Department of Aerospace Engineering Sciences
University of Colorado
ASEN 4018

INFERNO

INtegrated **F**light **E**nabled **R**over for **N**atural Disaster **O**bservation

Conceptual Design Document (CDD)

Project Customer

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Acronyms

ASL	Above Sea Level
CD	Child Drone
CDHS	Communication & Data Handling Subsystem
COA	Certificate of Authorization
CONOPS	Concept of Operations
COTS	Commercial off-the-shelf
DR	Derived Requirement
EPS	Electrical Power Subsystem
FAA	Federal Aviation Administration
FBD	Functional Block Diagram
FOV	Field of View
FR	Functional Requirement
GPS	Global Positioning System
GS	Ground Station
GSMRS	Ground Station and Mother Rover Simulator
JPL	Jet Propulsion Laboratory
LOI	Location of Interest
MR	Mother Rover
SP	Sensor Package
TBD	To Be Determined
V&V	Verification & Validation

1 Project Description

Wildfires are a highly prevalent, costly, and dangerous natural disaster in the United States, particularly in mountainous, difficult-to-access locations. Fire prevention and suppression efforts by the United States Forest Service currently total $320 million, and are projected to reach $1.8 billion by 2025.[1] Not only is wildfire mitigation and containment expensive, but it requires personnel to enter hostile conditions to obtain information about the fire, which often results in casualties. In order to reduce the expense and human risk associated with wildfires, the FireTracker project seeks to develop and implement an aerial drone-based data collection system for use in hazardous environments and areas impassible by ground-based methods.

1.1 Project Objectives and Functional Requirements

The FireTracker project is composed of four unique systems: a remote ground station (GS), a mother rover (MR), a flying child drone (CD), and a sensor package (SP). The ground station will serve as a deployment base for the mother rover, which will carry the child drone to a specified location. The child drone will then take off and fly to a GPS location designated by an operator, where it will deliver a sensor package. The sensor package will take and record temperature data to transmit back to the ground station. The child drone will also transmit video and/or photos of the area of interest to the ground station. Our project, INFERNO, includes the design and fabrication of the sensor package and child drone. These will be designed so that they can interface with a mother rover and ground station that are to be built by a separate, future project. Additionally, interface control documents will be created to allow future teams to interface with the child drone and sensor package.

The sensor package consists of a temperature sensor for two reasons. First, this is a cost effective manner with which to prove the system for future missions. Second, a follow on project could develop a fleet of drones and drop many sensors. These could be used to generate a heat map of an area at risk for fires, which would aid in fire prevention. The INFERNO system will require operational limitations. Due to the limited budget available, a child drone that can operate in an actual fire environment is beyond the scope of the project. As such, the child drone will not be designed to fly in such an environment. Issues such as fire-winds, ash, and other debris are not design concerns for INFERNO.

Based off the project CONOPS and FBD (seen in Sections 1.2 and 1.3), a Mission Functional Flow Diagram was generated in order to visualize the logical flow of a typical INFERNO mission, including commands, takeoff, flight, sensor deployment, reconnaissance, and data transmission. Each block of this diagram was then used to generate a baseline functional requirement for the INFERNO system.

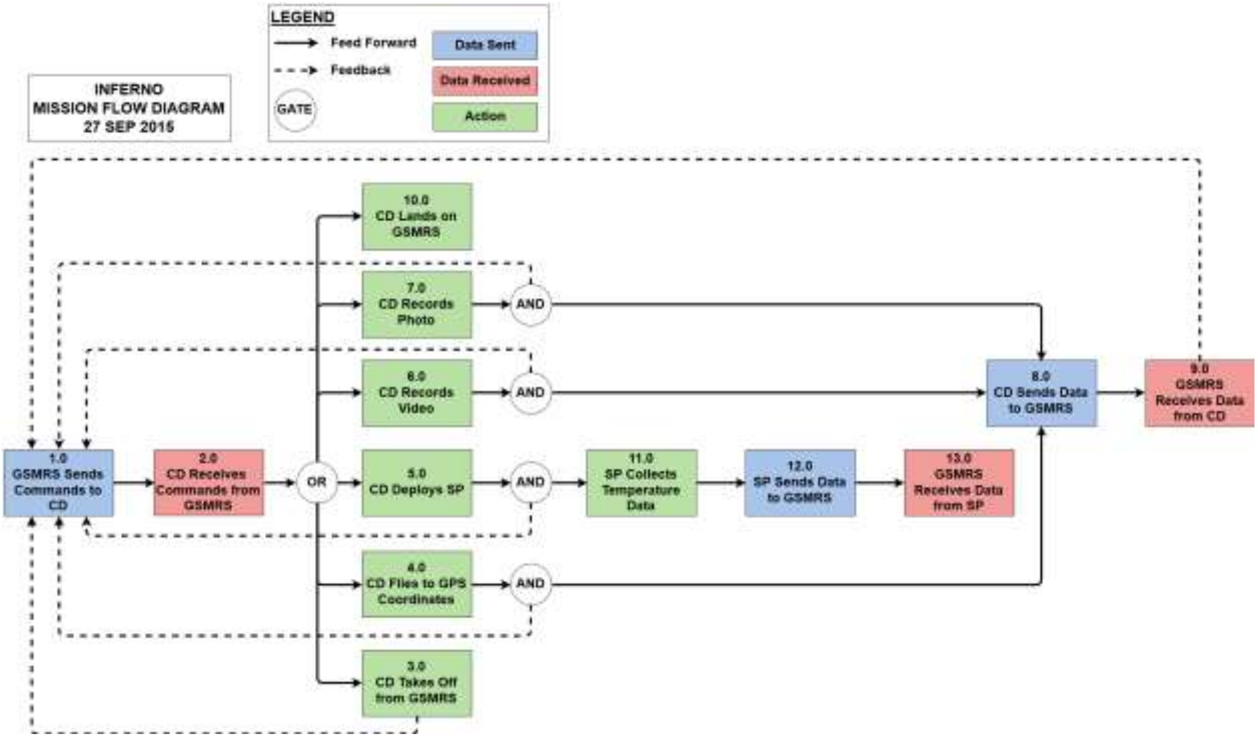


Figure 1.1-1: INFERNO Mission Functional Flow Diagram

As shown in Fig. 1.1-1, the INFERNO project is multi-faceted and complex, and thus there are several critical functional requirements necessary for mission success (Table 1.1-1). These requirements are arranged based on the chronological functionalities executed in the FireTracker mission profile and numerically correspond to the functional blocks in Fig 1.1-1.

