FLAME Concept R

The Fire Limiting Aerial Management Ensemble:

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Project Description

Mission Objective

- Limit the spread of wildfires through aerial deployment of fire retardant
- Autonomously fly to and from locations of interest through an Unmanned Aerial System (UAS)

Mission Challenges

- Deploy mock fire retardant payload (water) within 1 meter accuracy of 3 given target locations in 20 minutes
- Autonomous takeoff, flight, and landing capabilities, with ability for human-in-the-loop takeover
- Support at least 5 pounds of payload through takeoff and flight

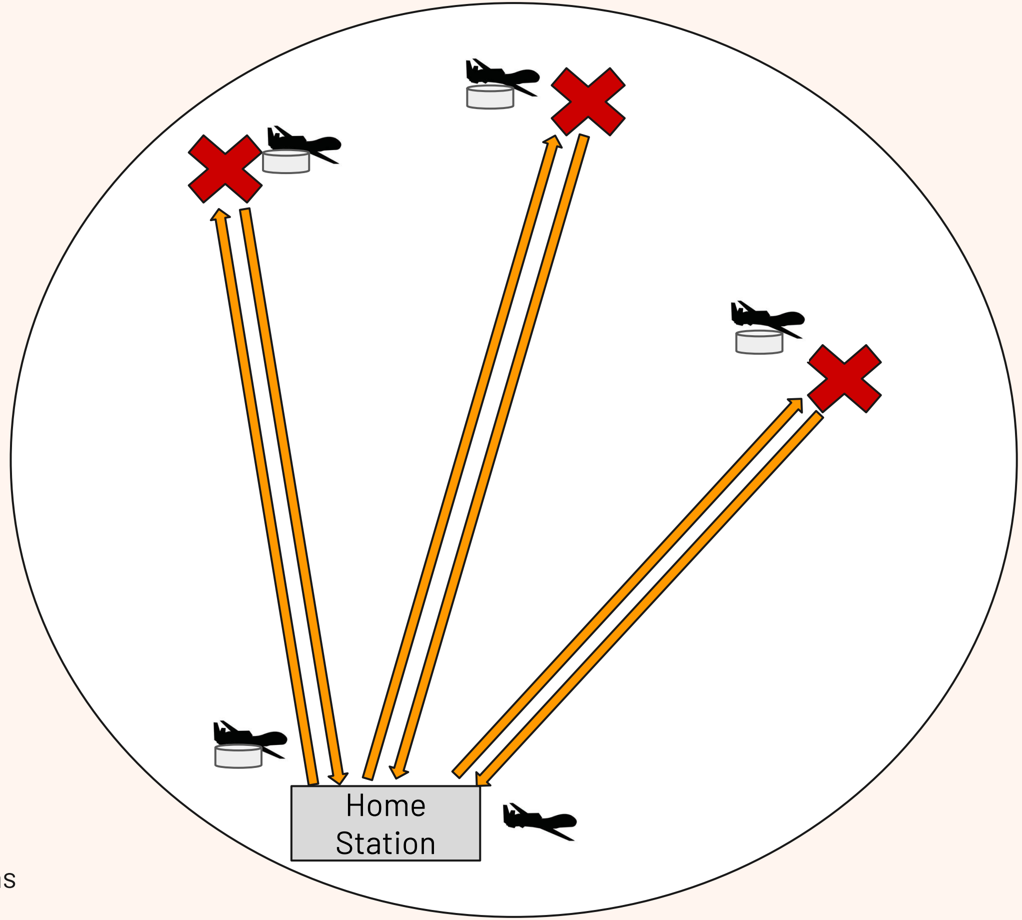
FLAME - Autonomous Firefighting UAS High-Level CONOPS

Legend:

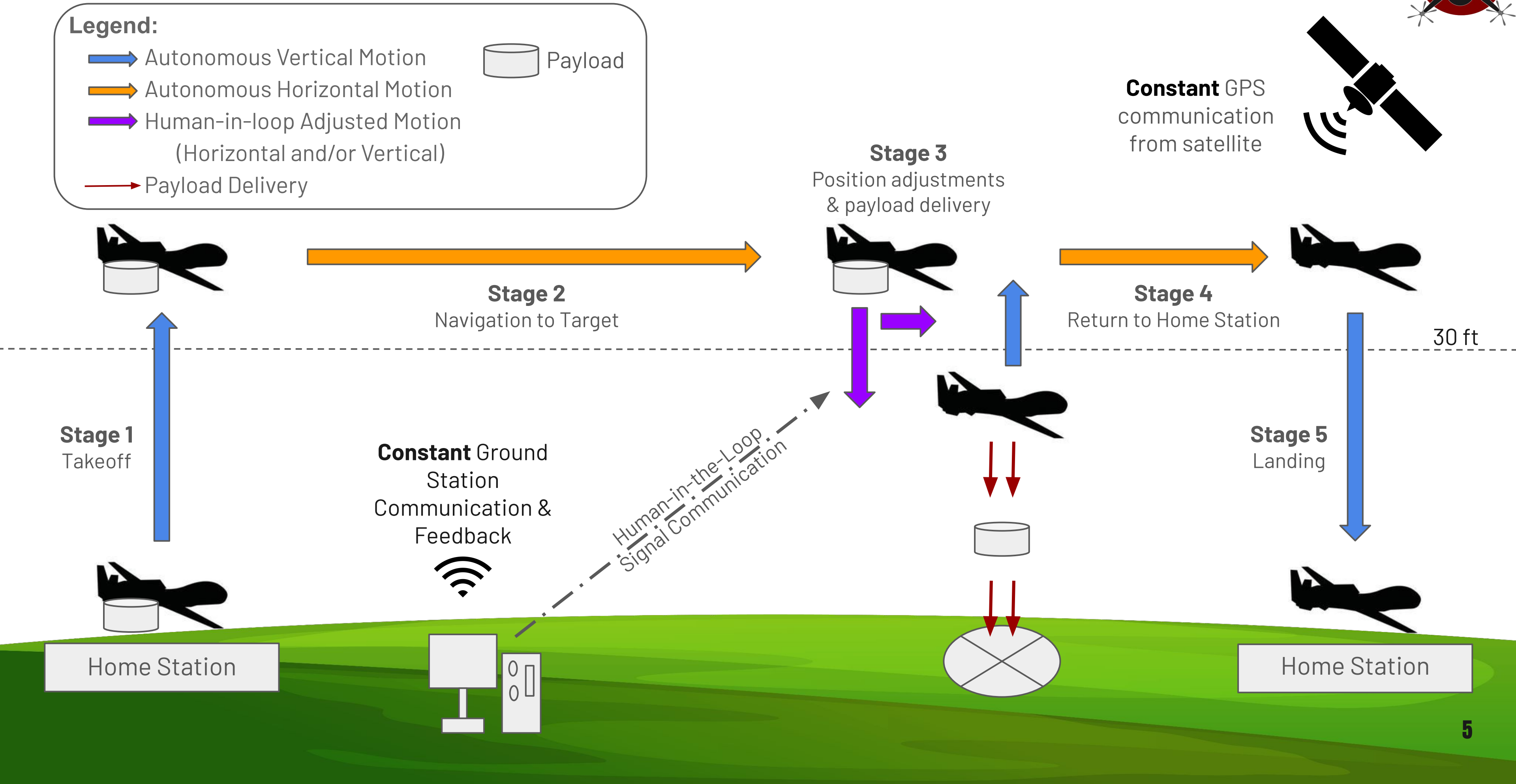
Target Location

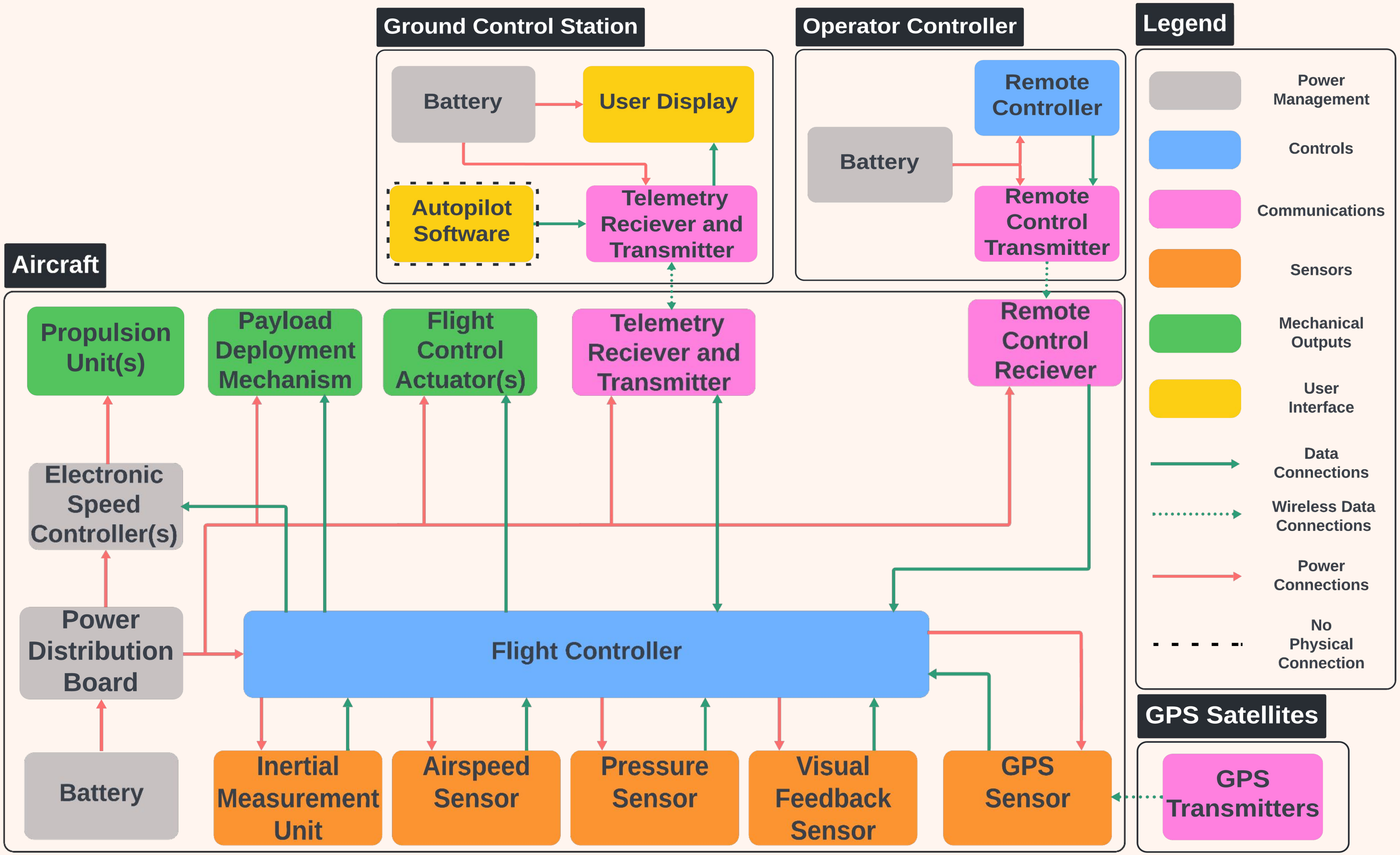
Autonomous Travel

- 100 meter diameter mission zone
- Given a home base location within mission zone
- Given GPS coordinates of three target locations
- Travel to target location
- Deploy payload
- Return to home station
- Ground team reloads a new 5 pound payload
- Repeat for 2 additional target locations



FLAME - Autonomous Firefighting UAS Low-Level CONOPS

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Visual Feedback Sensor
GPS Sensor
GPS Satellites
GPS Transmitters

Key Driving Requirements

Requirement	Requirement Description
FR 1.2	The system shall be able to take off autonomously
FR 1.3	The system shall be able to land autonomously
FR 1.4	The system shall be capable of making 3 drops in a 20-minute span
FR 2.1	The system shall carry and deploy 5 pounds of fire retardant per target location
FR 2.4	The system components shall be less than 55 pounds with payload
FR 3.1	The system shall utilize human-in-the-loop to navigate from 10 meters RMS accuracy to 1 meter from location of interest
FR 3.5	The system shall deploy the payload and have it land within a +/- 1 meter accuracy of target location

