environmental conditions. Overall test set may be amended based on conversations with sponsor, additional system information obtained during testing, and, or, other research and logistic factors that may be taken into account based on expertise and experience in UAV testing.

For maximum applicability to typical commercial drones, we will concentrate on our 3ft octocopter drone for testing as it is a symmetric drone configuration. This symmetric configuration means that the resulting data can be better extrapolated and more applicable to other drone configurations currently on the market, as a majority of drones on the market are symmetric configurations.

Test #	Key Development Need	Drone	Take-off Test	Direction	Payload	Landing Test
1	-	Tarot	Take-off, standard	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, standard
2	Pending power-allowance switch	Tarot	Take-off, one motor at half power	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor at half power
3	-	Tarot	Take-off, one motor cut	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor cut
4	-	4x8	Take-off, standard	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, standard
5	Pending power-allowance switch	4x8	Take-off, one motor at half power	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor at half power
6	-	4x8	Take-off, one motor cut	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor cut
7	Pending mid-flight power-allowance switch	Tarot	Take-off, one motor drops to half power midway through upward and lateral acceleration	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor drops to half power midway through downward and lateral acceleration
8	Pending mid-flight power-allowance switch	Tarot	Takes off, motor cuts out halfway through takeoff	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor cuts out midway through landing

9	Pending safety analysis, mid-flight power-allowance switch	4x8	Takes-off, motor drops to half power midway through	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, one motor drops to half power midway through downward and lateral acceleration
10	Pending safety analysis, mid-flight power-allowance switch	4x8	Takes-off, motor cuts out midway through	2x, N, S*	Constant, positioning to be determined based on increased analysis	Land, motor cuts out midway through
Add in multi-direction for environmental factors:				20 Total Tests		

Add in shifting and non-centered payload: **20 Total Flights**

40 Data Points: 20 Take-offs and 20 Landings

**flights to be performed in a there-and-back basis, where each flight goes in opposite directions relative to the wind there and back, and encompasses a take-off, short flight, landing, and return*

Additional planned Tests

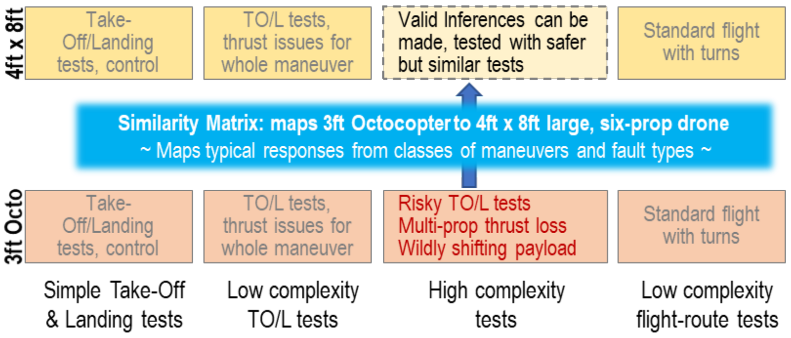
Incorporating live-shifting payloads into the test plan is part of the ideal test case, although additional analysis needs to take place to properly plan these tests and to ensure feasibility. These tests may be included pending analysis and effort levels required.

Test #	Key Development Need	Drone	Take-off Test	Direction	Payload	Landing Test
1	Pending power-allowance switch	Tarot	Take-off, one motor at half power	2x, N, S*	Live shifting payload	Land, one motor at half power
2		Tarot	Take-off, one motor cut	2x, N, S*	Live shifting payload	Land, one motor cut
3	Pending power-allowance switch	4x8	Take-off, one motor at half power	2x, N, S*	Live shifting payload	Land, one motor at half power
4		4x8	Take-off, one motor cut	2x, N, S*	Live shifting payload	Land, one motor cut
5	Pending mid-flight power-allowance switch	Tarot	Take-off, one motor drops to half power midway through upward and lateral acceleration	2x, N, S*	Live shifting payload	Land, one motor drops to half power midway through downward and lateral acceleration
6	Pending mid-flight power-allowance switch	Tarot	Takes off, motor cuts out halfway through takeoff	2x, N, S*	Live shifting payload	Land, one motor cuts out midway through landing
7	Pending safety analysis, mid-flight power-allowance switch	4x8	Takes-off, motor drops to half power midway through	2x, N, S*	Live shifting payload	Land, one motor drops to half power midway through downward and lateral acceleration

8	Pending safety analysis, mid-flight power-allowance switch	4x8	Takes-off, motor cuts out midway through	2x, N, S*	Live shifting payload	Land, motor cuts out midway through

**flights to be performed in a there-and-back basis, where each flight goes in opposite directions relative to the wind there and back, and encompasses a take-off, short flight, landing, and return*

7. FLIGHT TESTS: SCALABILITY, SIMILARITY MAPPING 3FT OCTO AND 4FT X 8FT VEHICLE



Mapping responses of the how the 3ft octocopter behaves with how the 4ft x 8ft six-prop drone behaves under the same conditions allows us to make valid inferences for cases where the 4ft x 8ft UAV cannot be used

Flight test scalability and the Similarity Matrix allow us to make inferences about flight dynamics with the large 4ft x 8ft flight vehicle while reducing risk by avoiding certain high complexity maneuvers with the large 4ft x 8ft flight vehicle. Specifically, by performing the same tests with the 3ft octocopter and the 4ft x 8ft six-propeller drone and creating mapping functions and logic that show how their responses are similar and connected allows us to perform certain tests with the 3ft octocopter, and infer what the behavior and response of the 4ft x 8ft multi-rotorcraft would be. Inferences can be tested by performing similar, but lower-complexity/lower-risk tests with the 4ft x 8ft multi-rotorcraft, and verifying it behaves as expected based on Similarity Matrix estimates.