Table 1.1-1: Description of INFERNO Function Requirements

Functional Requirement	Description	Motivation
FR 1.0	The GSMRS shall transmit wireless commands to the CD	In order for the Operator to be able to effectively control the CD through the mission, they must be able to send commands to the CD. A wireless link is far more practical than wired since the CD will be flying over long distances. In the full FireTracker system, this will be replaced by commands sent from the GS, relayed through the MR, and to the CD.
FR 2.0	The CD shall receive wireless commands from the GSMRS	In the full FireTracker system, the CD must receive the commands sent by the operator through the MR in order to perform its mission.
FR 3.0	The CD shall take off from the GSMRS	For full FireTracker mission success, the integration between the MR and CD is critical. The MR must be able to carry the CD while moving, and thus the CD must fit within the MR landing bay.
FR 4.0	The CD shall fly to GPS coordinates	In order to build a comprehensive view of ground-level conditions in an area under threat of wildfire, the Operator

		must be able to command the CD to deploy the SP and/or conduct reconnaissance at specific locations of interest. GPS coordinates provide a direct translation between mission planning and mission execution.
FR 5.0	The CD shall deploy the SP to a ground location of interest (LOI)	The primary purpose of the CD is to deploy the SP to a remote location to collect data.
FR 6.0	The CD shall be capable of recording video footage	Video footage will provide excellent reconnaissance data for scouting future SP deployment locations as well as observing wildfires in progress from a safe distance. Additionally, live-feed video would significantly aid the Operator during landing and SP deployment.
FR 7.0	The CD shall be capable of recording photos	Photos will be able to provide much higher resolution imagery than video, with lower data requirements.
FR 8.0	The CD shall transmit wireless data to the GSMRS	In order for the Operator to be aware of the CD's status, as well as to receive reconnaissance data, the CD must transmit this information to the GSMRS. This data will be passed to the MR in the full FireTracker system.
FR 9.0	The GSMRS shall receive wireless data from the CD	The GSMRS must accurately receive all data sent by the CD in order to provide it to the Operator.
FR 10.0	The CD shall land in the GSMRS docking bay	The CD is a highly expensive vehicle, and must be reusable. Thus, it must be able to land on the MR for the full FireTracker system in order to be driven back to the Operator following the completion of the FireTracker mission.
FR 11.0	The SP shall acquire ground temperature data after deployment	In order for the SP data to be useful in determining wildfire danger, the SP must have a mission endurance long enough to obtain a time dependent temperature profile of an area. An hour represents enough time to be able to discern temperature trends of an area while still remaining within the power requirements of a battery that would be light and small enough to be feasible for use.
FR 12.0	The SP shall transmit wireless data to the GSMRS	Since the SP is intended to be disposable, data must be sent back to the GSMRS to be available for analysis.
FR 13.0	The GSMRS shall receive wireless data from the SP	The GSMRS must be able to receive the temperature data from the SP in order to provide it to the operator for analysis.

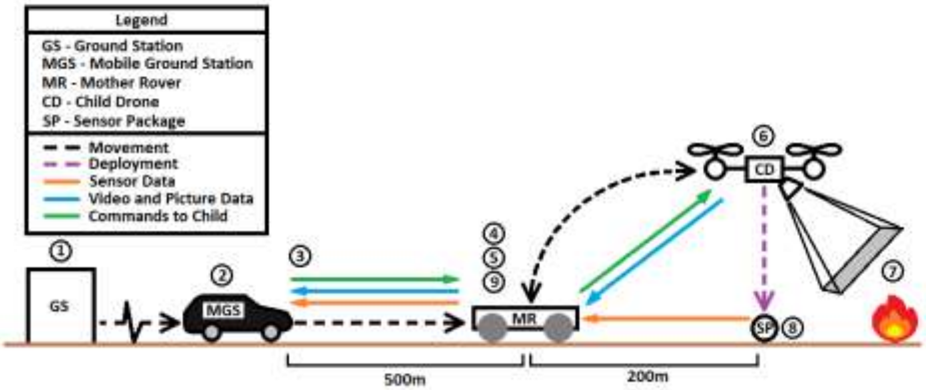
To succeed in this engineering project, team INFERNO must design a CD that can deliver a SP to a designated location, and then transmit that data back to the GSMRS. Four different levels to define the success of this project are laid out in Table 1.1-2. Level 1 success are requirements that are mission critical; without achieving Level 1 success, INFERNO will not be a useful system. At the most basic level of success, the CD shall be able to fly, the SP shall be able to acquire data and transmit over a wired data link, and the imaging system shall be able to capture 8 MP photos and transmit them over a wired data link. Level 4 success defines the goals that are likely difficult to achieve, but define overall completion of the INFERNO project. At this ultimate level of success, the CD shall be able to fly semi-autonomously, the imaging system shall capture and transmit 1080p video at 30 fps, and the SP shall collect data and have the capability to retransmit the data in case of communication loss.

Table 1.1-2: INFERNO Levels of Success

Level	Child Drone	Imaging	Sensor Package
1	• Wired communication with MR/GS Simulator • Simulated deployment of Sensor Package • Flight testing with simulated payload	• Burst 8MP photos • Time stamping • Wired communication with CD	• Temperature data taken at 1 Hz with 8-bit resolution • Time stamping • Wired data transmission
2	• Deploy Sensor Package on command • Flight Testing with Sensor package in deployment mechanism • 20 minute flight duration • Wireless communications link • Piloted landing	• Time stamped video wired to CD • TBD resolution less than 1080p @ 30fps	• Flight capable mass and volume (TBD) • Wireless transmission of 1 hour of data
3	• Flight with video-tracked piloting • 200 m wireless data/imagery transmission • GPS signal transmission		• Store 1 hour of data on-board • Transmit wirelessly 200 m • Be capable of collecting and transmitting data after deployment
4	• Semi-Autonomous flight via GPS waypoints, and landing within 5 m radius • Full system integration	• Full 1080p, 30fps transmitted to CD	• Retransmission of data in case of signal loss

The INFERNO team is designing the child drone and sensor package for JPL. The child drone and sensor package will be ultimately tested with a full system test, which will simulate the entire expected mission of the child drone and sensor package. Additionally, interface control documents will be created to allow future teams to interface with the child drone and sensor package.

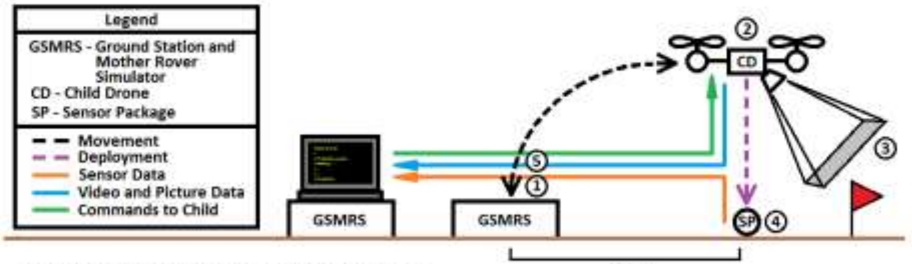
1.2 Concept of Operations (CONOPS)



1 - The GS determines that remote temperature data would be useful for either detecting or monitoring a fire.
2 - OPTIONAL: A MGS is dispatched to a location located within 700m of the intended SP deployment location.
3 - The MR is deployed from either the GS or the MGS if used.
4 - The MR travels up to 500 meters away from its original deployment location.
5 - The CD takes off from the MRM under pilot control.
6 - The CD flies to a GPS waypoint up to 200 meters away when commanded. The CD then maintains its commanded position to a 5 meter accuracy.
7 - The CD may be commanded to capture video and/or still images at any time. This data is transmitted to the MR which transmits it to the GS.
8 - The CD deploys the SP which collects, stores, and transmits up to 1 hour of data. This data is transmitted to the MR which transmits it to the GS.
9 - The CD lands on the MRM under pilot control within 20 minutes of takeoff.

Figure 1.2-1: FireTracker System Concept of Operations (CONOPS)

Figure 1.2-1 displays the concept of design for the full FireTracker system including its four components: the GS, MR, CD, and SP. Each component is intended to operate both independently and in concert with the other elements. This forms a complete system that can deliver a temperature sensor to a desired location and transmit the data back to the ground station. Aspects of this complex system fall outside of the defined scope of the INFERNO project scope; thus, they must be simulated in order to verify that INFERNO can operate within the context of the FireTracker system. Figure 1.2-2 below shows the concept of operations for simulating these excluded aspects in order to conduct a full test of the INFERNO Project deliverables.