Trade Study Progress

Trade Description	Dependency	Completion Status
UAS Platform Selection*	Independent	Complete
Payload Deployment Method*	Dependent	Complete
Rotor Count	Dependent	In Progress
Propeller Trade	Dependent	In Progress
Motor Selection	Dependent	In Progress
Payload Container Design	Dependent	In Progress
Airframe Selection	Dependent	Not Started
Visual Feedback Sensor	Independent	Not Started
Transmitters/Receivers	Dependant	Not Started

* Will be discussed in this presentation

Trade Study Progress

Trade Description	Dependency	Completion Status
Remote Controller Selection	Dependent	Not Started
Landing Gear Selection	Dependent	Not Started
GPS Selection	Independent	Not Started
Pressure Sensor Selection	Dependent	Not Started
Airspeed Sensor Selection	Dependent	Not Started
Autopilot Software Selection	Independent	Not Started
Flight Controller Selection	Dependent	Not Started
Battery Selection	Dependent	Not Started
Inertial Measurement Unit Selection	Dependent	Not Started

Trade Study 1:
UAS Platform

UAS Platform Overview

This trade study determines the most suitable aircraft type for **autonomous flight**, **vertical takeoff/landing, payload support** and **stable deployment**

- **Autonomous Flight:** The vehicle must navigate between targets autonomously as well as take off and land autonomously

- **Vertical Takeoff and Landing:** The vehicle must be capable of vertical takeoff and landing

- **Payload Support:** The vehicle must be capable of carrying a payload of at least 5 pounds over a maximum of 200 meter operational range

- **Stable Deployment:** The vehicle must be easy to control to enable 1 meter drop precision through mild inclement weather

UAS Platform Key Requirements

Key Requirement Number	Requirement Description
DR 2.1	The structure system shall support a payload capacity of at least 5 pounds for carrying fire retardant materials
DR 1.4	The avionics system shall support autonomous takeoff and landing with a specified payload of 5 pounds

Key Requirement Number	Requirement Description
FR 1.6	The system shall only vertically translate below the 30 foot hard deck, at the location of interest and take-off/landing position
DR 2.4	The structure system shall withstand mild weather conditions

UAS Platform Design Metrics

- **Mechanical Complexity**
  - More moving parts increases risk of failure
- **Cost**
  - Keep budget low
- **Availability**
  - Commercially off the shelf (COTS) airframes available
- **Maneuverability**
  - Vehicle can easily transition between vertical and horizontal flight modes
  - Response to human input
- **Stability**
  - Vehicle must stay in controlled flight during environmental factors
  - Wind and shifting cargo create key challenges
- **Performance**
  - Power-to-weight ratio impacts payload support capabilities
  - Speed of performing the mission

UAS Platform Considerations

Helicopter

Tail-Sitter

Multirotor

Fixed-wing / Multirotor Hybrid

Tiltrotor

Blimp

UAS Platform Criteria

Score	5	4	3	2	1
Mechanical Complexity	Requires minimal moving parts to function properly.	Requires limited moving parts to function properly.	Requires some moving parts to function properly.	Requires many moving parts to function properly	Requires a lot of moving parts to function properly
Cost	Cost range: <$2000	Cost range: $2000-2500	Cost range: $2500-3500	Cost range: $3500-4000	Cost range: $4000+
Availability	High availability for relevant COTS options.	-	Some availability for relevant COTS options.	-	Little to no availability for relevant COTS options

UAS Platform Criteria

Score	5	4	3	2	1
Maneuverability	Aircraft type can transition between flight modes and responds to human-in-the-loop inputs almost instantly	Aircraft type takes some time to transition between flight modes and responds to human-in-the-loop inputs instantly	Aircraft type takes some time to transition between flight modes and responds to human-in-the-loop inputs in a timely manner	Aircraft type takes more time to transition between flight modes and responds to human-in-the-loop inputs in a timely manner	Aircraft type takes more time to transition between flight modes and respond to human-in-the-loop inputs
Stability	Aircraft does not struggle to takeoff/land/hover due to conditions or payload	-	Aircraft may struggle to takeoff/land/hover due to gusts or payload weight shifts	-	Aircraft struggles under gusts or payload weight shifts
Performance	-	Aircraft is capable of speeds required to make necessary drops and minimizes power required for horizontal translation	-	Aircraft is capable of speeds required to make necessary drops but substantial power required for horizontal translation	-

UAS Platform Metric Weights

Metric	Justification	Weight
Mechanical Complexity	Less mechanical complexity leads to less possible points of failure and reduces risk	0.10
Cost	The vehicle should not dominate allotted $4,000 budget, allowing funds for other systems	0.15
Availability	Vehicle fabrication deemed un-feasible given time, so vehicle should be available for project continuation	0.15

UAS Platform Metric Weights

Metric	Justification	Weight
Stability	The vehicle must release the payload within 1 meter accuracy through light inclement weather	0.20
Maneuverability	The vehicle must take off and land vertically and be able to vertically translate to release payload	0.20
Performance	The vehicle must be able to physically support 5 pounds of payload through a minimum of 100 meters of flight in a 20 minute time frame	0.20

UAS Platform Engineering Analysis: Performance

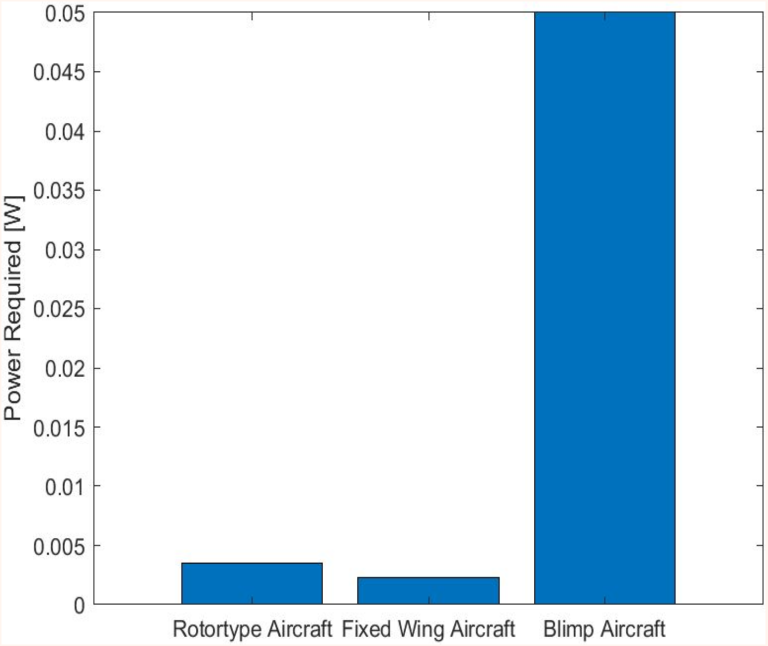
Assumptions:

-Half total time allotted for horizontal translation
-Maximum possible horizontal distance required
-Translational power used only to offset drag force
-Final weights of all systems end up the same
-Drag of payload ignored for all vehicle types

Governing Equations:

Drag force: $D = \frac{1}{2} \cdot \rho \cdot V^2 \cdot C_D \cdot A$

Translational power required: $P = \frac{D \cdot d}{t}$



UAS Platform Trade Matrix

	Helicopter	Multirotor	Tailsitter	Fixed Wing Hybrid	Tiltrotor	Blimp
Mechanical Complexity	1	4	3	4	2	5
Cost	2	3	2	3	2	2
Availability	1	5	3	5	3	3
Stability	5	5	1	5	3	3
Maneuverability	5	5	3	4	3	4
Performance	4	4	4	4	4	2
Total	18	26	16	25	17	19

UAS Platform Final Selection

- **Multirotor**
  - Low cost with COTS availability
  - Stable and maneuverable with good performance
  - Some mechanical complexity has potential to create issues down the line, will require extensive modeling
  - Directly impacts deployment method trade

	Helicopter	Multirotor	Tailsitter	Fixed Wing Hybrid	Tiltrotor	Blimp
Weighted Total	3.35	4.4	2.65	4.2	2.95	3.05

Trade Study 2: Payload Deployment Method

Payload Deployment Method Overview

This trade study determines the most suitable deployment method that can **hold/deploy 5 pound payload**, land within a **1 meter accuracy**, and withstand **mild weather conditions**.

- **Hold/Deploy 5 Pound Payload:** The payload deployment method must be capable of carrying and deploying a 5 pound payload without losing any of the payload during flight
- **1 Meter Diameter:** The payload deployment method must be able to hit the targets with an accuracy of 1 meter
- **Mild Weather Conditions:** The payload deployment method must be able to withstand mild weather conditions

Payload Deployment Method Key Requirements

Key Requirement Number	Requirement Description
FR 1.7	The system shall be operable in mild weather conditions.
FR 2.1	The system shall carry and deploy 5 pounds of fire retardant per target location.
FR 2.3	The payload shall consist of dyed water solution to mimic the viscosity and density of a PHOS-CHEK mixture.

Key Requirement Number	Requirement Description
DR 6.1.1	The payload deployment subsystem shall include a payload deployment mechanism that allows for release of fire retardant with a precision of +/- 1 meter.
DR 6.2.1	The payload deployment subsystem shall hold the payload of a dyed water solution while preventing leakage during flight.
DR 6.2.2	The payload deployment subsystem shall be capable of deploying a 5 pound payload per target location.

Payload Deployment Design Metrics

- **Deployment Speed:**
  - Mission time constraint of 20 minutes
  - Need to minimize time spent deploying payload so UAV can continue mission
  - How fast does the payload deploy?

- **Weather Impact Resilience:**
  - +/- 1 meter accuracy is required
  - Deployment method must work in mild weather conditions (light wind and rain) to meet tolerance
  - How much does weather impact this payload device and its deployment?

Payload Deployment Design Metrics

- **Ease of Deployment Verification:**
  - How easy is it to verify we deployed the payload, hit our target accurately, and dropped enough water?

- **Deployment Stability:**
  - Payload deployment will cause shift in the CG
  - Must ensure deployment method will not jeopardize control of vehicle
  - How much does this deployment method alter UAS stability?
  - Assumptions for grading:
    - Payload is directly below unloaded aircraft CG

Payload Deployment Design Metrics

- **Repeated Testability:**
  - Does this deployment device require more materials each time we test it?
  - If more materials are needed for every test, cost will go up

- **Reloading Process:**
  - Must minimize time spent reloading the device
  - Is it difficult to reload the payload?
    - Note: The weighing out of 5 pounds of water is not included in this metric

- **Power Consumption:**
  - Need to minimize power sent to deployment device
  - How much power does the deployment device draw?
  - Power budget will be a large concern depending on motors and overall weight
    - Note: The wattage varies heavily between pumps

Payload Deployment Options

Fall Release

Ballistic Release

Pump-based

Pressurized Tank

Payload Deployment Criteria

Score	5	4	3	2	1
Deployment Speed	Deployment time: < 2 seconds	-	Deployment time: 2 - 10 seconds	-	Deployment time: 10+ seconds
Weather Impact Resilience	Payload deployment is very resistant to light winds	Payload deployment is resilient to light winds, but there is still some impact on accuracy	Payload deployment will be affected by light winds, but the performance is adequate for the mission	Payload deployment will be affected by light winds and could potentially fail to deliver payload effectively	Payload deployment is highly sensitive to light winds
Ease of Deployment Verification	-	Verification may be done via inspection	-	Requires inflight monitoring	-

Payload Deployment Criteria

Score	5	4	3	2	1
Deployment Stability	CG shift or reaction force is negligible or very minimal	CG shift or reaction force is small, flight stability easily corrected	–	Large CG shift or reaction force, flight stability significantly altered	Extreme CG shift or reaction force – may cause instability
Repeated Testability	–	Testing will not require additional materials for each test	–	Testing requires additional materials for each test	–

Payload Deployment Criteria

Score	5	4	3	2	1
Reloading Process	Reload time: < 15 seconds	–	Reload time: 15 - 45 seconds	–	Reload time: > 45 seconds
Power Consumption	Very efficient power consumption – small portion of power budget <10 W	Efficient power consumption – allow flexibility in power budget 10-20 W	Manageable power consumption – must be considered for power budget 20-30 W	Large power consumption – issues meeting power budget 30-50 W	Extreme power consumption – severely limits power budget 60+ W

Payload Deployment Criteria Weights

Metric	Justification	Weight
Deployment Stability	Deployment of the payload should be stable and accurate enough to fulfill the 1 meter precision requirement	0.15
Repeated Testability	The deployment method should allow us to be able to test multiple times as this has the potential to drive cost up	0.30
Power Consumption	Power consumption will play an important role in design decisions for battery and weight	0.30
Reloading Process	With our 20 minute time frame, the reload process is not a large priority as all methods are expected to not be complex	0.05