Ideally, all tests would be performed with both the larger 4ft x 8ft six-propeller flight vehicle and the 3ft octocopter – analysis from low-complexity test flights will dictate the use of the Similarity Matrix. If it is deemed safe to perform sudden complete power and thrust loss with the 4ft x 8ft flight vehicle in the middle of a take-off, that will be performed; if it is deemed too high of a risk to the primary flight test platform for the key research questions in the R&D contract, such tests will be performed with the 3ft octocopter and inferences will be made about the 4ft x 8ft flight vehicle.

Furthermore, the creation and use of the Similarity Matrix allows for better extrapolation to larger flight vehicles. By examining and understanding the differences in response of the large 4ft x 8ft flight vehicle versus the 3ft octocopter, and extrapolating trends slightly upwards, we can begin to understand how larger flight vehicles deal with shifting payloads and power and thrust issues during take-off and landing. Differences in flight vehicle form factor can be accounted for by summing up thrusts in a given quadrant of a vehicle, we can actually merge information and are only slightly limited by the different numbers of propellers.

8. FLIGHT TESTS: STABILITY, SAFETY, AND POWER USE WITH SHIFTING PAYLOADS

As initially planned within the contract and goals of the R&D project, flight tests will occur to answer key research questions regarding control, safety, stability and power system stress and strain with shifting payloads during flight. Tests are using the 4ft x 8ft six-propeller flight vehicle and may include the addition of tests with the 3ft octocopter.

Goals of Tests

Key research areas to be answered include:

- If a payload of a certain weight shifts by a certain amount, what change in thrust per motor is required to maintain stability during hover, during forward flight, while turning
- How quickly must a flight vehicle adjust thrust per motor, and change motor RPMs, in order to maintain stability during hover, during forward flight, while turning
- Are there determinable safety envelopes based on payload mass and shape, flight vehicle mass, maximum possible shift amount, vehicle thrust capabilities, and flight route (maximum g-force/type of mission/turning) that are thresholds for maintaining or losing control of the vehicle such that it crashes into the ground
- Are there determinable safety envelopes based on payload mass and shape, flight vehicle mass, maximum possible shift amount, vehicle thrust capabilities, and flight route (maximum g-force/type of mission/turning) that are thresholds for maintaining or losing control of the vehicle such that it deviates significantly from its intended flight path
- What decrease in margin is achievable using non-hardware solutions to shifting CG, i.e., payload tethers, accounting for shifting CG within control systems, specific allowable flight dynamics or g-forces, etc
-

Flight Tests Answer Research Questions

The research question traceability matrix combines the research questions we want to answer, the models that describe the system we're investigating, the expected variance and error within our research system, and lets us determine, based on all of these factors, what input variables we need and how many tests we need to achieve statistically robust results. Test set quantification is presented in greater detail below, in Test Set Quantification, Shifting Payload on 4ft x 8ft Flight Vehicle.

Research Question	Quantifiable System to Test	Test Input Determination	Parameter Space Inputs	Flight Tests
Does a shift in payload require a thrust differential across motors to enable a flight vehicle to remain stable	Does a payload shift of x-lbs moving y-inches cause a measurable change in thrust per motor	Sample payload CG shifts with payload CG system variance and record thrust-per-motor results	Based on expected maximum payload CG shift detection variance, shifting a 30-lb payload 8-inches to the side and 14-inches forward while recording 75 data points yields statistically robust, measurable research results	Based on techniques to average data over 0.5-second intervals, and spacing our data points to avoid duplicate data, 75 data points can be recorded within 1.875 minutes of flight, assuming 2 seconds of time between recorded data points 30lb payloads are the baseline test input
Does a thrust differential cause RPM strains on motors producing added thrust	Does a payload shift of x-lbs moving y-inches cause a measurable change in RPM per motor	Include thrust differential to RPM models with variance around expected RPM flight telemetry recording		
Does a thrust differential cause power strains on a flight vehicle power system	Does a payload shift of x-lbs moving y-inches cause a measurable change in power per motor	Include thrust RPM to power use models with variance around measurability of power use		
Does a vehicle experience instability during flight if a payload CG changes	What is the sensitivity of system CG to payload shifts of y-inches for payloads of x-lbs	Model sensitivity of payload weight and shift versus total system CG shifts	Given weight of total flight vehicle, overall system CG is not highly sensitive to shifting payloads below 20-lbs	

Driving Factors of Test Set Definition

Based on quantifiable roll-ups from test modeling described below, a few key take-aways inform the minimum required baseline of tests.