1 - The CD takes off from the GSMRS under pilot control.
2 - The CD flies to a GPS waypoint up to 200 meters away using autopilot. The CD then maintains its commanded position to a 5 meter accuracy.
3 - The CD may be commanded to capture video and/or still images at any time. This data is transmitted to the GSMRS.
4 - The CD deploys the SP which collects, stores, and transmits up to 1 hour of data. This data is transmitted to the GSMRS.
5 - The CD lands on the GSMRS under pilot control within 20 minutes of takeoff.

Figure 1.2-2: INFERNO Project CONOPS

The diagram above shows the GS and MR from the FireTracker system scope reduced to a communications simulator and landing platform referred to together as the GSMRS. This component will be used to verify the functionality of the CD and SP. The landing platform will be used to test the CD's ability to integrate with the MR as well as its landing and takeoff capabilities. The communications simulator will imitate the communications duties of both the GS and MR to test the CD and SP's ability to send and receive data. This system is intended to operate such that the CD and

SP function as if the GS and MR are present rather than simulated, such that further work may be done to complete the FireTracker system without needing to redesign the INFERNO components. One may also notice that the diagram in Figure 1.2-2 does not include a depiction of fire, as operating around open flame or under the environmental conditions of a wildfire is not included within the scope of the INFERNO project.

1.3 Baseline Mission Profile

This mission profile is limited to the INFERNO scope. As such, it deals primarily with the child drone and sensor package. It does not focus on the mother rover or the ground station. The INFERNO team will simulate all interactions with the mother rover and the ground station with test equipment.

Event	Component(s)	Description	Approximate Time
Take-off	•Ground Station •Mother Rover •Child Drone	An operator will control the child drone and lift off from the mother rover.	30 s
Movement to Target	•Child Drone	The drone will move fly from the mother rover to the location of interest.	30 s
Sensor Deployment	•Child Drone •Sensor Package	The child drone will deploy the sensor package to the location of interest.	1 min
Reconnaissance	•Child Drone •Ground Station	The child drone will move to additional locations of interest and perform visual reconnaissance. These locations shall be located within 200m of the mother rover. The video and pictures will be transmitted to the ground station.	15 min
Return to Mother Rover	•Child Drone	The child drone will return to the mother rover.	30 s
Landing	•Child Drone •Mother Rover •Operator	An operator will control the child drone and land on the mother rover.	1 min
Sensor Data Collection	•Sensor Package •Mother Rover •Ground Station	The sensor package will collect and transmit data to the ground station.	1 hr

During take-off, the child drone will be manually controlled by an operator. The operator will lift the child drone from the mother rover and command the drone to hover. This should take no longer than 30 s. The child will then be commanded to fly to the location of interest. The child drone will then fly automatically to the location. The location of interest is required to be within 200 m of the mother rover, and the child drone can fly at 10 m/s. This means the child drone is able to move to the location of interest in 20 s under ideal conditions. The time is estimated at 30 s in order to maintain a 50% margin. Once at the location of interest, the child drone will deploy the sensor package. The deployment and deployment confirmation should take no longer that 1 min. Part of this time will be used by the child drone to visually confirm the deployment of the sensor package. Once the sensor package is deployed, the child drone will move into the reconnaissance phase of its mission. The child drone will fly to desired locations either by GPS waypoint or by manual control. During this phase, the child drone will take video and still images, which are transmitted to the ground station. The reconnaissance phase may take up to 15 min. Once the reconnaissance phase is completed, the child drone will return to the mother rover. This return should take no longer than 30 seconds, including a 50% margin. The child drone will then hover above the mother rover until an operator takes control of the child drone. The operator will then land the child drone on the mother rover. This should take no longer than 1 min. The sensor package will begin to collect and transmit data as soon as it is deployed. The sensor package will continue to collect and transmit data to the ground station for at least one hour. In total, the child drone will be airborne for a maximum of 18 min 30 s. This is within the 20 min endurance of the child drone, with a 7.5% design margin

1.4 Functional Block Diagram (FBD)

As previously noted, the INFERNO project will be designing, building, and testing the child drone and sensor package components of FireTracker. Trade studies will be performed to determine whether the CD will need to be custom-built to meet mission requirements, or if it may be acquired as a commercial off-the-shelf (COTS) vehicle and modified as necessary. The SP will be built to meet mission requirements, using COTS components where possible in order to reduce project cost. Sensor data may be relayed through the CD and/or sent directly to the MR, as determined by the results of future trade studies and prototyping.

In order to enable system-level testing of the CD and SP, as well as to verify that they will be able to operate as part of the overall FireTracker system, a single Ground Station & Mother Rover Simulator (GSMRS) will be built in order to provide an electrical and mechanical analog for the command, telemetry, and docking capabilities provided by the future ground station and mother rover. Figure 1.3-1 below shows the Functional Block Diagram for INFERNO, outlining internal and external connections between the CD, SP, and GSMRS.

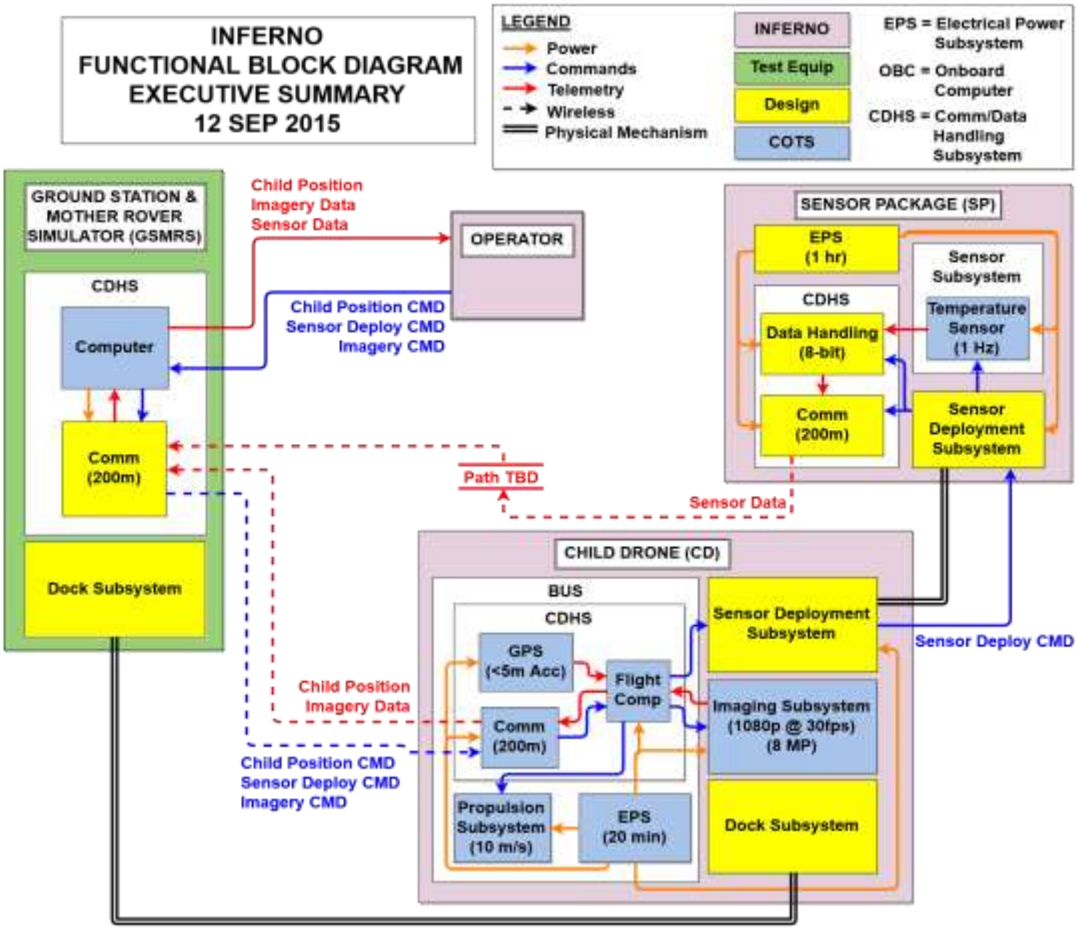


Figure 1.4-1: INFERNO Functional Block Diagram

2 Design Requirements

Given baseline, mission-based functional requirements, and through additional consultation with the customer to determine other desired capabilities, more detailed sets of derived requirements were deemed necessary to enable the INFERNO mission. The detailed list of functional requirements and their derived child requirements is provided below. See Fig. 1.1-1 to reference between each FR and its place within the INFERNO mission flow.