Payload Deployment Criteria Weights

Metric	Justification	Weight
Deployment Speed	While deployment speed is important, is expected that the payload deployment will be a small fraction of total mission time	0.10
Weather Impact Resilience	It is important that the payload can withstand weather environments but we are not expected to deploy in any weather of great risk	0.05
Ease of Deployment Verification	It is important to know that the payload has been deployed but all methods are expected to have a reliable way of verifying the deployment of the payload	0.05

Engineering Analysis - Power Consumption

	Latch	Pump-based	Valve
Power Draw (P=I*V)	18 - 36 W	1.2 - 120 W	6 - 32 W
Deployment Time activation time + flow time + fall time	(0.1-0.2 s) + (0-4 s) + (1-2 s)	(6-114 s) + (1-2 s)	<1 s + (0.3-1.2 s) + (1-2 s)
Energy Use (E=P*t)	3.6 - 5.76 J	136.8 - 939 J	6 - 32 J
Weight of Mechanism (not container)	0.3 - 2 lbs	0.1325 - 5.5 lbs	0.3125 - 1.76 lbs

Payload Deployment Trade Matrix

	Gravity/Fall Release	Ballistic Release	Pump-based	Pressurized Tank
Deployment Speed	3	5	1	3
Weather Impact Resilience	3	4	3	4
Ease of Deployment Verification	5	5	1	1
Deployment Stability	3	3	4	1
Repeated Testability	4	2	4	2
Reloading Process	3	5	3	1
Power Consumption	4	4	2	5
Total	25	28	18	17

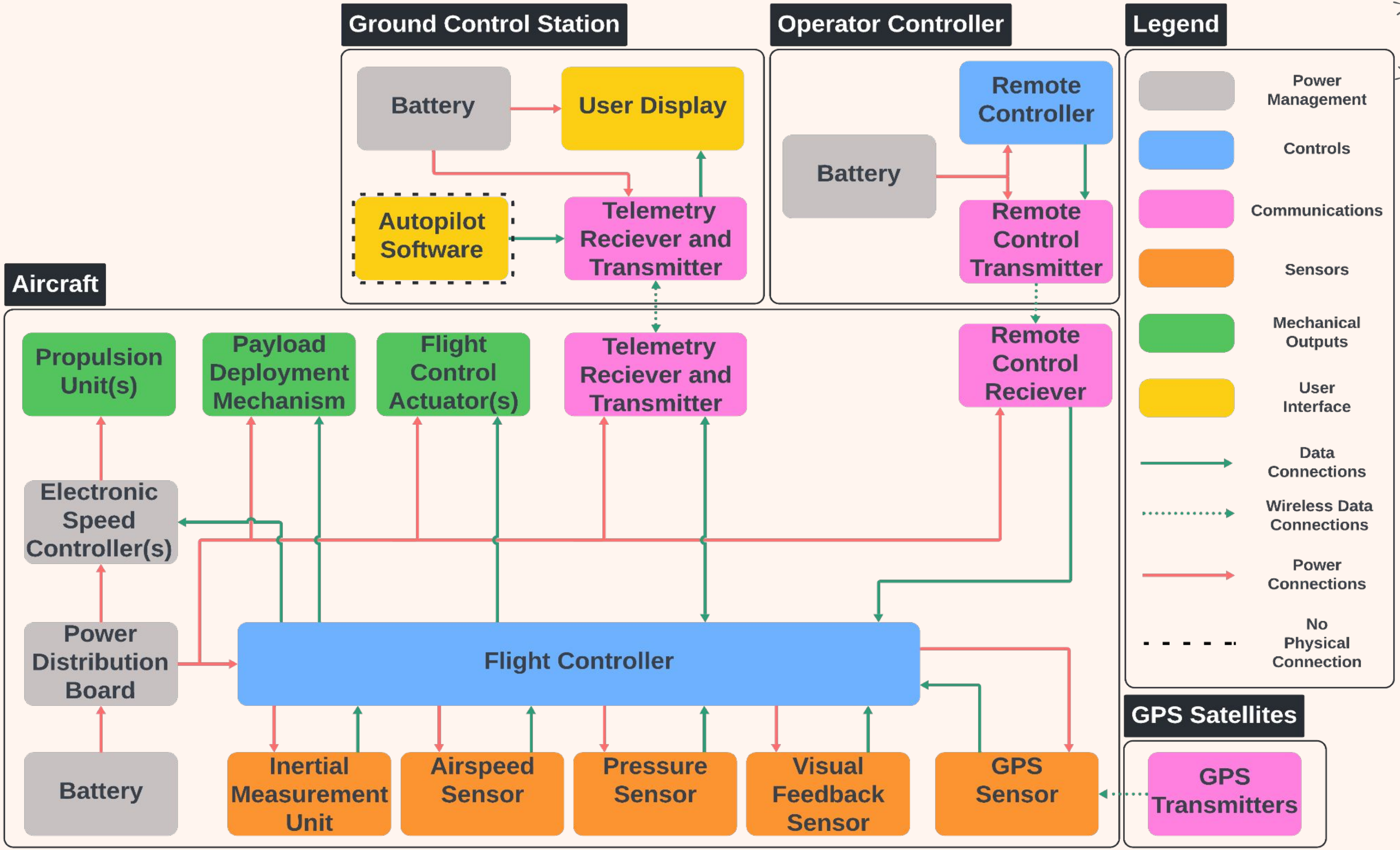
Payload Deployment Method Final Selection

- Gravity / Fall Release

  - Simple reloading and deployment verification
  - Easily repeated for testing
  - Low power consumption
  - Accuracy may become a problem, extensive modeling and testing required

	Gravity/Fall Release	Ballistic Release	Pump-based	Pressurized Tank
Weighted Total	3.7	3.45	2.65	2.65

Current Design Space



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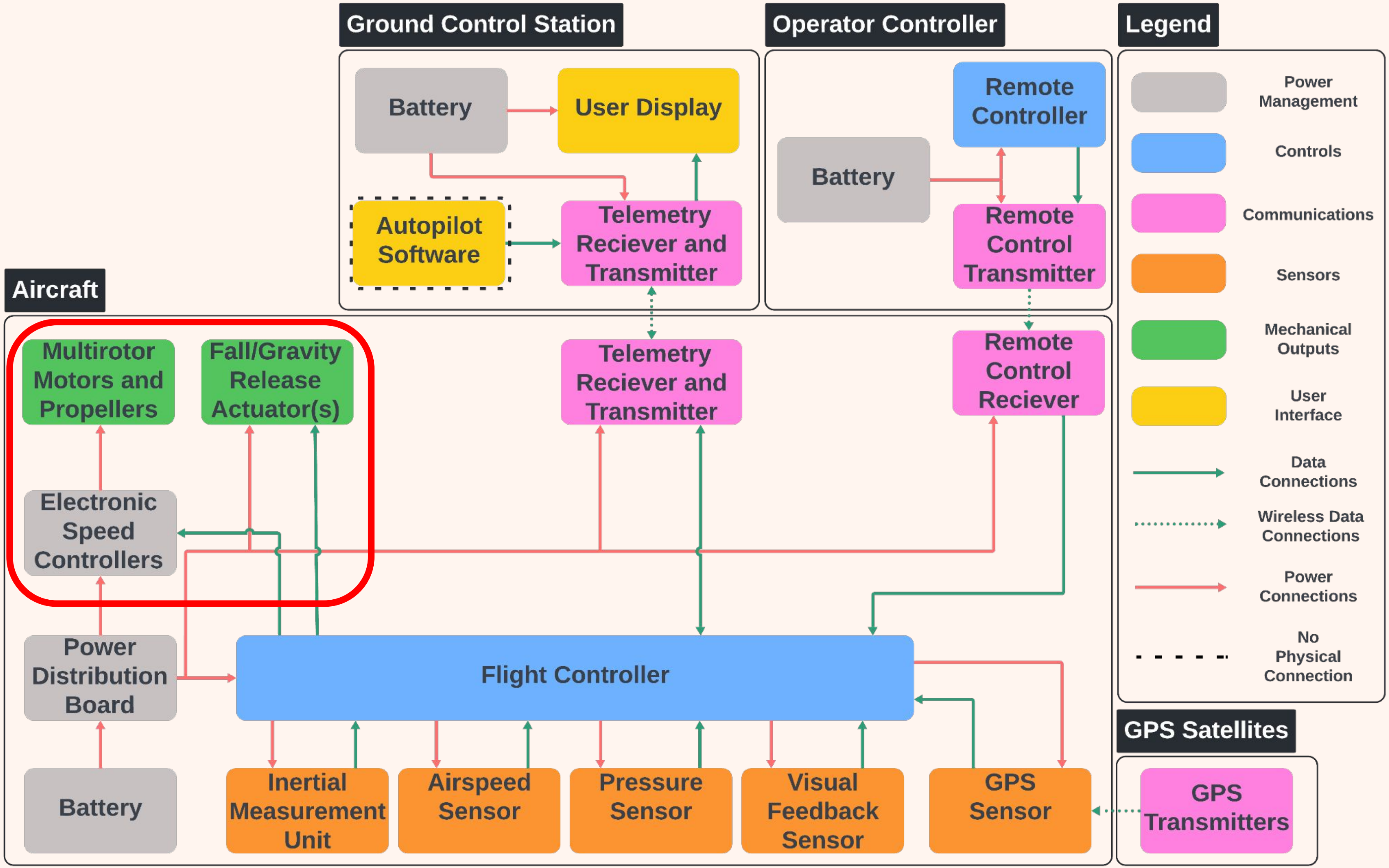

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FLAME

Impacts of UAS Platform Trade

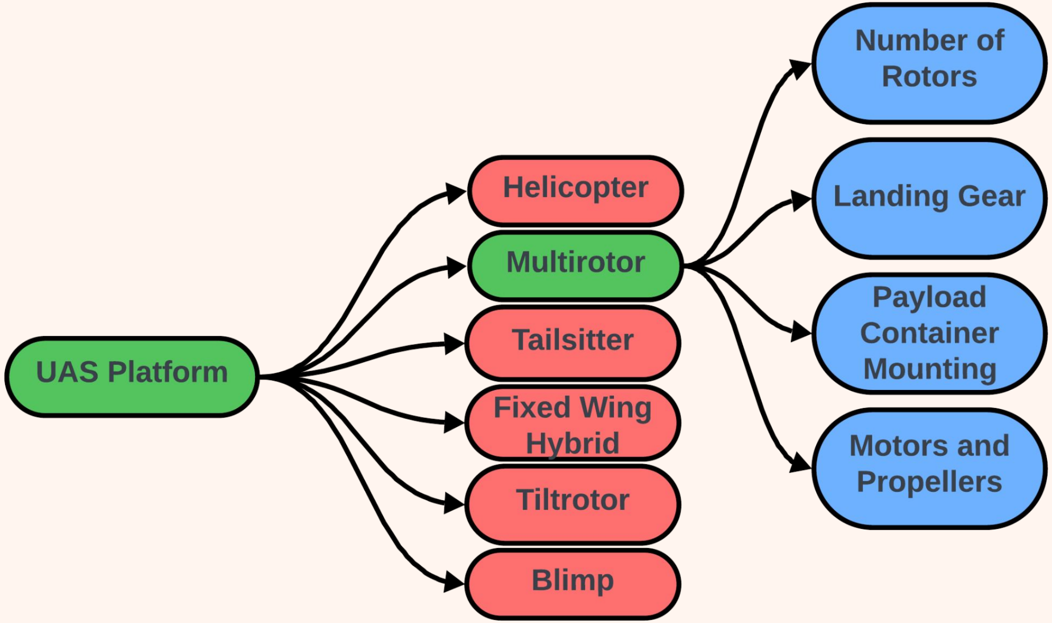
Vehicle Type Selection : Multirotor

Implications on further trades:

- Rotor configuration
- Landing gear
- Payload container mounting
- Motor and propeller selection

Initial Configurations:

- 3, 4, 5, 6, 7 and 8 rotors
- Coaxial variants

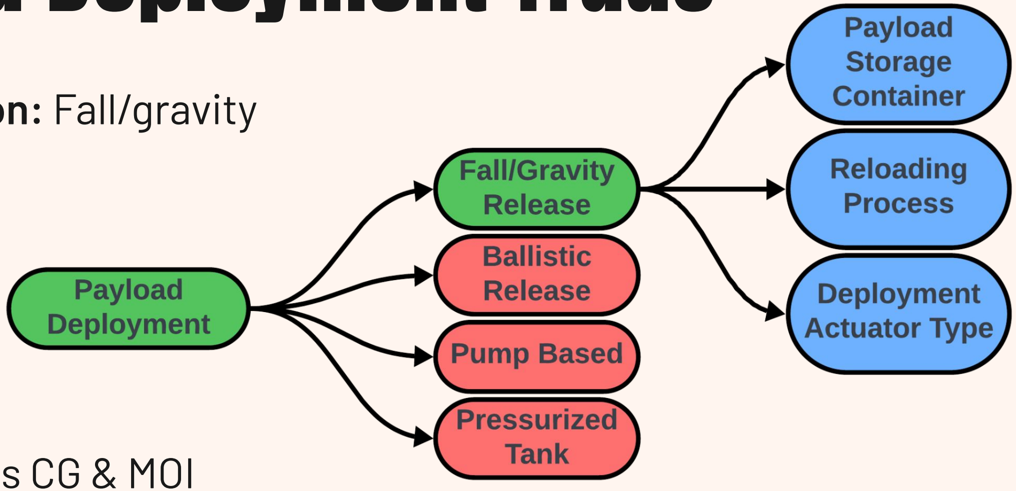


Impacts of Payload Deployment Trade

Payload Deployment method selection: Fall/gravity release

Implications on further trades:

- Limited storage methods



Initial Configurations:

- Prolate vs Oblate storage: affects CG & MOI
- Cylindrical vs Rectangular: affects flow rate through outlet
- Refill Inlet Position, top vs bottom vs side: affects possibility of leaking, reload time
- Deployment actuator type

Critical Remaining Advanced Prototyping & Modeling Trades

Critical Trades	Interdependencies	Needs
Rotor Count	UAS Platform	Advanced modeling
Payload Container Design	Payload Deployment Method	Advanced prototyping
Flight Controller Selection	UAS Platform, Rotor Count	Advanced modeling

Modeling & Prototyping Plans

Trades in Progress

Trade Description	Model/Prototyping Method	Completion Status	Description of Method
Rotor Count	Model	In Progress	Utilize MATLAB to model propulsion system
Payload Container Design	Prototype	In Progress	Conduct testing of different payload storage methods and verify the amount of payload that can be held
Motor Selection	Model	In Progress	Model the power consumption of the power subsystem during all stages of flight
Propeller Selection	Model	In Progress	Model the thrust v.s. weight for the different propeller types in MATLAB

Trades in Progress

Trade Description	Model/Prototyping Method	Completion Status	Description of Method
Airframe Selection	Model	Not Started	Model airframe performance characteristics
Landing Gear Selection	Prototype/Model	Not Started	Test different landing gear mechanisms for the aircraft using mission conditions and model landing gear performance characteristics
GPS Selection	Model	Not Started	Model the accuracy of different GPS receivers along with the error associated with each receiver

Trades in Progress

Trade Description	Model/Prototyping Method	Completion Status	Description of Method
Primary Sensor Selection	Model	Not Started	Model the wind speed collection and accuracy of different airspeed sensors
Secondary Sensor Selection	Model	Not Started	Model the pressure data along with the accuracy of the pressure data in different pressure sensors
Autopilot Software Selection	Model	Not Started	Test different autopilot softwares in a simulation and model the accuracy and precision of the different softwares

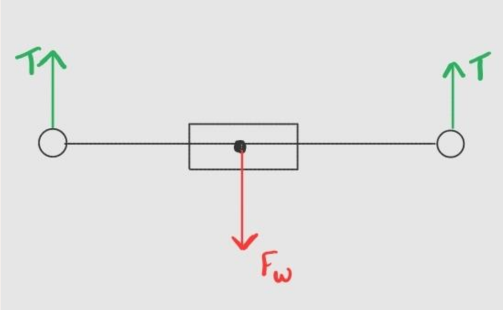
Trades in Progress

Trade Description	Model/Prototyping Method	Completion Status	Description of Method
Flight Controller Selection	Model/Prototype	Not Started	Model the stability and maneuverability of each of the different flight controllers of a simulated flight
Battery Selection	Model	Not Started	Model the amount of power provided by different batteries as well as the battery efficiencies

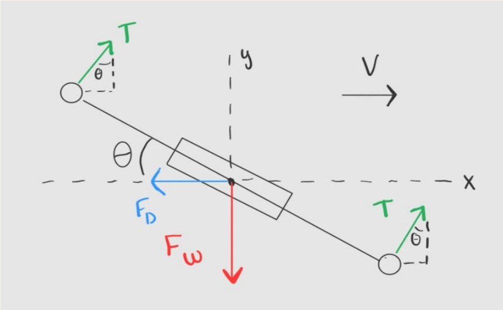
First Model: Multirotor Translation

- Assumptions
  - Symmetrical airframe
  - Constant, symmetrical thrust
  - Lift/drag negligible
  - No vertical translation
  - No initial velocity
  - No wind

Vertical Translation FBD



Horizontal Translation FBD



First Model Analysis

- Easily Known Inputs
  - Horizontal distance (d)
  - Vertical height (h)
  - Mass (m)
  - Time (t)
- Potentially Difficult to Measure Inputs
  - Rotation (θ)
  - Thrust (T)
- Useful results
  - Mass of the aircraft given a thrust value
  - Thrust needed to reach a destination within a specific time

Most Critical Remaining Trade: Number of Rotors

- Use of first model
  - Worst case scenario
    - Three horizontal 100m trips with 30 foot takeoff and landing, there and back, within 20 minutes
  - Input time, rotation angle, mass, height/distance, and gravity into MATLAB
    - Output thrust
  - Input thrust, time, height/distance, and gravity into MATLAB
    - Output mass
- How this supports number of rotors trade study
  - Desired mass and thrust known
    - Quantify parameters for trade study

Next Steps With Model

- Expand model to include drag, wind, etc.
- Testing plans
    - Power study of rotors to ensure they are producing desired thrust
        - Meet 20 minute requirement
    - Weigh the rotors
        - Meet mass requirement
    - Eventual test flights
        - Ensure it meets performance requirements

Questions?

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Backup Slides

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Level 0 Requirements

Level 0: Functional				
Requirement Number		Parent Requirement	Child Requirement	Verification Method
FR 1.1	The system shall have a minimum range of 100 meters		DR 1.3,DR 2.2	T/D
FR 1.2	The system shall be able to take off autonomously		DR 1.4	D
FR 1.3	The system shall be able to land autonomously		DR 1.4	D
FR 1.4	The system shall be capable of making 3 drops in a 20-minute span		DR 1.7	T
FR 1.5	The system shall reach target location above the 30 foot hard deck		DR 1.8	D
FR 1.6	The system shall only vertically translate below the 30 foot hard deck, at the location of interest and take-off/landing position		DR 1.6	T/A
FR 1.7	The system shall be operable in mild weather conditions		DR 1.9, DR 2.4	T/D/A
FR 1.8	The system shall return to a known safe waypoint altitude if loss of communication and control		DR 1.12	D
FR 2.1	The system shall carry and deploy 5 pounds of fire retardant per target location		DR 2.5, DR 3.1	T/D
FR 2.2	The system shall be able to take off, fly, and land with a minimum fire retardant weight of 5 pounds		DR 1.4, DR 2.1	T/D

Level 0 Requirements

FR 2.3	The payload shall consist of dyed water solution to mimic the viscosity and density of a PHOS-CHEK mixture		DR 1.10	I
FR 2.4	The system components shall be less than 55 pounds with payload		DR 2.3, DR 2.6,	I
FR 3.1	The system shall utilize human-in-the-loop to navigate from 10 meters RMS accuracy to 1 meter from location of interest		DR 1.2, DR 1.5	D
FR 3.2	The system shall be able to fly in US airspace		DR 1.11,DR 2.7	I
FR 3.3	The system components shall maintain visual line of sight from pilot		DR 3.3	D
FR 3.4	The system components meet the certification requirements set by CU flight operations		DR 1.13	I
FR 3.5	The system shall deploy the payload and have it land within a +/- 1 meter accuracy of target location		DR 1.1	T

Level 1 Requirements

Level 1: System Requirements				
Requirement Number	Requirement	Parent Requirement	Child Requirement	Verification Method
DR 1.1	The avionics system shall control the deployment mechanism for the fire retardant with a precision of +/- 1 meter from the intended drop zone	FR 3.5	DR 4.1.1, DR 6.1.1	T/A
DR 1.2	The avionics system shall ensure autonomous navigation within 10 meters RMS accuracy	FR 3.1	DR 1.1.1	T/D
DR 1.3	The avionics system shall be capable of maintaining operational control and communication within a 100 meter diameter	FR 1.1	DR 2.1.1, DR 5.1.1	A/D
DR 1.4	The avionics system shall support autonomous takeoff and landing with a specified payload of 5 pounds	FR 2.2	DR 3.1.1, DR 3.1.2, DR 3.1.3, DR 5.1.4, DR 5.1.5	D
DR 1.5	The avionics system shall allow human-in-the-loop input for precision navigation within 1 meter of the target using visual markers and payload deployment	FR 3.1	DR 5.1.3, DR 6.1.3	D
DR 1.6	The avionics system shall only allow vertical translation below the 30 foot hard deck only at the locations of interest.	FR 1.6	DR 3.1.4	T/D
DR 1.7	The avionics system shall enable at least 3, 5 pound fire retardant drops in 20 minutes	FR 1.4	DR 5.1.6	T
DR 1.8	The avionics system shall maintain an altitude greater than 30 feet during approach to the target location	FR 1.5	DR 3.1.4, DR 5.1.2	D
DR 1.9	The avionics system shall ensure stable operation under mild weather conditions	FR 1.7	DR 1.2.1, DR 2.1.2, DR 4.1.2, DR 5.1.7	D

Level 1 Requirements

DR 1.10	The avionics system shall be capable of deploying a dyed water solution that mimics the viscosity and density of a PHOS-CHEK mixture	FR 2.3	DR 6.1.2	D
DR 1.11	The avionics system shall comply with FAA regulations for unmanned aircraft systems operating in US airspace	FR 3.2	DR 1.1.3 DR 4.1.4, DR 5.1.9, DR 6.1.4, DR 7.1.2	I
DR 1.12	The avionics system shall autonomously return the aircraft to a predefined safe waypoint altitude upon loss of communication	FR 1.8	DR 1.1.2, DR 2.1.3, DR 3.1.5, DR 4.1.3, DR 5.1.8 DR 7.1.1	D
DR 1.13	The avionics system shall meet the specific certification requirements set by CU flight operations	FR 3.4	DR 1.1.3, DR 4.1.4, DR 5.1.9, DR 6.1.4, DR 7.1.2	I
DR 2.1	The structure system shall support a payload capacity of at least 5 pounds for carrying fire retardant materials	FR 2.2	DR 6.2.2, DR 7.2.3	T/D

Level 1 Requirements

DR 2.2	The structure system shall support flight over a minimum operational range of 100 meters	FR 1.1	DR 3.2.1, DR 4.2.1, DR 7.2.6	T/D
DR 2.3	The structure system shall handle a maximum takeoff weight not exceeding 55 pounds	FR 2.4	DR 7.2.5	A/D
DR 2.4	The structure system shall withstand mild weather conditions	FR 1.7	DR 1.2.1, DR 7.2.2	T/D/I
DR 2.5	The structure system shall accommodate a payload designed to hold the dyed water solution without leakage	FR 2.1	DR 6.2.1, DR 7.2.4	D
DR 2.6	The structure system shall ensure that the total weight, including all components and payload, does not exceed 55 pounds	FR 2.4	DR 7.2.1	I
DR 2.7	The structure system shall be FAA compliant	FR 3.2	DR 1.1.3, DR 4.1.4, DR 5.1.9, DR 6.1.4, DR 7.1.2	I
DR 3.1	The ground system shall allow for pre-programming of target locations for fire retardant deployment	FR 2.1	DR 4.3.1, DR 5.3.1	I/D
DR 3.2	The ground system shall provide telemetry data to the operator during flight	FR 1.2, FR 1.3	DR 1.3.1, DR 4.3.2, DR 4.3.3	D
DR 3.3	The ground control system shall allow the operator to maintain line of sight with the UAS	FR 3.3	DR 4.2.1	D