- Data recorded during flight is averaged over 0.5 seconds to get smooth and representative data points; during analysis, data will be examined with 0.25 and 0.5 averages (initial estimates of data averaging over 1 second is too long, as a flight vehicle can make multiple turns within 1 second, we want snapshots from during the turn)
- We don't want all of our data points to have 0 seconds time interval between them, so we'll allow 1 seconds of flight between each 0.5 second averaged data point (initially 5 seconds of spacing was considered to reduce auto-correlation, but 5 seconds of flight is too long: a vehicle can entirely change directions in 5 seconds, meaning that the telemetry snapshots of the flight vehicle during the turn would be missed; also, auto-correlation between data points that are measured during a flight can only be partially mitigated by data-recording spacing, analysis where all data points from the vehicle while at a certain angle can be performed at once, which will allow different wind directions and other factors to average out)
- The combination of 0.5 seconds of data for 1 second of data separation resulting in 1.5 seconds per data point indicates that 75 datapoints can be achieved in 112.5 seconds of flight, or 1.875 minutes of flight (initial estimates using 5 seconds of separation with 1 second of data yielded 450 seconds of flight; we will certainly perform many 50 to 10 minute flights, but it is good to know that we can achieve statistical robustness with short flights)
- 112.5 seconds of flight indicates that 2 minutes of flight will yield a complete test
- Complete double data sets can be achieved with 4 minutes of flight
- 1 minute in each direction for each test
- For each test with a shifted payload, we'll perform baseline tests with no shifted payload
- We'll perform at least one of the same tests with each payload method, to ensure that they are working as planned, and to see which has the highest fidelity, works best
- We'll perform the majority of tests with one payload center of mass detection system, using the system with the best fidelity; this is partly based on trading redundant and duplicate tests to incorporate take-off and landing tests
- Given that we expect a flight time of 8 to 12 minutes, we should be able to capture multiple complete data sets with one vehicle charge
- We may perform multiple complete tests with a single flight, by planning multiple tests with a single payload weight and placement

Flight Tests to be Performed

Minimum Tests to be Performed

Using the defined results from above, a minimum test set is defined. A circular flight route would enact a constant acceleration which would expand the 'difference' of the inputs, but it would not examine turns and mid turn stability best, a Figure-8 would be the best mixture of acceleration with turning with alternating between sides/directions of turns. Additionally, Figure-8s allow for ample time flying in multiple directions, as well as in exactly opposite directions, to counteract wind and environmental factors.

Minimum Test Set, Control and Stability with Shifting Payload

(Includes over 2x margin on data collection)

- At a minimum, *to determine statistically robust differences in power use, safety, and stability, with shifted payload of 30lbs shifted 8 and 14 inches*, we need to perform 6 key tests
  - Planned Figure-8 with 100-250ft circle radius
  - 2x Baseline flight, no payload shift (4 mins)
  - Test with shifted payload
    - Same Figure-8 flight with chosen highest fidelity, main PL-CG system (4 mins)
    - Same flight as main PL-CG system with other systems
      - 2nd method (4 min)
      - 3rd method (4 min)
      - 4th method (4 min)
  - Test with shifting payload
    - Baseline flight (4 min, uses the same as first baseline flight)
    - Same flight with shifting payload with main PL-CG system

For all of the above, adequate data would be collected with straight flight, for 1.875 minutes of straight flight; by using turns in planned flight, we increase magnitude of inputs, thereby increasing the power of the test, and by doubling the time from 2 minutes to 4 minutes, we again add significant statistical robustness to the test. At a bare minimum, these 6 tests must be completed. Of course, we plan multiple other tests to inform our analysis and the nuance and detail of the results.

Additional planned Tests

Rhoman and the FAA did not collaborate on such an interesting R&D contract with such an interesting and capable vehicle to perform only the minimum number of tests and flights to answer the baseline required questions, Rhoman plans to execute additional test flights to augment the R&D contracts research questions and to extend inference and analysis to new and useful areas. We intend to perform more tests to add significant nuance and derive more detailed and nuanced results

Additional Test Set, Control and Stability with Shifting Payload, Added Nuance

(Significantly expands on already achieved 2x margin on data collection)

- Based on adding nuance to data to answer R&D contract research questions, additional tests are planned and will be executed on a best effort basis
  - Flight in a circle
    - With centered payload
    - With off-center payload
    - With live-shifting payload
  - Flight in an S-shape
    - With centered payload
    - With off-center payload
    - With live-shifting payload
  - Flight in a typical resupply-mission route
    - With centered payload
    - With off-center payload
    - With live-shifting payload
- Other flights
  - Flight with hanging payload
  - Flight with multiple shifting payloads
  - Additional flights as deemed valuable based on ongoing tests and analysis

The test setup is designed to first secure 2x the data required to answer primary R&D contract research questions; based on analysis presented, this data can be captured via a small number of flights, and multiple additional, follow-on flights are planned and expected, although not required.

9. APPENDIX: TEST SET QUANTIFICATION FROM PRIOR DELIVERABLES

Prior analysis for test set planning to answer the R&D contract research questions is presented, system models, input and model variance, and simulated tests to show sample size are discussed.

Models to Describe our Research System

Descriptions of the models that prescribe our research system are presented, and coded models used in simulations to determine input parameter space are presented in the following table.

CG Shift to Thrust

CG Shift to thrust models encompass the flight vehicle during hover, flying straight, and while turning, these models determine the total thrust needed to stay in the air based on payload and total vehicle weight, and most importantly, they allocate thrust to each motor as a function of overall system center of gravity.