FR 1.0	**The GSMRS shall transmit wireless commands to the CD** *Motivation:* In order for the Operator to be able to effectively control the CD through the mission, they must be able to send commands to the CD. A wireless link is far more practical than wired since the CD will be flying over long distances. In the full FireTracker system, this will be replaced by commands sent from the GS, relayed through the MR, and to the CD.	
	DR 1.1	**The GSMRS shall be able to command the CD to take off** *V&V:* Test – GSMRS software and comm system tested to verify takeoff command is sent.
	DR 1.2	**The GSMRS shall be able to transmit GPS coordinate commands to the CD** *V&V:* Test – GSMRS software and comm system tested to verify GPS coordinate commands are correctly sent.
	DR 1.3	**The GSMRS shall be able to command the CD to deploy the SP** *V&V:* Test – GSMRS software and comm system tested to verify SP deployment command is sent.
	DR 1.4	**The GSMRS shall be able to command the CD to record video** *V&V:* Test – GSMRS software and comm system tested to verify video record command is sent.
	DR 1.5	**The GSMRS shall be able to command the CD to record photos** *V&V:* Test – GSMRS software and comm system tested to verify SP photo record command is sent.
	DR 1.6	**The GSMRS shall be able to transmit manual flight control commands to the CD** *Motivation:* Operator control will be required to land the CD in the landing bay, may be useful during deployment to deploy the SP at a precise location, and may be useful during reconnaissance to observe specific areas. Additionally, this will add safety in case of emergencies, and may be required to obtain a COA. *V&V:* Demonstration – Operator uses GSMRS manual control interface to control CD during flight.

FR 2.0	**The CD shall receive wireless commands from the GSMRS** *Motivation:* In the full FireTracker system, the CD must receive the commands sent by the operator through the MR in order to perform its mission.	
	DR 2.1	**The CD shall receive takeoff command(s) from the GSMRS** *V&V:* Test – CD software and comm system is tested to verify it receives takeoff command from a wireless signal. *V&V:* Demonstration – GSMRS sends takeoff command and CD successfully executes takeoff.

DR 2.2	**The CD shall receive GPS coordinate commands from the GSMRS** *V&V:* Test – CD software and comm system is tested to verify it receives GPS coordinates from a wireless signal. *V&V:* Demonstration – GSMRS sends GPS coordinate command and CD successfully moves to GPS coordinates.
DR 2.3	**The CD shall receive SP deployment command(s) from the GSMRS** *V&V:* Test – CD software and comm system is tested to verify it receives SP deployment commands from a wireless signal. *V&V:* Demonstration – GSMRS sends deployment command and CD successfully enables deployment mechanism.
DR 2.4	**The CD shall receive commands to record video from the GSMRS** *V&V:* Test – CD software and comm system is tested to verify it receives video record command from a wireless signal. ***V&V:*** Demonstration & Inspection – GSMRS sends video record command. Video retrieved from CD, camera, and/or GSMRS.
DR 2.5	**The CD shall receive commands to record photos from the GSMRS** *V&V:* Test – CD software and comm system is tested to verify it receives photo record command from a wireless signal. *V&V:* Demonstration & Inspection – GSMRS sends photo record command. Photo retrieved from CD, camera, and/or GSMRS.
DR 2.6	**The CD shall receive manual flight control commands from the GSMRS** *V&V:* Demonstration – Operator uses GSMRS manual control interface to control CD during flight.
DR 2.7	**The CD shall autonomously return to the GSMRS if communication is lost** *Motivation:* The CD will be the most expensive component of the INFERNO project. In order to prevent its loss or destruction in case of a loss of communications, it should automatically return to the last known position of the MR. *V&V:* Test – CD software is tested to verify it enters “return mode” following loss of communication with GSMRS. *V&V:* Demonstration – GSMRS communications link with CD is intentionally interrupted during flight and CD is observed to return to GSMRS.

FR 3.0	**The CD shall take off from the GSMRS** *Motivation:* For full FireTracker mission success, the integration between the MR and CD is critical. The MR must be able to carry the CD while moving, and thus the CD must fit within the MR landing bay. *V&V*: Demonstration – CD is able to take off from GSMRS landing bay.
DR 3.1	**The CD shall fit in the GSMRS landing bay** *V&V*: Demonstration – CD placed in GSMRS landing bay.

DR 3.1.1	**The CD shall have a footprint no greater than TBD** *Motivation:* The CD's landing hardware (e.g. legs or wheels) may not occupy a footprint greater than the area of the landing bay. *V&V:* Inspection – CD footprint will be measured. *Note:* Footprint requirements have not yet been established for the future MR. These will be established in conjunction with the customer during detailed design.
DR 3.1.2	**The CD shall have overall dimensions no greater than TBD** *Motivation:* The CD cannot have such large dimensions (e.g. wingspan) that it interferes with other equipment on the MR. *V&V:* Inspection – CD dimensions will be measured. *Note:* Dimension requirements have not yet been established for the future MR. These will be established in conjunction with the customer during detailed design.

FR 4.0	**The CD shall fly to GPS coordinates** *Motivation:* In order to build a comprehensive view of ground-level conditions in an area under threat of wildfire, the Operator must be able to command the CD to deploy the SP and/or conduct reconnaissance at specific locations of interest. GPS coordinates provide a direct translation between mission planning and mission execution.
DR 4.1	**The CD shall have an autopilot** *Motivation:* An autopilot will allow the onboard computer to quickly navigate to a desired position without the need for direct operator control. *V&V:* Inspection & Demonstration – Autopilot hardware and/or software is installed, and CD is able to navigate to remote-commanded or preprogrammed GPS coordinates.
DR 4.1.1	**The CD shall be capable of holding position at GPS coordinates with an accuracy no less than 5m** *Motivation:* The ability to hold position will greatly aid SP deployment, reconnaissance, and Operator awareness of the CD's status. *V&V:* Demonstration – CD is able to remain within a measured range of a known position.
DR 4.1.1.1	**The CD shall have a GPS receiver with a minimum accuracy of 5m** *V&V:* Inspection & Test – GPS receiver is installed on CD. Receiver, when placed at a known position, provides coordinate data with no more than 5 m error.