Level 2 Requirements

Level 2: Sub System Requirements				
Requirement Number	Requirement	Parent Requirement	Child Requirement	Verification Method
Sensing				
DR 1.1.1	The sensing subsystem shall be capable of providing real-time location data with an accuracy of +/- 10 meters	DR 1.2		T/D
DR 1.3.1	The sensing subsystem shall be capable of determining orientation and motion direction	DR 3.2		I/D
DR 1.3.2	The sensing subsystem shall be capable of tracking the aircraft's position in [x,y,z] coordinates	DR 3.2		D
DR 1.2.1	The sensing subsystem shall be capable of measuring wind speed	DR 1.9, DR 2.4		D
DR 1.1.2	The sensing subsystem shall continuously monitor communication signals to detect loss of connectivity with ground control	DR 1.12		D
DR 1.1.3	The sensing subsystem shall be capable of detecting when a 5 pound payload has been deployed	DR 1.7		A/I
DR 1.1.4	The sensing subsystem shall comply with FAA and CU Flight Op guidelines	DR 1.11, DR 1.13, DR 2.7		I

Level 2 Requirements

Power				
DR 2.1.1	The power subsystem shall provide power to support operation of all systems for the mission duration	DR 1.3		D
DR 2.1.2	The power subsystem shall be able to operate in mild weather conditions	DR 1.9, DR 2.4		D
DR 2.1.3	The power subsystem shall provide power to support operation of essential systems under fail-safe conditions	DR 1.12		T/D

Level 2 Requirements

Power				
DR 2.1.1	The power subsystem shall provide power to support operation of all systems for the mission duration	DR 1.3		D
DR 2.1.2	The power subsystem shall be able to operate in mild weather conditions	DR 1.9, DR 2.4		D
DR 2.1.3	The power subsystem shall provide power to support operation of essential systems under fail-safe conditions	DR 1.12		T/D

Level 2 Requirements

Propulsion				
DR 3.1.1	The propulsion subsystem shall provide thrust sufficient to lift the aircraft and its payload during take off and landing	DR 1.4		D
DR 3.1.2	The propulsion subsystem shall support autonomous takeoff capabilities	DR 1.4		D
DR 3.1.3	The propulsion subsystem shall support autonomous landing capabilities	DR 1.4		D
DR 3.1.4	The propulsion subsystem shall provide sufficient thrust to reach the 30 foot hard deck	DR 1.6, DR 1.8		D
DR 3.1.5	The propulsion subsystem shall be able to maneuver under fail-safe conditions	DR 1.12		D
DR 3.2.1	The propulsion subsystem shall deliver thrust within an operational range of a 100 meter diameter	DR 2.2		T/D

Level 2 Requirements

Communications				
DR 4.2.1	The communication subsystem shall be capable of data transmission between the avionics and ground systems during the mission with a range of a 100 meter diameter	DR 2.2, DR 3.3		T/D
DR 4.3.1	The communication subsystem shall be capable of receiving and transmitting GPS data	DR 3.1		T/D/I
DR 4.3.2	The communication subsystem shall update the ground system with telemetry data	DR 3.2		I/D
DR 4.1.1	The communication subsystem shall transmit the status of the payload deployment to the ground control system in real-time	DR 1.1		D
DR 4.3.3	The communication subsystem shall update the avionics system with telemetry data	DR 3.2		D/I
DR 4.1.2	The communication subsystem shall be capable of transmitting environmental data	DR 1.9		T/D/I
DR 4.1.3	The communication subsystem shall be capable of detecting communication loss	DR 1.12		T/D
DR 4.1.4	The communication subsystem shall comply with FAA and CU Flight Op guidelines	DR 1.11, DR 1.13, DR 2.7		I

Level 2 Requirements

Control				
DR 5.1.1	The control subsystem shall ensure stability and responsiveness of the aircraft during operation	DR 1.3		T
DR 5.1.2	The control subsystem shall maintain flight above the 30 foot hard deck during horizontal translation	DR 1.8		T/D
DR 5.3.1	The control subsystem shall enable autonomous movement between locations of interest	DR 3.1		D
DR 5.1.3	The control subsystem shall allow for human-in-the-loop control	DR 1.5		D
DR 5.1.4	The control subsystem shall support autonomous take-off	DR 1.4		D
DR 5.1.5	The control subsystem shall support autonomous landing	DR 1.4		D
DR 5.1.6	The control subsystem shall maintain stable operation in mild weather conditions	DR 1.9		T/D/A
DR 5.1.7	The control subsystem shall allow for an automatic return to a predefined safe waypoint upon loss of communication	DR 1.12		D
DR 5.1.8	The control subsystem shall comply with FAA and CU Flight Op guidelines on autonomous flight	DR 1.11, DR 1.13, DR 2.7		I

Level 2 Requirements

Payload Deployment				
DR 6.1.1	The payload deployment subsystem shall include a payload deployment mechanism that allows for release of fire retardant with a precision of +/- 1 meter	DR 1.1		T
DR 6.2.1	The payload deployment subsystem shall hold the payload of a dyed water solution while preventing leakage during flight	DR 2.5		I/D
DR 6.1.2	The payload deployment subsystem shall be capable of deploying the dyed water solution at the locations of interest	DR 1.10		D
DR 6.2.2	The payload deployment subsystem shall be capable of deploying a 5 pound payload per target location	DR 2.1		A/I
DR 6.1.3	The payload deployment subsystem shall support human-in-the-loop deployment capabilities	DR 1.5		D
DR 6.1.4	The payload deployment subsystem shall comply with FAA and CU Flight Op guidelines	DR 1.11, DR 1.13, DR 2.7		I

Level 2 Requirements

Airframe				
DR 7.2.1	The airframe subsystem shall be able to support the total weight of the UAS	DR 2.6		D
DR 7.2.2	The airframe subsystem shall be constructed using materials that can resist mild weather conditions	DR 2.4		I
DR 7.2.3	The airframe subsystem shall include payload mounting and storage capabilities of an at least 5 pound payload	DR 2.1		I/D
DR 7.2.4	The airframe subsystem shall include appropriate storage of the payload to prevent spillage	DR 2.5		I/D
DR 7.2.5	The airframe subsystem shall be constructed to withstand the forces associated with controlled takeoffs, descents and landings at locations of interest	DR 2.3		D
DR 7.1.1	The airframe subsystem shall be designed to withstand flight during fail-safe conditions	DR 1.12		D
DR 7.2.6	The airframe subsystem shall be designed to support operational ranges within a 100 meter diameter	DR 2.2		D
DR 7.1.2	The airframe shall be designed to comply with FAA and CU Flight Op guidelines	DR 1.11, DR 1.13, DR 2.7		I

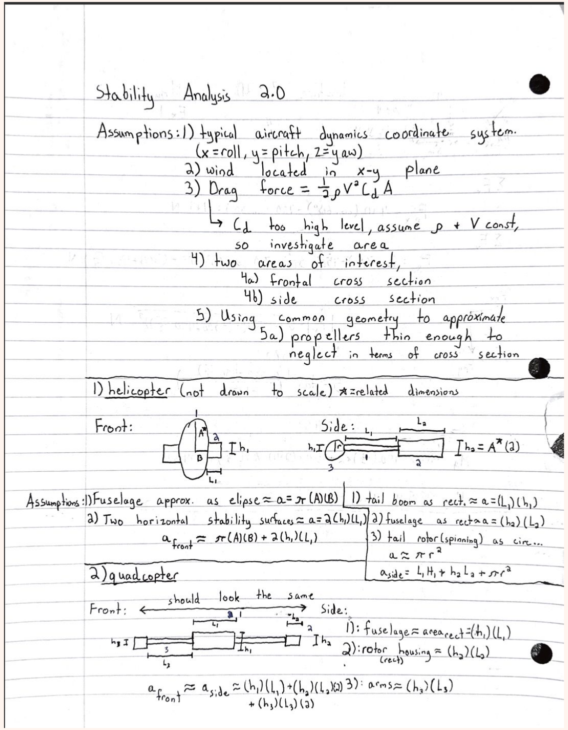
UAS Engineering Analysis: Stability

- Developed a model analyzing the cross sectional areas in the x-y plane to determine the impact of drag forces from light winds
    - Two areas for each vehicles type: frontal-view cross section and side-view cross section

- Model utilizes simple geometric shapes to approximate components of each UAS type, along with common physical dimensions relative to each aircraft type and the mission requirements

- Other assumptions assert that vehicle propellers are thin enough to be treated as two dimensional and all wind sources are located in the x-y plane

UAS Engineering Analysis: Stability



Stability Analysis 2.0

Assumptions: 1) typical aircraft dynamics coordinate system. (x = roll, y = pitch, z = yaw)
2) wind located in x-y plane
3) Drag force $= \frac{1}{2}\rho V^2 C_d A$
→ C_d too high level, assume ρ + V const, so investigate area
4) two areas of interest,
4a) frontal cross section
4b) side cross section
5) Using common geometry to approximate
5a) propellers thin enough to neglect in terms of cross section

1) helicopter (not drawn to scale) ★ = related dimensions

Front:

Side: $h_2 = A^*(2)$

Assumptions: 1) Fuselage approx. as elipse $\approx a = \pi(A)(B)$
2) Two horizontal stability surfaces $\approx a = 2(h_1)(L_1)$
$a_{front} \approx \pi(A)(B) + 2(h_1)(L_1)$

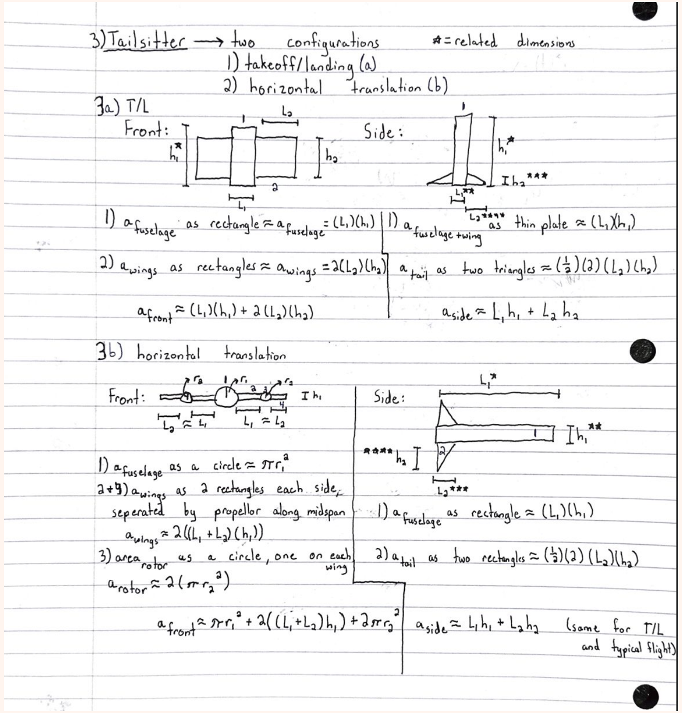
1) tail boom as rect. $\approx a = (L_1)(h_1)$
2) fuselage as rect $\approx a = (h_2)(L_2)$
3) tail rotor (spinning) as circ... $a \approx \pi r^2$
$a_{side} = L_1 H_1 + h_2 L_2 + \pi r^2$

2) quadcopter

Front: ← should look the same → Side:

1): fuselage $\approx area_{rect} = (h_1)(L_1)$
2): rotor housing (rect) $\approx (h_2)(L_2)$
3): arms $\approx (h_3)(L_3)$

$a_{front} \approx a_{side} \approx (h_1)(L_1) + (h_2)(L_2)(2) + (h_3)(L_3)(2)$



3) Tailsitter → two configurations ★ = related dimensions
1) takeoff/landing (a)
2) horizontal translation (b)

3a) T/L

Front:

Side:

1) $a_{fuselage}$ as rectangle $\approx a_{fuselage} = (L_1)(h_1)$
2) a_{wings} as rectangles $\approx a_{wings} = 2(L_2)(h_2)$
$a_{front} \approx (L_1)(h_1) + 2(L_2)(h_2)$

1) $a_{fuselage+wing}$ as thin plate $\approx (L_1)(h_1)$
a_{tail} as two triangles $\approx (\frac{1}{2})(2)(L_2)(h_2)$
$a_{side} \approx L_1 h_1 + L_2 h_2$

3b) horizontal translation

Front: $L_2 \approx L_1$, $L_1 \approx L_2$

Side:

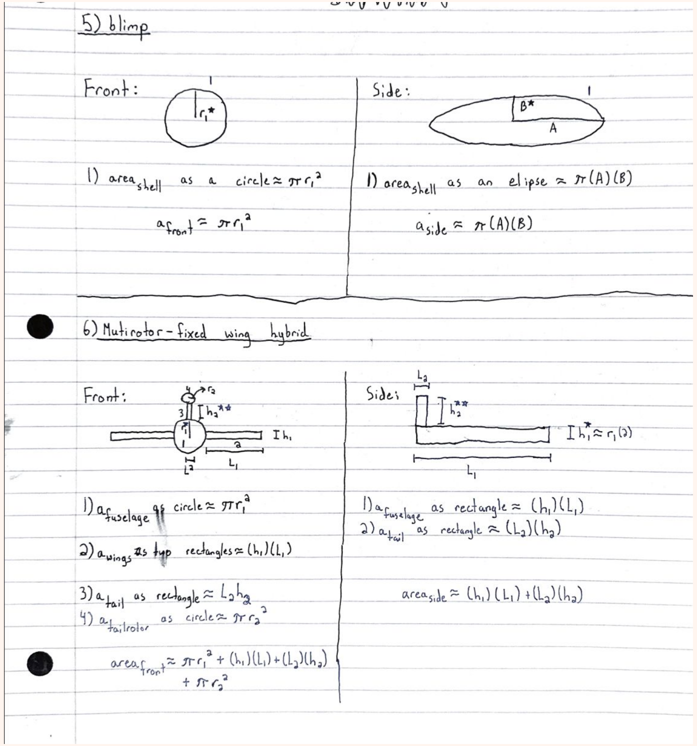
1) $a_{fuselage}$ as a circle $\approx \pi r_1^2$
2+4) a_{wings} as 2 rectangles each side, seperated by propellor along midspan
$a_{wings} \approx 2((L_1 + L_2)(h_1))$
3) $area_{rotor}$ as a circle, one on each wing
$a_{rotor} \approx 2(\pi r_2^2)$

1) $a_{fuselage}$ as rectangle $\approx (L_1)(h_1)$
2) a_{tail} as two rectangles $\approx (\frac{1}{2})(2)(L_2)(h_2)$

$a_{front} \approx \pi r_1^2 + 2((L_1 + L_2)h_1) + 2\pi r_2^2$

$a_{side} \approx L_1 h_1 + L_2 h_2$ (same for T/L and typical flight)

UAS Engineering Analysis: Stability



Analysis Results:

- After using MATLAB to compute respective cross sectional areas, the following data was computed. Note that each UAS has two cross sectional area values, frontal and side, but the highest one is listed here as it's the most relevant to the UAS trade study
  - Helicopter = 0.2659 (side CS)
  - Quadrotor = 0.0632 (frontal CS)
  - Blimp = 4.3779 (side CS)
  - Hybrid = 0.1945 (side CS)
  - Tailsitter takeoff configuration = 0.5109 (frontal CS)
  - Tiltrotor = 0.2 (Side CS)

Note that CS is shorthand for cross section, and all values are in units of square meters. Additionally, the tilt rotor UAS type is very similar in terms of geometry to the hybrid model, and can be approximated as having roughly the same CS areas.

UAS Engineering Analysis: Stability

Driving analysis assumption:

- A higher cross sectional area will result in a larger drag force from wind perturbations, and therefore increase the likelihood of instability

Resultant stability rankings and takeaways from computed CS areas:

1: Quadrotor (Great)
- Compactness and symmetry help reduce wind effects.

2: Hybrid (Good)
- Fuselage and wing design dominate drag impacts.

3: Tilt rotor (Good)
- Similar to the hybrid model, the fuselage and wing geometry are paramount to stability analysis.

4: Helicopter (Good)
- Slim frontal CS, but poor side CS due to tail boom length.

5: Tail sitter takeoff configuration (Poor)
- Unique design that excels in standard flight, but prone to instability during takeoff and landing stages.

6: Blimp (Poor)
- Massive surface area invites problems at any wind speed.

Final thoughts:

- Model provides a good foundation to analyze the stability of each UAS type, but fails to include the complex effects of the moments of inertia and control methods specific to each vehicle configuration and must be supplemented with research.

Payload Deployment - Weight Reasoning

- Deployment Stability = 0.25
  - Very important
  - Must be able to control the UAS during deployment
    - Cannot crash or become unstable – especially through means of payload deployment
- Reloading Process - 0.05
  - Not very important
  - Time to deploy is <1% of overall mission time
- Power Consumption
  - Very important
  - Power budget may be strained
  - Need payload system to minimize its power
    - Other parts of the system need more power flexibility

Payload Deployment - Weight Reasoning

- Deployment speed - 0.05
  - Not deemed vital for mission objectives
  - Time to deploy is <1% of overall mission time
- Weather Impact Resilience - 0.15
  - Important that payload is not
  - Often times, wind and weather is quite prevalent in forest fires, especially ones that start naturally – drone's entire mission is to be able to put out these fires in their respective conditions
- Ease of Deployment Verification - 0.1
  - Somewhat vital
  - Must be able to verify the tests we do
- Repeated Testability - 0.2
  - Important
  - Incorporates added costs for deployment
    - Cost budget is strained
  - Incorporates time spent testing
    - Time allotted for testing is small

Time to Deploy: Pressurized Vessel

$$P_o = P_e + \frac{1}{2}\rho V^2$$

$$V = \sqrt{\frac{2(P_o - P_e)}{\rho}}$$

$$\dot{Q} = AV = A\sqrt{\frac{2(P_o - P_e)}{\rho}}$$ (volumetric flow rate)

$$\Delta t = \frac{\forall}{\dot{Q}} = \frac{\forall}{A\sqrt{\frac{2(P_o - P_e)}{\rho}}}$$

P_e: atmosphere pressure for Boulder, CO on standard day

P_o: design choice on how much tank is pressurized

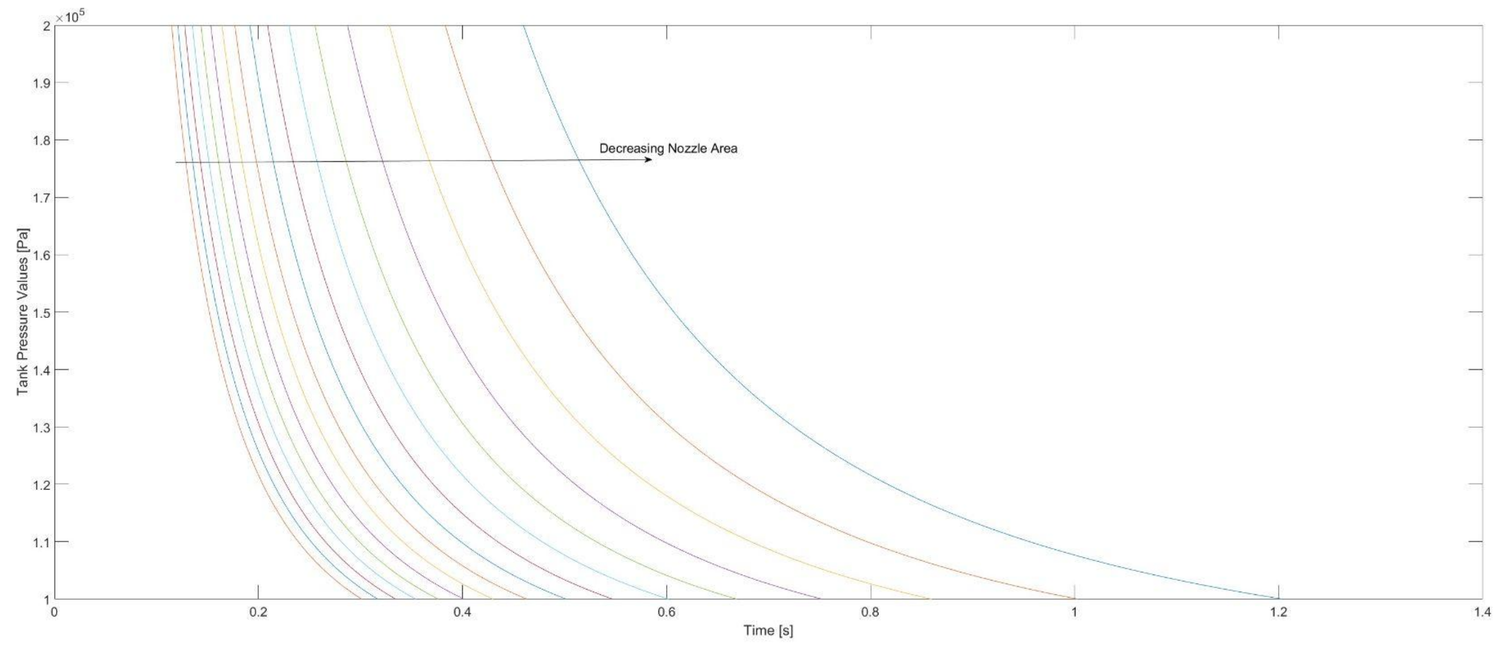
ρ: density of water for Boulder, CO on standard day

A: design choice on exit area of nozzle

$\forall$: volume of water (given)

- Plug equations into MATLAB
- Test for different tank pressures (100,000-200,000 Pa)
- Test different nozzle exit areas (0.5-2.0 in^2)
- Assumptions:
  - Volumetric flow rate is constant
  - Standard day atmosphere conditions in Boulder, CO
  - Water is incompressible

Time to Deploy: Pressurized Vessel



Drag Coefficients Based on Shape

DRAG OF TWO-DIMENSIONAL BODIES AT $Re = 10^5$

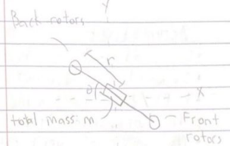
Shape	C_D based on frontal area
Plate:	
→ plate	2.0
Square cylinder:	
→ square	2.1
→ diamond	1.6
Half tube:	
→ concave side facing flow	1.2
→ convex side facing flow	2.3
Half-cylinder:	
→ curved side facing flow	1.2
→ flat side facing flow	1.7
Equilateral triangle:	
→ point facing flow	1.6
→ flat side facing flow	2.0

Elliptical cylinder:	Laminar	Turbulent
1:1 →	1.2	0.3
2:1 →	0.6	0.2
4:1 →	0.35	0.15
8:1 →	0.25	0.1

Type of body	Reference area S (b = length)	Reynolds number Re	Drag coefficient C_D
Square rod	S = b D	$Re > 10^4$	→ 2.00
Square rod (rotated 45°)	S = b D	$Re > 10^4$	→ 1.50
Semicircular shell	S = b D	$Re > 10^4$	→ 1.20 ← 2.30
Semicircular cylinder	S = b D	$Re > 10^4$	→ 1.15 ← 2.15
Equilateral triangle cylinder	S = b D	$Re > 10^4$	→ 1.40 ← 2.10
Flat plate	S = b D	$Re > 10^4$	→ 1.90
T-beam	S = b D	$Re > 10^4$	→ 1.80 ← 1.65
I-beam	S = b D	$Re > 10^4$	→ 2.05
Hexagon	S = b D	$Re > 10^4$	→ 1.00
Hexagon	S = b D	$Re > 10^4$	→ 0.70
Circular cylinder	S = b D	$Re > 10^4$	→ 0.51

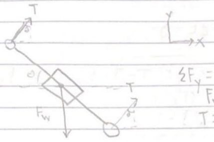
Model One

Multirotor Model
Horizontal Translation



Assumptions:
- Symmetrical airframe
- symmetrical thrust
- Lift/drag negligible
- No vertical translation
- No initial horizontal velocity
- Constant thrust
- No wind

FBD



$$\Sigma F_y = 0 = T\cos\theta + T\cos\theta - F_w$$

$$F_w = 2T\cos\theta \qquad F_w = mg$$

$$T = \frac{mg}{2\cos\theta}$$

$$\Sigma F_x = T\sin\theta + T\sin\theta$$

$$\Sigma F_x = ma_x$$

$$ma_x = 2T\sin\theta$$

$$a_x = \frac{2T\sin\theta}{m}$$

$$v_{fx}^2 = \cancel{v_{0x}^2} + 2a_x d \qquad v_{fx} = \sqrt{2a_x d}$$

$$\boxed{v_{fx} = \sqrt{\frac{4Td\sin\theta}{m}}}$$

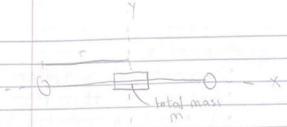
$$v_{fx} = \cancel{v_{0x}} + a_x t$$

$$\sqrt{\frac{4Td\sin\theta}{m}} = \frac{2T\sin\theta}{m} t$$

$$t = \frac{m}{\cancel{2}T\sin\theta}\sqrt{\frac{\cancel{4}Td\sin\theta}{\cancel{m}}} = \sqrt{\frac{md}{T\sin\theta}}$$