When a payload shifts, the weight distribution changes, and so the thrust needs of each motor changes. We need to be able to detect, with statistical robustness, differences in expected thrust needs per motor based on payload shifts, so these models are important, and are the baseline for looking at RPM and Power needs.

Thrust Needs to RPM

Thrust to RPM is a simple calculation that is based on multiple factors relating to the motors and propellers used – but based on combining these input parameters, we end up with a smooth power function (^2).

RPM Needs to Power

Modelling the required power versus RPMs achievable to reach the desired thrust again takes a number of inputs based on motors and propellers, but again, once the parameters are taken into account, a smooth power function (^3) is used.

Payload Shift and CG Variance

Given the overall size and mass of the flight vehicle, payload shifts can only have so much of an effect on the total system center of gravity. By examining what payload shifts create what magnitude of total system CG shift, we can examine the most dangerous and/or impactful shifting payload scenarios.

Payload Shift and Response Variable Sensitivity Curves and Variance

In order to measure a statistically significant difference between RPM and Power Levels versus Payload CG shift, we'll apply the reasonable variances around Payload CG shift and measurement, and RPM sensor measurement and power use measurement.

Sample Size

Based on the input variance of the payload CG detection models, combined with any flight vehicle telemetry sensor variance, and the magnitude of the differences of the inputs to our models, we can determine a sample size, a number of distinct data points from flight tests, that create adequate statistical robustness for analysis. Specifically, based on the input variables that we can use based on the reachable edges of the parameter space, we can determine the number of input data test points that we need.

Number of Tests

As defined in prior analysis in deliverable 4.1 Payload Center-of-Mass Detection System Designs, simulations have been performed in order to determine a required baseline number of tests to perform.

Key Inputs

Input variables are variables that we input into the system, including variables that we can directly control like flight speed, as well as other variables that we can't explicitly control, but that we choose to input into the system with specific values, i.e. performing test flights at a certain elevation or waiting for a particularly cold day. Models that use these variables are presented in 5 Model for Analysis.

Input Variable	Parameter Space
Mass of payload	• 0lb, as control up to ~50lb
Shape and type of payload	• Non-tipping sturdy tall & thin payloads with concentrated CMs • Single large containers of sloshing liquid • Single large containers of sloshing liquid with baffles • Pallet of water bottles • Round or cylindrical payload that can roll during flight (within a safe container) • Box of small loose heavy items (like hammers) • Untethered emergency medical supplies • RC car that we can control remotely to enact specific intentional live shifts
Location of payload	• Center of payload area • Shifted forward along the center axis • Shifted sideways along the center axis • Shifted backwards along the center axis • Shifted forard and sideways • Shifted backward and sideways • Slung/hanging payload (optional add-on to testing)
G-force experienced by payload in x-y plane (created intentionally through speed and arc of turns)	• No g-force (constant motion) • Forward g-force (acceleration forward) • Backward g-force (acceleration backward) • Sideways g-force (centripetal acceleration during even-arc turn) • Sideways and forward/backward acceleration during turn with concurrent increasing speed
G-force experienced by payload in x-y-z plane (created intentionally through speed and arc of turns, including changing altitude and changing altitude while turning)	• Inclusion of flight vehicle height AGL changes with specific x-y plane g-force tests
Flight profile; specific applications of g-force answer specific shifting and stability tests, running complete sample mission profiles examines overall system stress and strain under expected sample mission cases	• Straight line launch, fly, land missions • S-turn launch, fly land missions • Complex navigation (as if through trees or buildings) launch, fly land missions • Pitch/yaw/roll changes & differentials • Cargo delivery launch, fly, hover, return to launch point missions • Start and end point elevation differential missions
Elevation at which tests occur	• 0ft, 100-200ft, and ideally 5,000ft (pending testing region availability)
Chosen temperature and humidity levels at which tests occur	• 50F and 100F, optionally include 20-30F • Low and high humidity

Other weather factors chosen for different tests	• Various, pending test environments

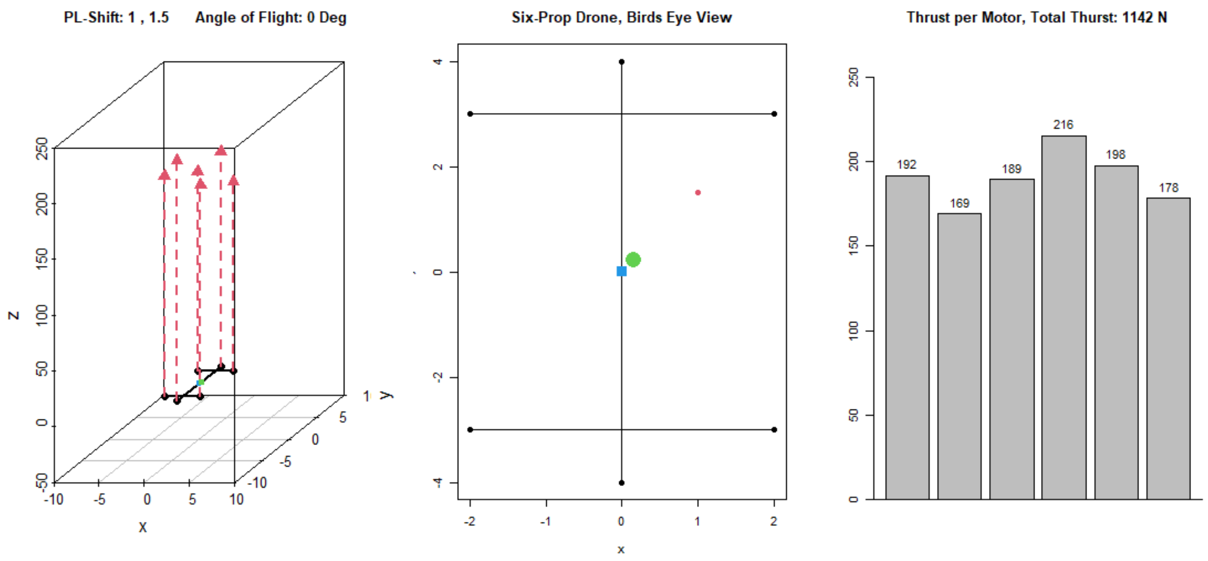
Simulations in Test Space to Inform Input Parameters