DR 4.2	**The CD shall have a flight endurance of a minimum of 20 minutes under ambient conditions similar to those of Colorado during peak wildfire season.** *Motivation:* A twenty minute flight endurance provides ample time for the vehicle to fly to its deployment location, drop the SP, fly to multiple other locations for image reconnaissance, and fly back to the MR with margin left over. Ambient conditions will be chosen according to the general weather in Colorado during wildfire season, when INFERNO will be utilized. *V&V:* Analysis – Models of CD flight performance and power consumption are used to estimate its endurance. *V&V:* Demonstration – CD is able to fly for 20 minutes, including an operational mission profile.
DR 4.2.1	**The CD shall have a flight service ceiling of a minimum of 5400 ft / 1646 m ASL** *Motivation:* In order to test in or near Boulder, CO, the vehicle must be capable of flight at least at 5400 ft ASL. A service ceiling of 5400 ft will provide margin for variation in atmospheric conditions. *V&V:* Demonstration – CD is capable of controlled, sustained flight at altitudes up to 5400 ft.
DR 4.2.2	**The CD shall operate with ground temperatures between 50°F / 10°C and 118°F / 47.8°C** *Motivation:* During the months of April to October (peak wildfire season)[1], temperatures generally may reach as low as 50°F.[2] The all-time record high temperature in Colorado is 118°F.[3] *V&V:* Analysis – Thermal and flight performance modeling will evaluate CD flight capabilities over temperature range. *V&V:* Test – Environmental chamber will be used to verify electronic systems operate nominally over temperature range.
DR 4.2.3	**The CD shall operate in wind speeds a maximum of 10 mph / 4.5 m/s** *Motivation:* Average wind speeds in Colorado during the months of April to October are typically near 10 mph.[4] *V&V:* Demonstration – Outdoor flight with wind, pending weather conditions.
DR 4.2.3.1	**The CD shall be capable of flight at a minimum of airspeeds of 22.4 mph / 10 m/s** *Motivation:* An airspeed capability of 10 m/s will allow the CD to fly at a groundspeed of 5.5 m/s in 10 mph headwinds, allowing ample speed to complete a full mission within its endurance. *V&V:* Demonstration – Measured groundspeed during indoor flight with no wind.

DR 4.2.4	**The CD shall operate in a maximum humidity of 80%** *Motivation:* During the months of April to October (peak wildfire season), average humidity may reach levels as high as 80% during morning hours.[5] *V&V:* Analysis – Flight performance modeling will evaluate CD flight capabilities over humidity range. *V&V:* Test – Environmental chamber will be used to verify electronic systems operate nominally over humidity range.
DR 4.3	**The CD shall have a minimum operational radius of 200 m away from the MR** *Motivation:* A 200m operational radius will allow the CD to explore a large area, much faster than a ground rover, while still maintaining a high-speed communication link.
DR 4.3.1	**The GSMRS shall be capable of sending all required commands a minimum of 200 m** *V&V:* Demonstration – The CD receives and/or executes commands sent from the GSMRS at a distance of 200 m.
DR 4.3.2	**The CD shall be capable of sending all required data a minimum of 200 m** *V&V:* Demonstration – The GSMRS receives data sent from the CD at a distance of 200 m.
DR 4.3.3	**The SP shall be capable of sending all required data a minimum of 200 m** *Motivation:* The SP can be deployed no farther than the CD can carry it, and thus must be able to transmit data back to the GSMRS up to 200 m away. *V&V:* Demonstration – The GSMRS receives data sent from the SP at a distance of 200 m.

FR 5.0	**The CD shall deploy the SP to a ground location of interest (LOI)** *Motivation:* The primary purpose of the CD is to deploy the SP to a remote location to collect data.
DR 5.1	**The CD shall be capable of housing the SP** *V&V:* Demonstration – The SP is attached to the CD such that it will not detach from the CD during the flight conditions described in **FR 5.0**.
DR 5.1.1	**The SP shall have a maximum mass of TBD** *Motivation:* The SP must be light enough for the CD to carry it during flight and execute its mission, and does not break the CD's carry mechanism. *V&V:* Inspection – The SP will be weighed. *Note:* Weight requirements cannot be determined until the capabilities of the chosen CD design are known.

		DR 5.1.2	**The SP shall have maximum dimensions of TBD** *Motivation:* The SP must be small enough for the CD to carry it while in the MR landing bay, during takeoff, and during flight. *V&V:* Inspection – The SP will be measured and modeled in CAD to verify fit with the CD *Note:* Dimension requirements cannot be determined until the size of the CD is known.
	DR 5.2	**The CD shall be capable of releasing the SP during flight** *V&V:* Test & Inspection – The detachment mechanism will be initiated. SP detachment will be visually verified.	
	DR 5.3	**The SP shall remain within 5 m of the LOI after deployment** *Motivation:* Since deployment of the SP from the CD at a desired GPS location does not necessarily mean the SP will come to rest within 5 m of the GPS location (i.e. if it rolls), this requirement specifies that the SP must indeed remain within 5 m of the GPS location. If the SP comes to rest outside of 5 m, the data captured may no longer represent the conditions at the desired location. However, the slope of the terrain will have a large effect on the ability for the SP to remain in the desired area, thus a maximum slope of 5° will be required for deployment. *V&V:* Demonstration – The SP remains within 5 m of a known LOI with a known slope following deployment.	

FR 6.0	**The CD shall be capable of recording video footage** *Motivation:* Video footage will provide excellent reconnaissance data for scouting future SP deployment locations as well as general situational awareness of the terrain. Additionally, live-feed video would significantly aid the Operator during landing and SP deployment.		
	DR 6.1	**The CD shall have a video camera** *V&V:* Inspection – Video camera is installed on CD.	
		DR 6.1.1	**The video camera shall record video at a minimum of 1080p resolution.** *Motivation:* High-resolution video will provide superior imagery for reconnaissance. *V&V:* Analysis – Video data shall be processed with imaging software to verify its resolution.
		DR 6.1.2	**The video camera shall record video at a minimum of 30 frames per second** *Motivation:* High frame rate will aid in the analysis of video reconnaissance, and will also aid pilot control of the vehicle in conjunction with live-feed. *V&V:* Analysis – Video data shall be processed with imaging software to verify the number of frames per second.

DR 6.1.3	**The video camera shall record video with a minimum of 100° field of view** *Motivation:* A high field of view will provide superior situational awareness during both reconnaissance and pilot control. *V&V:* Test – Video will be taken of markers marking a 100° cone relative to the camera lens, then viewed to verify capture of the markers.
DR 6.1.4	**The video camera shall have a maximum mass of TBD** *Motivation:* The video camera must be light enough for the CD to carry it during flight and execute its mission. *V&V:* Inspection – The video camera will be weighed. *Note:* Weight requirements cannot be determined until the capabilities of the chosen CD design are known.
DR 6.1.5	**The video camera shall have maximum dimensions TBD** *Motivation:* The video camera must be small enough for the CD to carry it while in the landing bay, during takeoff, and during flight. *V&V:* Inspection – The video camera will be measured and modeled in CAD to verify fit with CD. *Note:* Size requirements cannot be determined until the dimensions of the chosen CD design are known.
DR 6.2	**Captured video data shall be timestamped** *Motivation:* Timestamped video will allow reconnaissance imagery to be matched to the CD's GPS location record, thus allowing determination of *what* or *where* the camera is looking at. *V&V*: Test – Video imagery processing software will be verified to ensure timestamping occurs following video capture.

FR 7.0	**The CD shall be capable of recording photos** *Motivation:* Photos will be able to provide much higher resolution imagery than video, with lower data requirements.
DR 7.1	**The CD shall have a photo camera** *V&V:* Inspection – Photo camera is installed on CD.
DR 7.1.1	**The photo camera shall record photos at a minimum of 8 MP resolution** *Motivation:* 8 MP photos will provide superior imagery for reconnaissance. *V&V:* Analysis – Photo data shall be processed with imaging software to verify its resolution.
DR 7.1.2	**The photo camera shall have a maximum mass of TBD** *Motivation:* The photo camera must be light enough for the CD to carry it during flight and execute its mission. *V&V:* Inspection – The photo camera will be weighed. *Note:* Weight requirements cannot be determined until the capabilities of the chosen CD design are known.