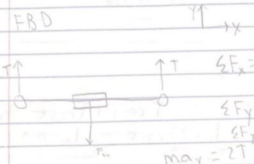
$$\boxed{t = \sqrt{\frac{md}{T\sin\theta}}}$$

Multirotor Model
Vertical Translation



Assumptions:
- Symmetrical airframe
- Symmetrical thrust
- Lift/drag negligible
- No horizontal translation
- No initial vertical velocity
- Constant thrust
- No wind

FBD



$$\Sigma F_x = 0$$

$$\Sigma F_y = T + T - F_w \qquad F_w = mg$$

$$\Sigma F_y = ma_y$$

$$ma_y = 2T - mg$$

$$a_y = \frac{2T - mg}{m}$$

$$v_{fy}^2 = \cancel{v_{0y}^2} + 2a_y h$$

$$v_{fy}^2 = 2\left(\frac{2T - mg}{m}\right)h$$

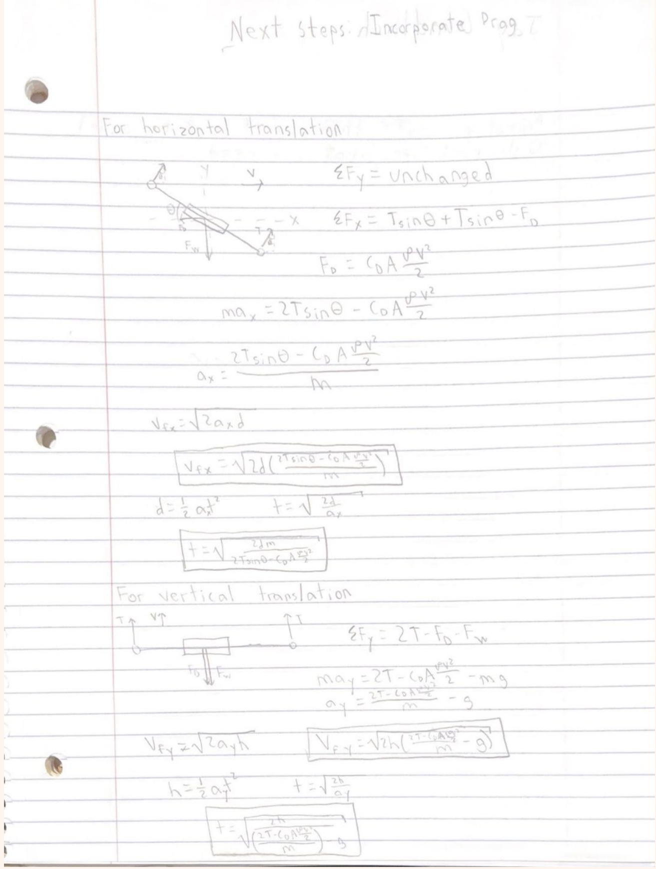
$$\boxed{v_{fy} = \sqrt{\left(\frac{4T - 2mg}{m}\right)h}}$$

$$v_{fy} = \cancel{v_{0y}} + a_y t$$

$$\sqrt{\left(\frac{2T - mg}{m}\right)2h} = \frac{2T - mg}{m} t$$

$$\boxed{t = \sqrt{\frac{2hm}{(2T - mg)}}}$$

Model 2



Next steps: Incorporate Drag

For horizontal translation

$\Sigma F_y = \text{unchanged}$

$\Sigma F_x = T\sin\theta + T\sin\theta - F_D$

$F_D = C_D A \frac{\rho v^2}{2}$

$ma_x = 2T\sin\theta - C_D A \frac{\rho v^2}{2}$

$a_x = \frac{2T\sin\theta - C_D A \frac{\rho v^2}{2}}{m}$

$v_{fx} = \sqrt{2a_x d}$

$\boxed{v_{fx} = \sqrt{2d\left(\frac{2T\sin\theta - C_D A \frac{\rho v^2}{2}}{m}\right)}}$

$d = \frac{1}{2}a_x t^2$ $\quad t = \sqrt{\frac{2d}{a_x}}$

$\boxed{t = \sqrt{\frac{2dm}{2T\sin\theta - C_D A \frac{\rho v^2}{2}}}}$

For vertical translation

$\Sigma F_y = 2T - F_D - F_w$

$ma_y = 2T - C_D A \frac{\rho v^2}{2} - mg$

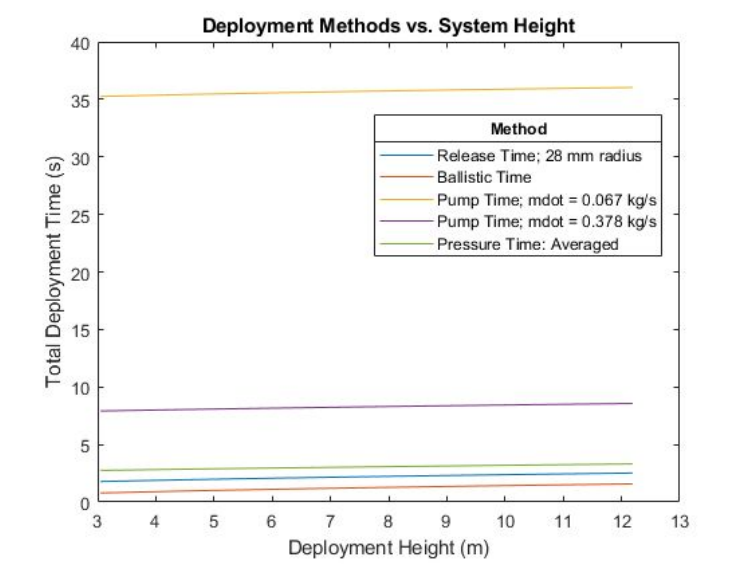
$a_y = \frac{2T - C_D A \frac{\rho v^2}{2}}{m} - g$

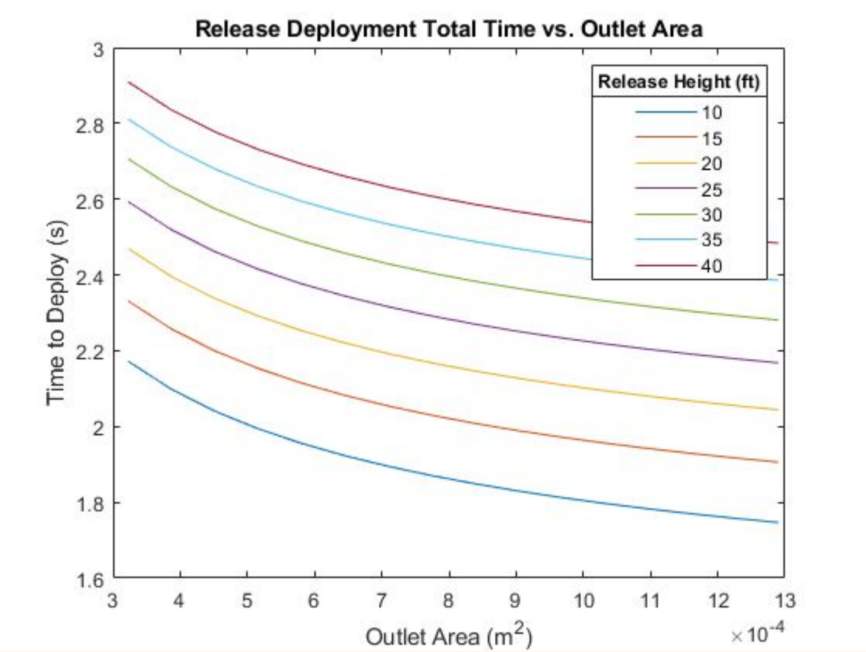
$v_{fy} = \sqrt{2a_y h}$ $\quad \boxed{v_{fy} = \sqrt{2h\left(\frac{2T - C_D A \frac{\rho v^2}{2}}{m} - g\right)}}$

$h = \frac{1}{2}a_y t^2$ $\quad t = \sqrt{\frac{2h}{a_y}}$

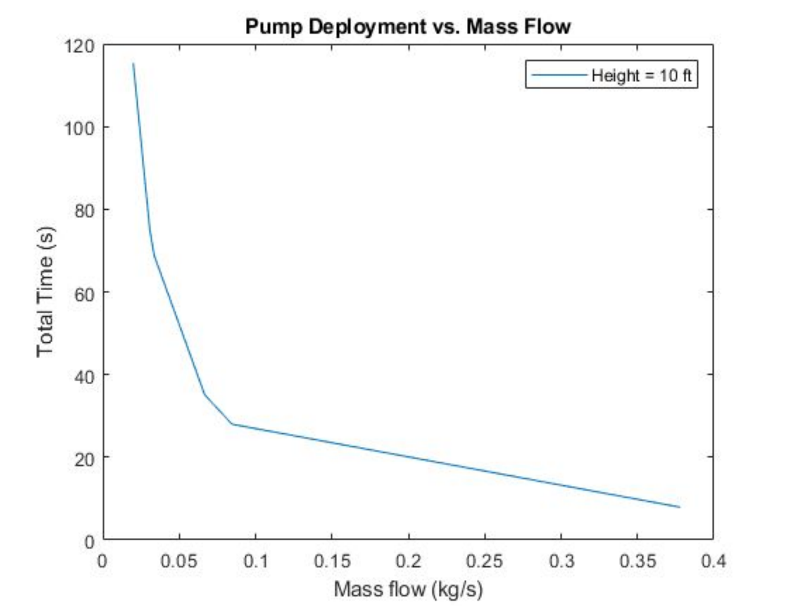
$\boxed{t = \sqrt{\frac{2h}{\left(\frac{2T - C_D A \frac{\rho v^2}{2}}{m}\right) - g}}}$

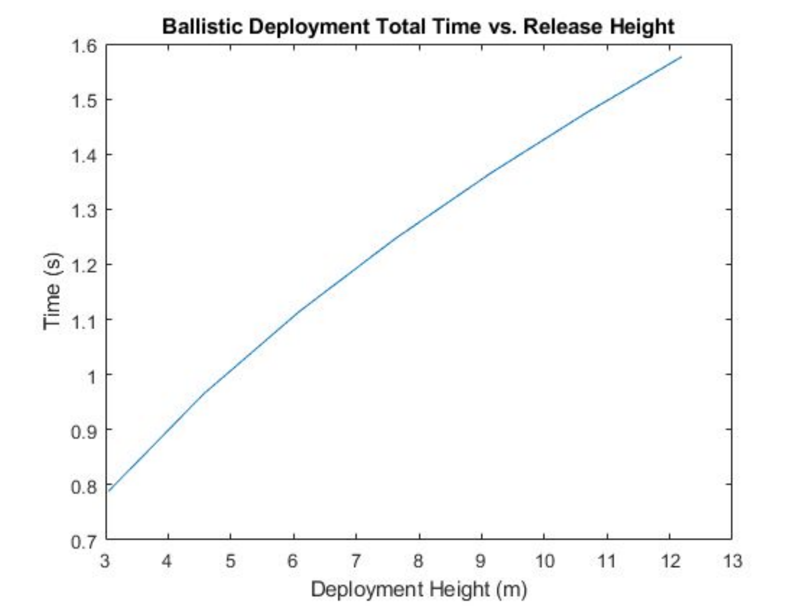
Deployment Time MATLAB Figures



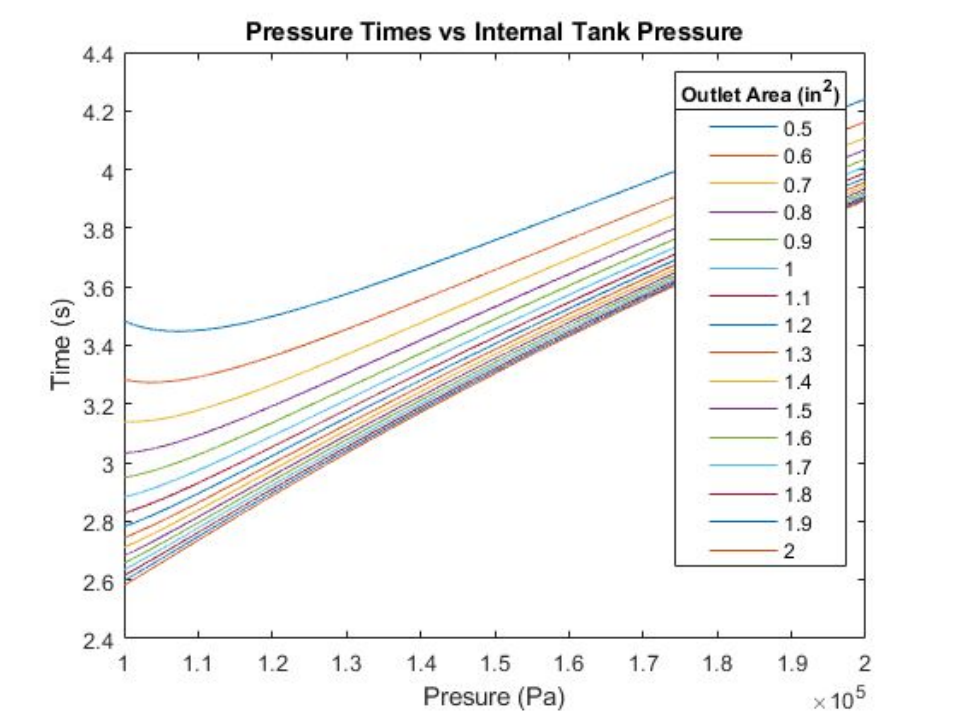


Deployment Time MATLAB Figures Cont.