The goal of the simulations based on the models presented above is to simulate various payload shifts in order to determine the needed payload weights and payload shift inputs to use during testing, in order to get measurably different, and statistically different, flight telemetry results during flight tests, in order to ascertain exactly what payload shifts results in what flight vehicle performance differences. The research system is described, and the models outlined above are included in flight vehicle simulations to examine expected thrust, power and RPM versus different payload inputs.

In the following simulations, a 250lb vehicle is used with the dimensions of 4ft x 8ft, with variance placed around the payload CG detections based on the above analysis of +/-1", and a standard deviation placed on flight vehicle telemetry of 5% of the measured value with a normal distribution (applied to RPM and Power telemetry). These are conservative estimates of variance. In the following simulations the vehicle is assumed to be flying forward with a constant pitch of 25 degrees. Tests at hover would require greater distance between inputs and tests during turns would require less distance between inputs.

Research System

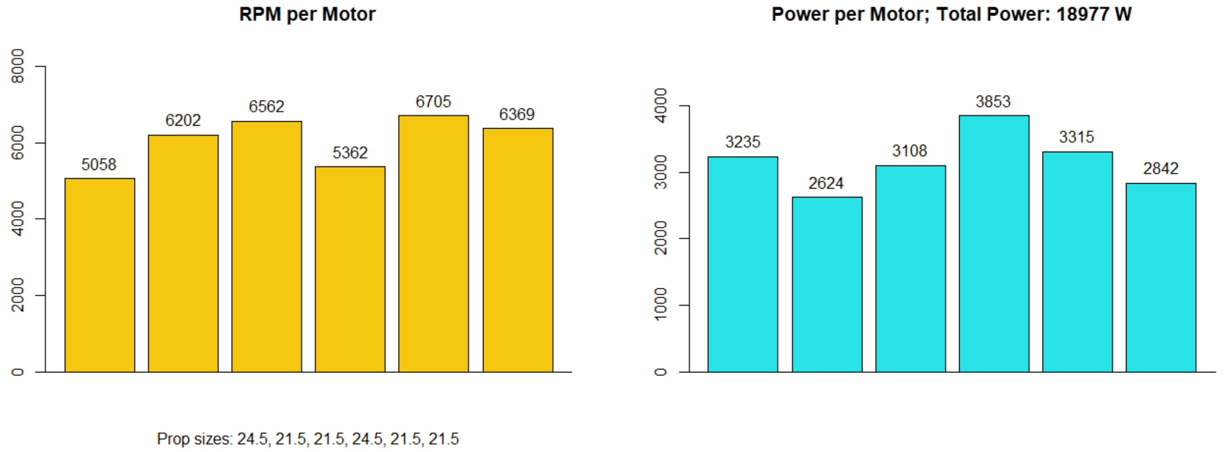
The flight vehicle, required thrusts, and needed RPM and power per thrust are shown versus different payload placements.



By examining the forces needed for thrust at each motor (red dashed lines with arrows) versus the payload shift (red dot) and the resulting updated system center of mass (green dot) versus the original center of mass (blue square), we can use those estimates while determining what magnitude of overall system shift in center of mass results in flight telemetry differences that are detectable with adequate statistical robustness

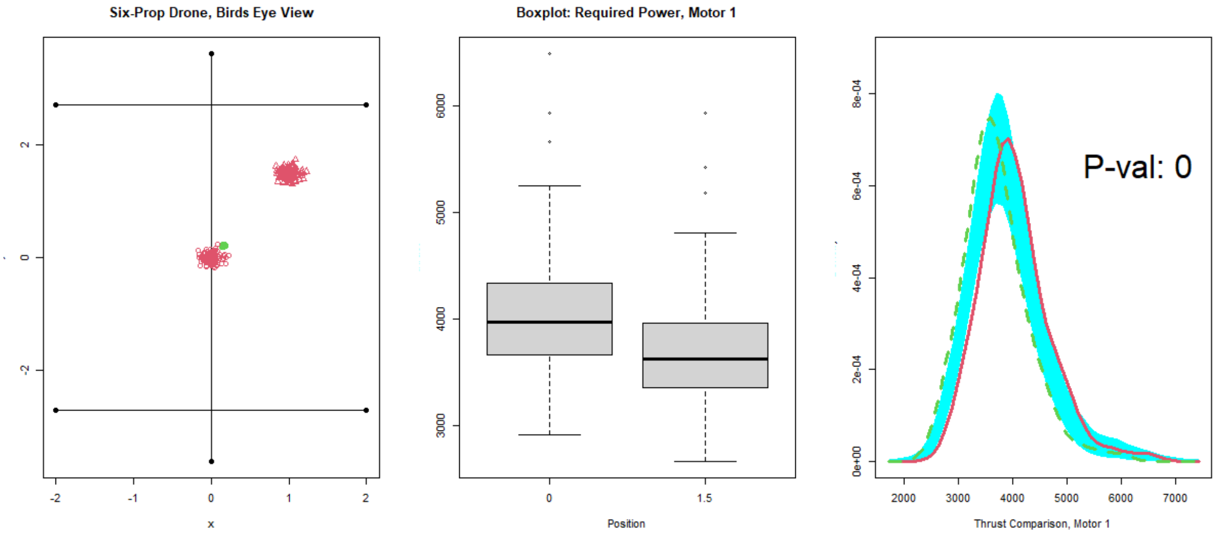
Measurable Flight Telemetry and Sensitivities