DR 7.1.3	**The photo camera shall have maximum dimensions of TBD** *Motivation:* The photo camera must be small enough for the CD to carry it while in the landing bay, during takeoff, and during flight. *V&V:* Inspection – The photo camera will be measured and modeled in CAD to verify fit with CD. *Note:* Size requirements cannot be determined until the dimensions of the chosen CD design are known.
DR 7.2	**Captured photo data shall be timestamped** *Motivation:* Timestamped photos will allow reconnaissance imagery to be matched to the CD's GPS location record, thus allowing determination of *what* or *where* the camera is looking at. *V&V*: Test – Photo imagery processing software will be verified to ensure timestamping occurs following video capture.

FR 8.0	**The CD shall transmit wireless data to the GSMRS** *Motivation:* In order for the Operator to be aware of the CD's status, as well as to receive reconnaissance data, the CD must transmit this information to the GSMRS. This data will be passed to the MR in the full FireTracker system.	
	DR 8.1	**The CD shall transmit GPS position data to the GSMRS** *Motivation*: The Operator must be aware of the CD's location to verify it is in the correct position for SP deployment and/or reconnaissance. *V&V:* Test – CD software and comm system tested to GPS position data is sent
	DR 8.2	**The CD shall transmit video imagery to the GSMRS** *V&V:* Test – CD transmits video data, and GSMRS receives readable video data.
	DR 8.3	**The CD shall transmit photo imagery to the GSMRS** *V&V:* Test – CD transmits video data, and GSMRS receives readable video data.
	DR 8.4	**The CD shall be capable of transmitting all data from its maximum operational radius** *Motivation:* If the CD does not have enough power to transmit data from its maximum operational radius, then the Operator will have no situational awareness, and the mission cannot be completed. *V&V:* Demonstration & Inspection – CD sends data to GSMRS from maximum operational range. GSMRS receives and reads all data correctly.

FR 9.0	**The GSMRS shall receive wireless data from the CD** *Motivation:* The GSMRS must accurately receive all data sent by the CD in order to provide it to the Operator.	
	DR 9.1	**The GSMRS shall receive GPS position data from the CD** *V&V:* Demonstration & Inspection – CD transmits GPS position data. GSMRS receives and reads GPS position correctly.
	DR 9.2	**The GSMRS shall receive video imagery from the CD** *V&V:* Demonstration & Inspection – CD transmits video imagery. GSMRS receives and reads video imagery correctly.

DR 9.3	**The GSMRS shall receive photo imagery from the CD** *V&V:* Demonstration & Inspection – CD transmits photo imagery. GSMRS receives and reads photo imagery correctly.

FR 10.0	**The CD shall land in the GSMRS docking bay** *Motivation*: The CD is a highly expensive vehicle, and must be reusable. Thus, it must be able to land on the MR for the full FireTracker system in order to be driven back to the Operator following the completion of the FireTracker mission.
FR 10.1	**The CD shall land under operator control** *Motivation:* Hardware and software to enable automatic landing of the CD within the MR landing bay will be prohibitively time-consuming and expensive within the schedule and budget available to INFERNO. *V&V:* Demonstration – CD is able to land within the GSMRS docking bay while under operator control.

FR 11.0	**The SP shall acquire ground temperature data after deployment** *Motivation*: Collecting remote temperature data at a location will allow temperature trends to be determined. Collecting data at multiple locations may allow a temperature field to be built. Both of these abilities will aid in the prediction of potential wildfire occurrence.
DR 11.1	**The SP shall acquire data for 1 hour** *Motivation:* In order for the SP data to be useful in determining wildfire danger, the SP must have a mission endurance long enough to obtain a time dependent temperature profile of an area. An hour represents enough time to be able to discern temperature trends of an area while still remaining within the power requirements of a battery that would be light and small enough to be feasible for use. *V&V*: Test & Inspection – Timestamps of the first and last data-point received during a test are checked for a duration of 1 hour between them
DR 11.2	**DR 11.2: The SP shall acquire data at 1 Hz frequency** *Motivation:* Data collection frequency is an important consideration as it drives the minimum time scale on which temperature trending may be observed by the FireTracker system. For FireTracker, major temperature trending is significantly more important than very small scale trending, thus 1 Hz is a good middle ground. *V&V*: Test & Inspection – Timestamps of data points received during a test are checked for a difference of 1 second in concurrent points.
DR 11.3	**DR 11.3: The SP shall acquire data at 8-bit resolution** *Motivation*: The resolution of the SP data collected is driven by both data storage limitations and the minimum temperature differences that the SP is required to discern. Because the FireTracker system is attempting to determine differences in temperature indicative of wildfire danger, large trends in temperature of several degrees are more important than small variations, which may be subject to transient trending. Eight-bit resolution temperature data is enough to discern applicable changes in temperature while remaining well within expected data storage and transmission capabilities. *V&V:* Test & Inspection – SP data received during a test is checked for an 8-bit resolution

DR 11.4	**The SP shall timestamp data** *Motivation:* Data received from the SP must be timestamped in order for the operator to construct an accurate and reliable time-continuous data set. *V&V*: Test and Inspection - SP data shall be checked for proper timestamping

FR 12.0	**The SP shall transmit wireless data to the GSMRS** *Motivation:* Since the SP is intended to be disposable, data must be sent back to the GSMRS to be available for analysis.
DR 12.1	**The SP shall transmit timestamped temperature data to the GSMRS** *V&V:* Test – The SP software and comm system are tested to verify that timestamped temperature data is sent correctly.
DR 12.2	**The SP shall be capable of retransmitting temperature data** *Motivation:* If contact is temporarily lost with the SP, data taken during that period will be missing from trending unless somehow retransmitted. *V&V:* Test – Verify that SP retransmits buffered temperature data. Method TBD.
DR 12.2.1	**The SP shall be capable of buffering up to 1 hour of timestamped temperature data** *V&V:* Inspection & Test – Storage hardware installed on SP capable of holding 1 hour of data. SP allowed to collect 1 hour of data, then inspected to ensure data has been stored.

FR 13.0	**The GSMRS shall receive wireless data from the SP** *Motivation:* The GSMRS must be able to receive the temperature data from the SP in order to provide it to the operator for analysis.
DR 13.1	**The GSMRS shall receive temperature data from the SP** *V&V:* Test & Inspection – SP transmits temperature data. Verify that GSMRS receives correct data.

3 Key Design Options Considered

3.1 Aircraft

The following aircraft options are derived from **FR 4.0**, which states that the CD shall fly to GPS coordinates. Because of the broad spectrum of the design space, there were a large number of flight vehicle design options to consider. These will be presented below as well as the justification for why they were selected with respect to various mission requirements and what advantages and disadvantages each one brings to the overall project.

3.1.1 Rotor UAS

Although there are multiple rotor designs that fit this description, the basic idea is that of a quadcopter. However, the final design may have any number of rotors. A rotor aircraft functions much like a helicopter in that it hovers until the vehicle is tilted at some degree with the horizontal. By doing so, the vertical component of lift generated by the rotors is transferred into some degree of horizontal lift, causing translation.

This UAS design option is highly favorable for the INFERNO project due to the need to take off from and land on the MR (**FR 3.0** and **10.0**). The rotor aircraft is optimal for takeoff and landing from the MR as it is capable of purely vertical motion (unlike a fixed wing aircraft that generally needs horizontal air flow during takeoff and landing). After takeoff, the CD can then navigate to a designated Location of Interest (LOI) in order to drop the SP (**FR 4.0** and **5.0**). One major advantage of the rotor aircraft is the ability hover; after flying to the LOI, the rotor aircraft can then reorient itself vertically to hover above the deployment location **(DR 4.1.1**), allowing for a controlled drop of the SP (**DR 5.3**).