Deployment Time MATLAB Figure Cont.



Deployment Time MATLAB Code: Main

```matlab
% Maximillian Brown
% Payload deployment time to deploy initial model/engi analysis
clc; clear; close all; format longG

tic %timing
%% Main
%constants / givens:
Fgrav = 22.411; %N
g = 9.81; %m/s^2
m0 = Fgrav/g; %kg
rho = 997.05; %kg/m^3

%independent vars:
A_square = linspace(2.4414e-04,0.0156,24); %area of outlet from 1/64 m a side to 1/8 m a side, assumed square
R_circs = 0.004:0.002:0.05; %8mm diameter to 10 cm diameter, in meters
A_circs = pi.*R_circs.^2;
h = (10:5:40)./3.281; %10-40 ft converted to m
h = h';

A = 0.5:0.1:2; % in^2
A= A .* 0.00064516; % in^2 -> m^2
%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~Release Stuff~~~~~~~~~~~~~~~~~~~~~~~~~~~~~%
%find times for release method with both matrices:
Release_fall = zeros(7,16);
Release_empty = zeros(7,16);
for i = 1:7
    for j = 1:length(A)
        test_release_times = getTime_Release(m0,g,rho,A(:,j),h(i,:));
        Release_fall(i,:) = test_release_times(2);
        Release_empty(:,j) = test_release_times(1);
        Release_times_tot = Release_empty + Release_fall;
    end
end

%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~Pump Stuff~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~%
A_pump = pi*(0.004)^2;
mdot_pump = [0.0199521,0.0308,0.03339,0.0336,0.06657147,0.0672,0.08456,0.378];

%preallocate
Pump_empty = zeros(1,8);
Pump_fall = zeros(7,1);
Pump_time_tot = zeros(7,8);
for i = 1:7
    for j = 1:length(mdot_pump)
        Pump_time = getTime_Pump(m0,g,rho,A_pump,h(i,:),mdot_pump(:,j));
        Pump_empty(:,j) = Pump_time(1);
        Pump_fall(i,:) = Pump_time(2);
        Pump_time_tot(i,j) = Pump_time(3);
    end
end

%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~Ballistic Stuff~~~~~~~~~~~~~~~~~~~~~~~~~~~~%
Ballistic_time_tot = zeros(1,7);
for i = 1:7
    Ballistic_time_tot(:,i) = getTime_Ballistic(h(i,:),g);
end

%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~Pressure Stuff~~~~~~~~~~~~~~~~~~~~~~~~~~~~~%
%define internal pressure values
Po = 100000:10:200000;

%height -> outlet area -> internal pressure --> Pressure times:
Pressure_tot = zeros(7,16);
Pressure_middlevariable = zeros(1,10001);
Pressure_middle2 = zeros(1,10001);
Pressure_middle3 = zeros(1,10001);
Pressure_AP_tot = zeros(16,10001);
Pressure_AP_empty = zeros(16,10001);
Pressure_AP_fall = zeros(16,10001);
for i = 1:7
    for j = 1:16
        for m = 1:10001
            x = getTime_Pressure(m0,g,rho,A(:,j),h(i,:),Po(:,m));
            Pressure_middlevariable(:,m) = x(3); %extract total time
            Pressure_middle2(:,m) = x(1); %extract time to empty
            Pressure_middle3(:,m) = x(2); % "" fall
        end
        Pressure_AP_tot(j,:) = Pressure_middlevariable; %save pressure vs Area values for separate graph
        Pressure_AP_empty(j,:) = Pressure_middle2;
        Pressure_AP_fall(j,:) = Pressure_middle3;
        Pressure_tot(i,j) = mean(Pressure_middlevariable,2); %average total times for all tested pressure values
    end
end
```

Deployment Time MATLAB Code: Graphing

```
figure('Name','Payload System Total Deployment Times') %analyze vs drop height (good for analysis and addressing assumptions)
    plot(h,Release_times_tot(:,13)); hold on
    plot(h,Ballistic_time_tot);
    plot(h,Pump_time_tot(:,5));
    plot(h,Pump_time_tot(:,8));
    plot(h,Pressure_tot(:,13));
    legend('Release Time; 28 mm radius','Ballistic Time','Pump Time; mdot = 0.067 kg/s','Pump Time; mdot = 0.378 kg/s','Pressure Time: Averaged')
    ylabel('Total Deployment Time (s)')
    xlabel('Deployment Height (m)')
    leg = legend('show');
    title('Deployment Methods vs. System Height')
    title(leg,'Method')

figure('Name','Fall Release Times') %release times vs area
    plot(A,Release_times_tot);
    legend('10','15','20','25','30','35','40');
    xlabel('Outlet Area (m^2)')
    ylabel('Time to Deploy (s)')
    leg = legend('show');
    title('Release Deployment Total Time vs. Outlet Area')
    title(leg,'Release Height (ft)')

figure('Name','Ballistic Times')
    plot(h,Ballistic_time_tot)
    xlabel('Deployment Height (m)')
    ylabel('Time (s)')
    title('Ballistic Deployment Total Time vs. Release Height')

figure('Name','Pump Times')
    plot(mdot_pump',Pump_time_tot(1,:))
    xlabel('Mass flow (kg/s)')
    ylabel('Total Time (s)')
    title('Pump Deployment vs. Mass Flow')
    legend('Height = 10 ft')

figure('Name','Pressure Times');
plot(Po,Pressure_AP_tot)
    xlabel('Presure (Pa)')
    ylabel('Time (s)')
    title('Pressure Times vs Internal Tank Pressure')
    leg = legend('show');
    title(leg,'Outlet Area (in^2)')
    legend('0.5','0.6','0.7','0.8','0.9','1','1.1','1.2','1.3','1.4','1.5', ...
        '1.6','1.7','1.8','1.9','2')
```

Deployment Time MATLAB Code: Functions

```matlab
function Release_times = getTime_Release(m0,g,rho,A,h)
%function to calculate release design's total deployment time
%   assume: -water density is constant and approximated through tables
%           -flow velocity is constant
%           -A is opened instantinously
%           -only force being applied is gravity
%           -flow is continuous
%           -air resistance is negligible for now (needs assessment)
    %calculate the velocity, v0
    v0 = sqrt((m0*g)/(rho*A));

    %calculate mdot; the continuous flow out of the nozzle/outlet
    mdot = rho*A*v0;

    %calculate t_empty; the time for all the water to leave the outlet
    t_empty = m0/mdot;

    %calculate t_fall, must use raw coding to select the highest and/or pos
    %value for general estimate (good for high level est. but needs further
    %fidelity to decide which time value is more accurate if both are
    %positive:
    t_fall_plus = (2*v0+sqrt(4*v0^2+8*g*h))/(2*g);
    t_fall_minus = (2*v0-sqrt(4*v0^2+8*g*h))/(2*g);
    if t_fall_minus >= t_fall_plus
        t_fall = t_fall_minus;
    else
        t_fall = t_fall_plus;
    end

    %combine
    Fall_time_tot = t_empty + t_fall;

    %output
    Release_times = [t_empty,t_fall,Fall_time_tot];
end
```

```matlab
function Ballistic_time = getTime_Ballistic(h,g)
%function for finding the time for the ballistic unit of water to drop
%   assume: -air in the ballistic unit is negligible compared to water
%           -verticle air resistance is negligible
%           -holding for ballistic unit is oiled; no friction
%           -ballistic unit at rest when released, v0 = 0
%           -acceleration due to gravity is constant

    %use kinematic equations with no air-resistance & v0=0 to solve for
    %time to fall:
    Ballistic_time = abs(sqrt((2*h)/g));
end
```

Deployment Time MATLAB Code: Functions

```
function Pressure_times = getTime_Pressure(~,g,rho,A,h,Po)
    % Credit: Jared Steffen
    %[~,a,T,Pe,nu,z] = atmos(1655); %Jared's original call
    [~,~,Pe,~,~] = atmosisa(1655); %adjusted for using atmosisa (works with my code not sure the error with atmos)

    V = sqrt((2.*(Po-Pe)/rho));

    Q = A'*V;

    volume = 0.5991 * 0.00378541; % gal -> m^3

    Pressure_times_empty = volume./Q; %changed time variable name to match syntax of others

    %find time for water to fall: (similar to t_fall from release method)
    t_pressure_plus = (2*V+sqrt(4*V^2+8*g*h))/(2*g);
    t_pressure_minus = (2*V-sqrt(4*V^2+8*g*h))/(2*g);
    if t_pressure_minus >= t_pressure_plus
        t_pressure_fall = t_pressure_minus;
    else
        t_pressure_fall = t_pressure_plus;
    end

    %combine
    Pressure_time_tot = Pressure_times_empty + t_pressure_fall;
    Pressure_times = [Pressure_times_empty,t_pressure_fall, Pressure_time_tot];
end
```

```
function Pump_time = getTime_Pump(m0,g,rho,A,h,mdot)
%function to find the total time for the pump system to empty & for water
%to drop to ground from height h.
%   assume: -air resistance is negligible vertically (needs assessment)
%           -flow rate from pump is constant

    %find the time to empty the tank:
    t_empty = m0/mdot;

    %find exit velocity:
    v0 = mdot/(rho*A);

    %find time for water to fall: (similar to t_fall from release method)
    t_fall_plus = (2*v0+sqrt(4*v0^2+8*g*h))/(2*g);
    t_fall_minus = (2*v0-sqrt(4*v0^2+8*g*h))/(2*g);
    if t_fall_minus >= t_fall_plus
        t_fall = t_fall_minus;
    else
        t_fall = t_fall_plus;
    end

    %combine to get total time:
    Pump_time_tot = t_empty + t_fall;

    %output
    Pump_time = [t_empty,t_fall,Pump_time_tot];
end
```

UAS Engineering Analysis: Performance

Multirotor Example: Indago 4 Of Lockheed Martin for size

Max translational distance required: d = 100m * 2 * 3 = **600m**
Minimum translational speed required: v = 600m / (10min*60s) = **1 m/s**

```
clc; clear; close all;
d = 100*2*3; %{m}
t = 10*60; %{s}
v = d/t;
rho = 1.0556; %{kg/m3} standard atm at boulder altitude
q = v^2*rho/2;

%Vehicle type = [cd, A];
quadrotor = [0.02, 1*0.3];
fixedwing = [0.0125, 3*0.1];
blimp = [0.4, pi*1.57^2];

Fd_quadrotor = drag(quadrotor(1), q, quadrotor(2));
Fd_fixedwing = drag(fixedwing(1), q, fixedwing(2));
Fd_blimp = drag(blimp(1), q, blimp(2));

Preq_rotor = Fd_quadrotor*d/t;
Preq_fixedwing = Fd_fixedwing*d/t;
Preq_blimp = Fd_blimp*d/t;
Preqs = [Preq_rotor, Preq_fixedwing, Preq_blimp];
x = ["Rotortype Aircraft", "Fixed Wing Aircraft", "Blimp Aircraft"];
bar(x,Preqs);
ylim([0 0.05]);
ylabel("Power Required [W]");


function [Fd] = drag(cd, q, A)
Fd = q*cd*A;
end
```