In order to achieve the required thrusts to maintain stability despite shifting payloads, the propeller RPM and power needs per thrust need per motor are determined.



Here we see an example of the payload shifting forward and to the side, and the resulting noticeable differences in thrust required per motor to maintain stability

Once thrust, rpm and power measurements are made, the system is sampled, and distributions for telemetry versus shifted payloads (including variance) are analyzed, in order to determine what inputs yield statistically valid results.

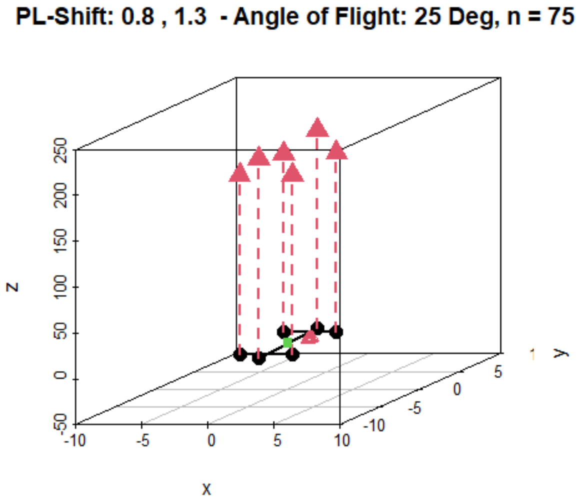


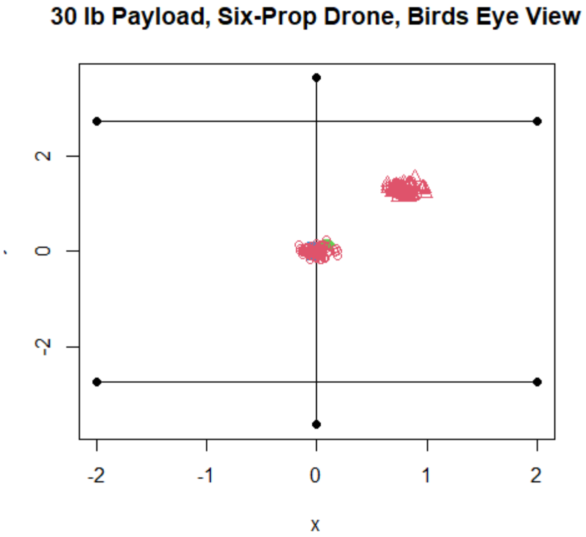
When we apply statistical distributions to our response variables, this is where we start to zero in on the required sample size and difference in inputs required to achieve statistically different and measurable responses and response distributions

Results of Simulations, Required Input Variables

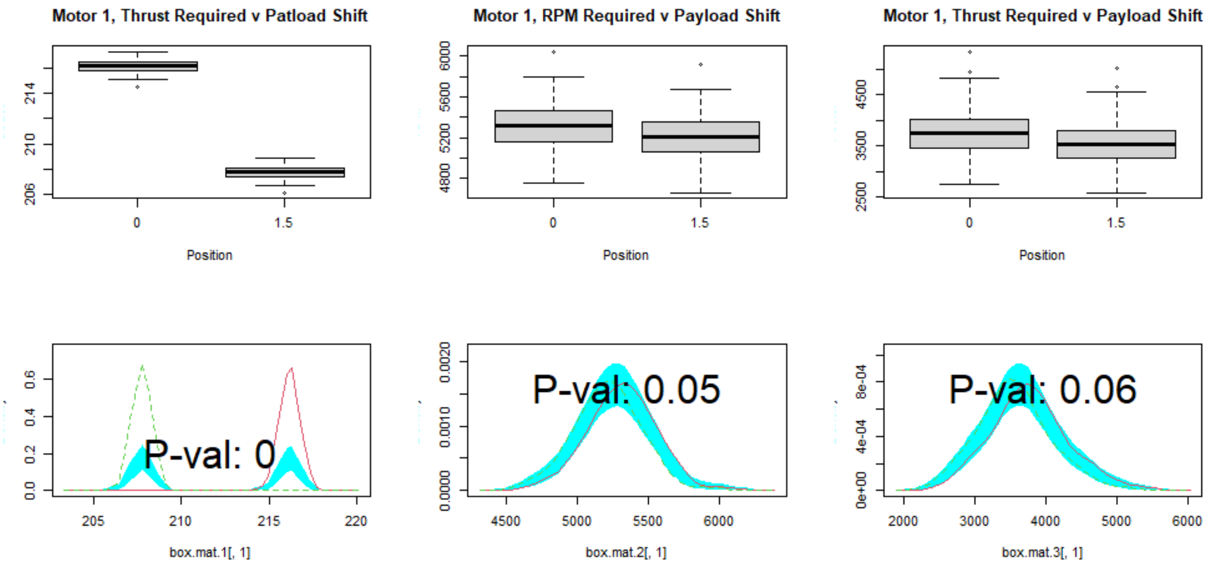
Variance around measurable payload center of mass, and therefore system mass, is input into the model, variance around RPM and power use measurements are put into the model, and multiple simulations are made. The resulting distributions in data allow us to determine the separation of input parameters needed to ascertain statistically robust results despite input and sensor variance.