While the rotor has many important advantages, there are a few downsides that will drive design decisions and could add complexity to the project. If a COTS aircraft cannot be secured, the design and manufacturing of a rotor aircraft would be very involved. However, the downside of buying a COTS aircraft is that it will easily require well over 1/5 of the total project budget. In addition, rotor aircrafts require much more power than lighter-than-air vehicles and fixed-wing aircrafts (**DR 4.2**), and also have a much more limited payload capacity that would limit the mass of the SP and cameras (**DR 5.1.1, 6.1.4, 7.1.2**), and therefore the design of our sensor package. COTS aircrafts are also designed in such a way that physically integrating a payload attachment (and the payload itself) will likely be difficult **(DR 5.1** and **5.2**).

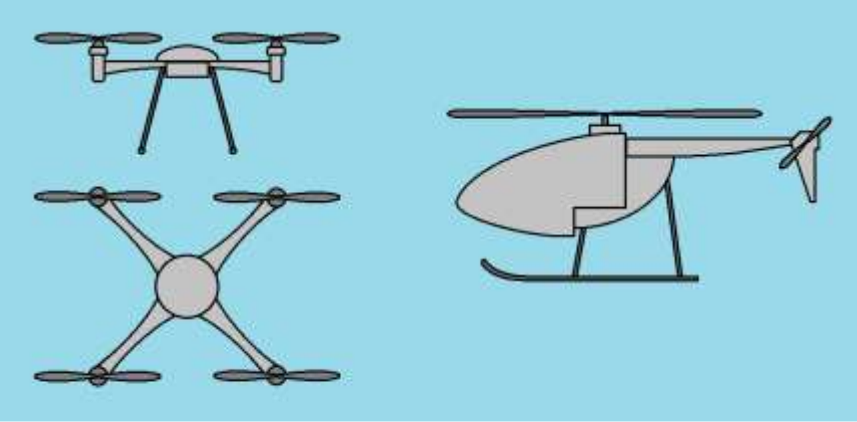


Figure 3.1.1-1: Diagram of Rotor Aircraft

Table 3.1.1-1: Pros and Cons of Rotor Aircraft

Advantages	Disadvantages
• Vertical takeoff and landing • Hover ability for easy reconnaissance and SP deployment • Many COTS options • Footprint of vehicle will integrate well with MR docking bay • Better GPS accuracy • Large knowledge base on campus • Highly maneuverable • Customer support for COTS design	• Complex flight controls • Complex structure if not COTS • Expensive • Low endurance • Limited/small payload capacity • Payload mechanism integration will prove difficult with structure

3.1.2 Fixed Wing UAS

The next design option considered is a fixed wing aircraft. A fixed wing aircraft must first accelerate horizontally to a takeoff speed, at which point the control surfaces can be adjusted to generate sufficient lift over the airfoil to propel the aircraft off the ground. That, or it must be launched by some mechanism. Once airborne, the aircraft can move much faster than a rotor design (**DR 4.2.3.1**) and will require less power to operate (**DR 4.2**).

However, given the requirement that the CD must take off from the MR (**FR 3.0**), this design is highly problematic. This is further complicated by the requirement that the CD is to remain within 5 meters of the LOI (**DR 4.1.1**) and deploy the SP with the same accuracy **(FR 5.0** and **DR 5.3**). As the fixed wing aircraft is not capable of hovering without loss of lift, this requirement is virtually impossible to satisfy. Another problem that arises from the lack of hovering capability is image quality. Since the fixed wing vehicle must be constantly in flight, the camera will constantly be in motion, and as a result, the video and imagery may be of lower quality **(FR 6.0** and **7.0**). The camera will also not be capable of viewing a constant target if that is desired by the ground operator. Additionally, the choice of a fixed wing UAS will force many design constraints on the size/shape of the SP and its deployment mechanism (**DR 5.1** and **5.2**), as both structures could hinder the aerodynamic performance of the aircraft to a much larger extent than that of a rotor aircraft or LTA aircraft.

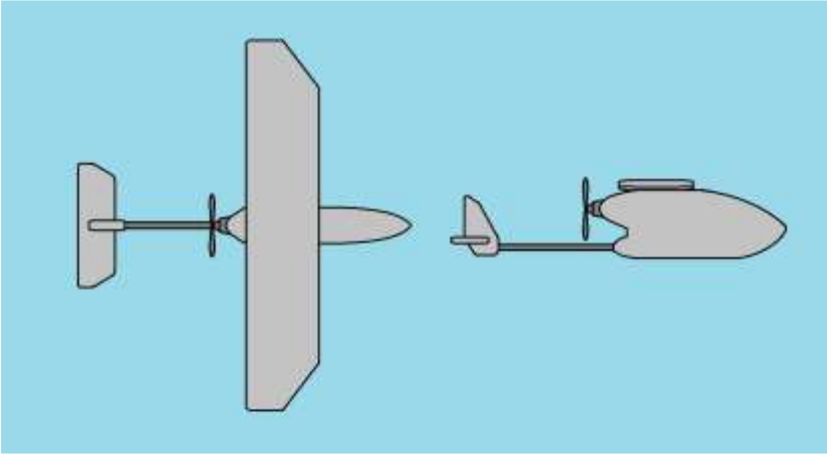


Figure 3.1.2-1: Diagram of Fixed Wing Aircraft

Table 3.1.2-1: Pros and Cons of Fixed Wing Aircraft

Advantages	Disadvantages
• Large knowledge base on campus • High payload capacity • Medium endurance • Many COTS options • Customer support for COTS design • Good flight speed	• Landing and takeoff will be very difficult to integrate with MR • Lack of hover capability will make it difficult to place the SP in the correct GPS location • Staying within 5 meters of designated GPS waypoint is exceedingly difficult • Constant change in position can cause problems with GPS receiver • Degraded image quality due to continuously moving platform

	• Difficult to land safely with attached SP deployment mechanism

3.1.3 Lighter-than-Air UAS

The next design option for the CD is a lighter-than-air (LTA) vehicle, such as a rigid airship or blimp, as shown in Figure 3.1.3-1. Any form of LTA vehicle would require some form of propulsion and maneuverability, which could be accomplished in multiple ways. Perhaps the simplest form of propulsion would be a small propeller or series of propellers allowing for better maneuverability. LTA vehicles (as their name implies) use a lighter than air gas contained in a sealed structure. Because the surrounding air is denser than the LTA, the vehicle is displaced upward by the buoyant force, thus producing “lift”.

The strongest argument for this design option is the low power consumption as compared to the fixed wing and rotor aircrafts. Like the rotor UAS, it is capable of vertical takeoff and landing (**FR 3.0** and **10.0**); however, instead of using active power to create lift, the gas inside the LTA vehicle passively raises it to a height in which equilibrium is reached. In addition, hovering in one place to deploy the SP and take imagery will require little power, and thus allow for a long flight time (**DR 4.2**).

Unfortunately, this design option is both slow and difficult to control (**FR 4.0, DR 4.1.1** and **4.2.3.1**). Changes in atmospheric density in addition to wind and temperature will translate to effects on the altitude and location of the flight vehicle. These effects will be difficult to compensate for, and sudden movements caused by environmental factors will make accurate deployment of the SP problematic (**FR 5.0, DR 5.3**). Additionally, as releasing the lighter than air gas is the most effective way to lower the aircraft, decreasing the altitude of the vehicle is likely irreversible. The integration with the MR may also be difficult. The vehicle would either have to be secured in such a way that it could not float away, or a lighter than air gas would need to be carried on the MR to fill the vehicle before launch, which would be quite complex.