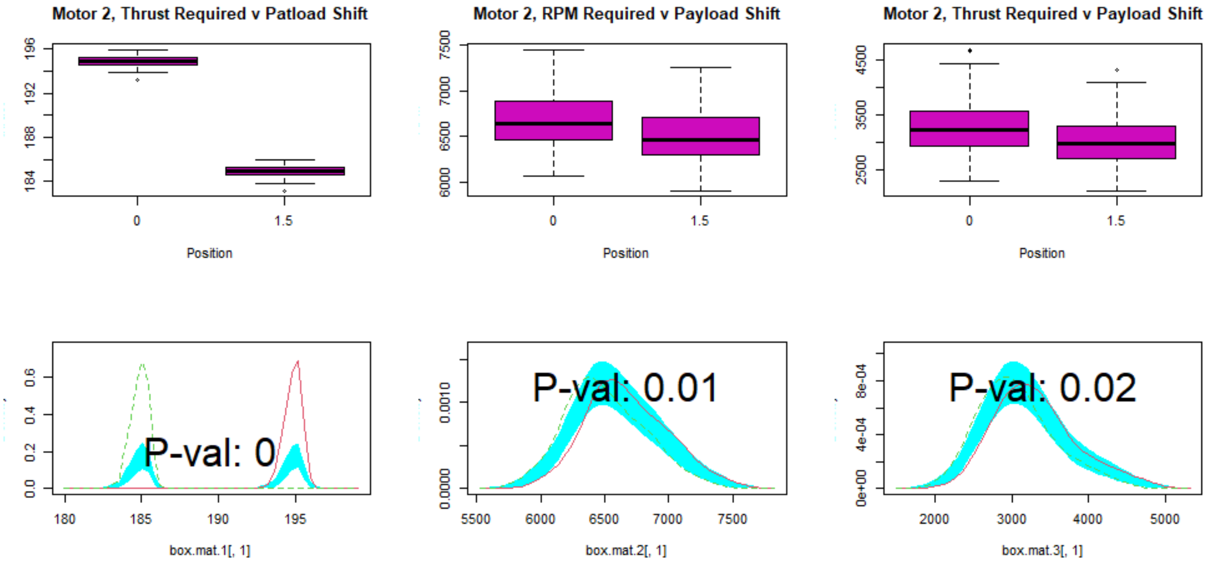
Adequate Sample Size, 30lb PL & Medium Shift, 8in, and 14in, n = 75





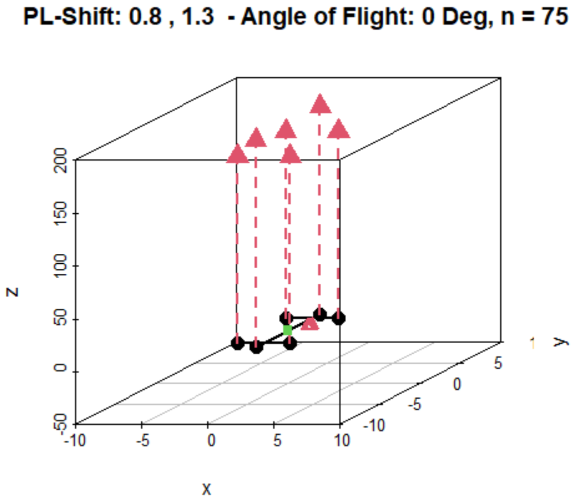
With the angle of flight at 25 degrees, we increase the total thrust used in the system, and like increasing the weight of the payload, this means that larger amounts of thrust, and larger thrust differentials, are used and required; we can in fact trade payload weight, shift, and speed or turn radius, to some degree, to increase the size of the difference in our response variables, and the detectability

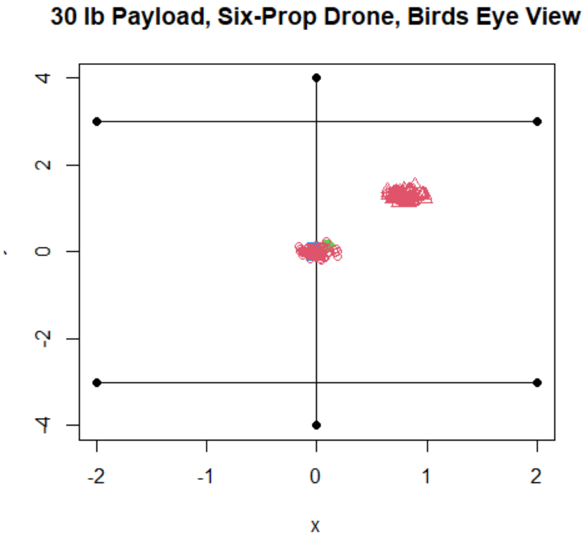




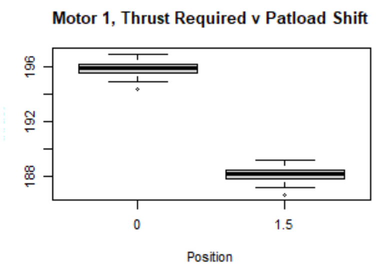
Based on these results, we can see that using a payload of 30lbs shifted right and forwards by 8-inches and 14-inches yields statistically significant results for a flight vehicle traveling with a constant pitch of 25 degrees.

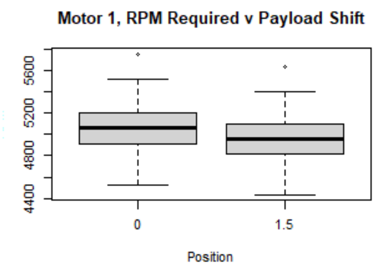
Input Variables, Hovering and Turning

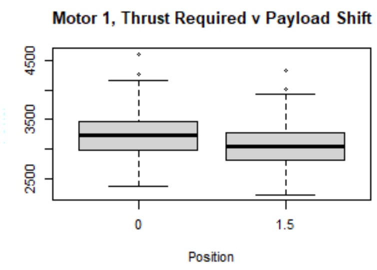


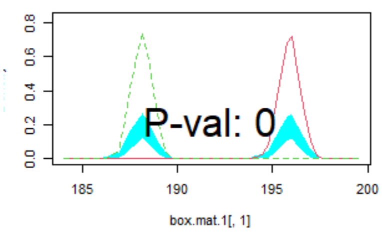


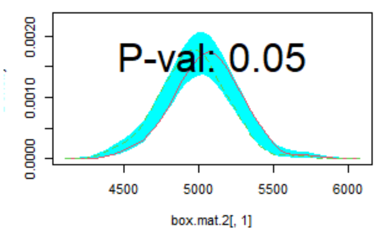
With a moderate payload and a moderate shift, we have found a good balance of payload shift, weight, and total sample size to determine a good starting point for planning our flight tests

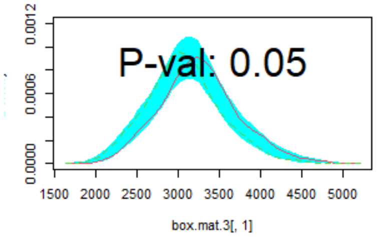


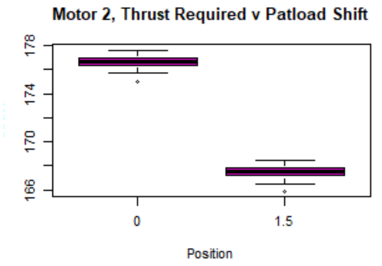


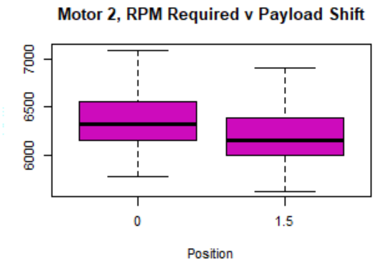


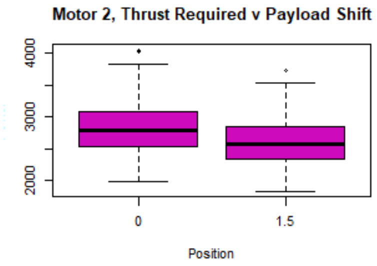


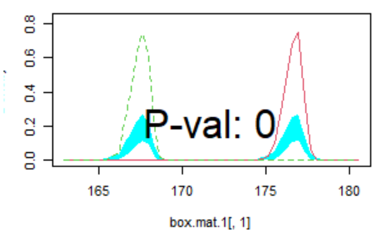


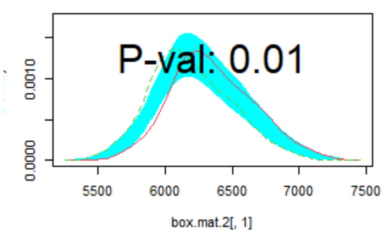


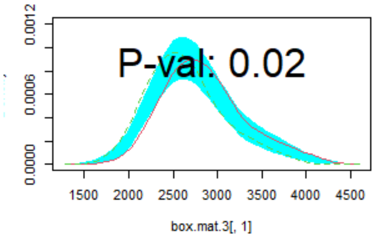












Even though the total thrust requirements are less for the vehicle at hover than while flying forward with constant pitch of 25 degrees, the inputs of 30lbs shifted to the right and forward by 8-inshes and 14-inches still yield robust flight telemetry differences. Likewise during a turn, while experiencing centripetal acceleration, all of the forces would be magnified, so a smaller number of tests with the same payload weight and shift would yield statistically robust results.