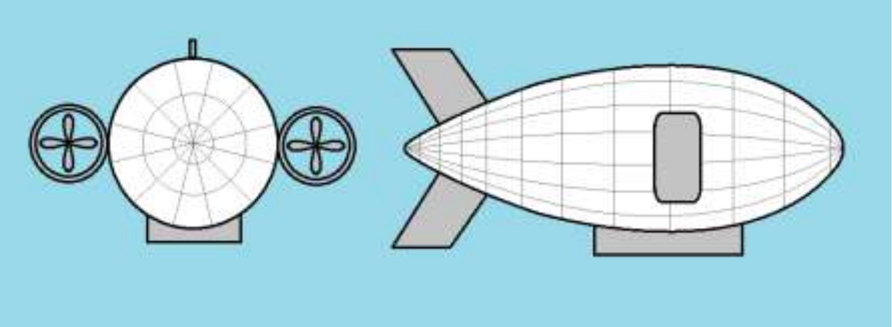


Figure 3.1.3-1: Diagram of Lighter Than Air Aircraft

Table 3.1.3-1: Pros and Cons of Lighter Than Air Aircraft

Advantages	Disadvantages
• Requires low power and high endurance • Hover ability for easy reconnaissance and SP deployment • Greater freedom when designing the payload mass and volume • Less expensive than other options	• Lack of commercial availability will require significant design work • Difficult to reuse • Not a common flight vehicle – lack of resources • Altitude will be difficult to control

• Mechanically simple • Allows for vertical takeoff and landing	• Landing safely will be difficult • Poor flight speed • Highly susceptible to weather variation (including winds and temperature) • Physical integration with MR will be difficult

3.1.4 LTA/Rotor UAS (Hybrid)

In addition to standard aircraft design, the team also considered several hybrid design options that could prove to be more advantageous than the aforementioned design options. The first hybrid considered was a rotor aircraft with some form of LTA component. Although this odd hybrid could take on many forms, perhaps the main concept is that of a rotor aircraft with an LTA component as seen in Fig. 3.1.4-1. This would be an enhancement to the rotor design to allow for much higher endurance and payload capacity than the base rotor design.

However, this increased power and payload capacity (**DR 4.2, 5.1.1, 6.1.4, 7.1.2**) would come at a high cost; the hybrid vehicle would have a much poorer stability (**FR 4.0, DR 4.1, DR 4.1.1**) than the base rotor design and run the risk of the rotors coming into contact with the LTA structure, likely damaging the whole system. The LTA component would also create additional drag, leading to a slower system than the rotor (**DR 4.2.3.1**).

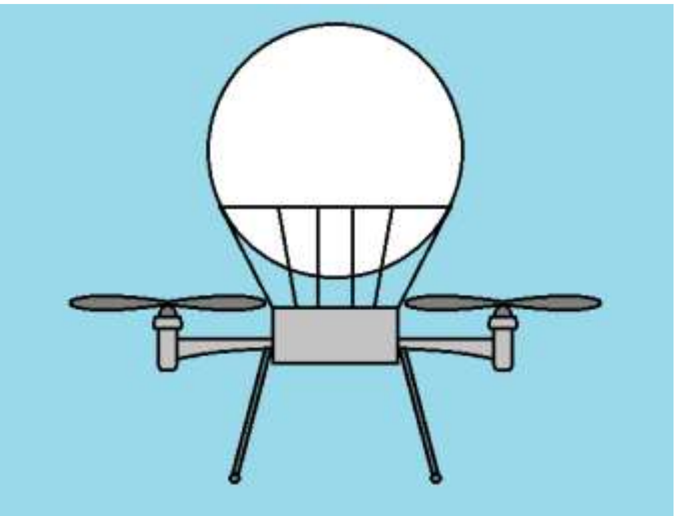


Figure 3.1.4-1: Diagram of Lighter Than Air/ Rotor Hybrid

Table 3.1.4-1: Pros and Cons of Lighter than Air and Rotor Hybrid

Advantages	Disadvantages
• Lower power requirements and higher endurance than rotor • Better control than LTA • Better payload capacity than rotor	• Mechanical interface with MR difficult • Unstable flight controls • Issues arise if rotor blades interact with LTA component • Slower flight speeds than the rotor

	• Complex integration between LTA and rotor • More susceptible to weather than rotor

3.1.5 LTA/Fixed Wing UAS (Hybrid)

The next hybrid consideration is that of a fixed wing aircraft with a LTA component. This would likely take the form of a zeppelin with wings that could be integrated onto a solid structure where the LTA gas is held (see Figure 3.1.5-1). Unlike the fixed wing UAS, the addition of the LTA gas allows for vertical takeoff and landing (**FR 3.0** and **10.0**). However, the low flight speeds of the LTA vehicle (**DR 4.2.3.1**) would render the attached wings nearly useless, thus making this design relatively infeasible.

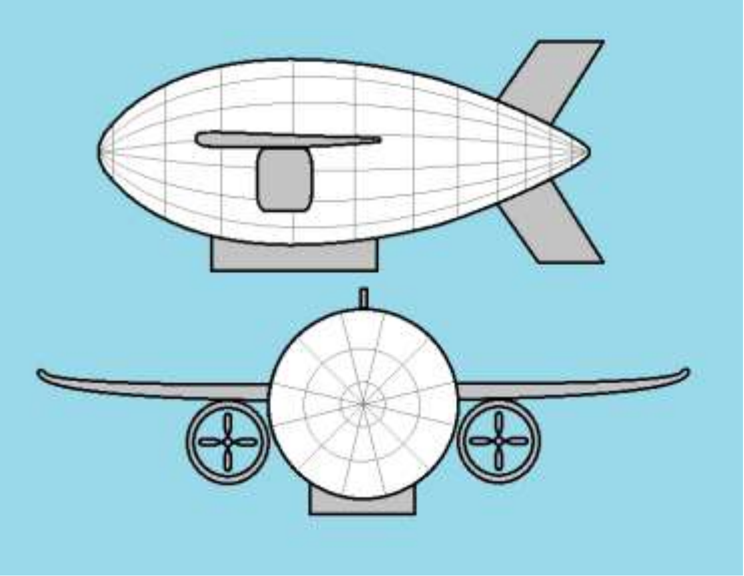


Figure 3.1.5-1: Diagram of Lighter than Air/ Fixed Wing Hybrid

Table 3.1.5-1: Pros and Cons of Lighter than Air and Fixed Wing Hybrid

Advantages	**Disadvantages**
• Allows for vertical takeoff and landing • Higher endurance than fixed wing	• Complex design • Aircraft will be more susceptible to weather conditions than fixed wing • Slower than fixed wing • LTA component renders wing portion nearly useless

3.1.6 Fixed Wing/Rotor UAS (Hybrid)

The final hybrid design that the team considered was a fixed wing/rotor combination as seen in figure 3.1.6-1. The idea behind the fixed wing/rotor hybrid is to have multiple propellers attached to the aircraft wings. These propellers would allow the hybrid to vertically take off (**FR 3.0**), followed by an eventual transition to horizontal flight. Thus, this vehicle would also have the capability to hover for video/imagery and SP deployment (**FR 4.0, 5.0, 6.0, 7.0, DR 4.1.1, 5.3**). If designed aerodynamically, the addition of the fixed wing design to the rotor would permit higher flight speeds (**FR 4.2.3.1**).

Although the theoretical implications of this design are of significant interest, the feasibility of the team to create this complex hybrid, due to the lack of COTS designs, within the time allotted is infeasible.

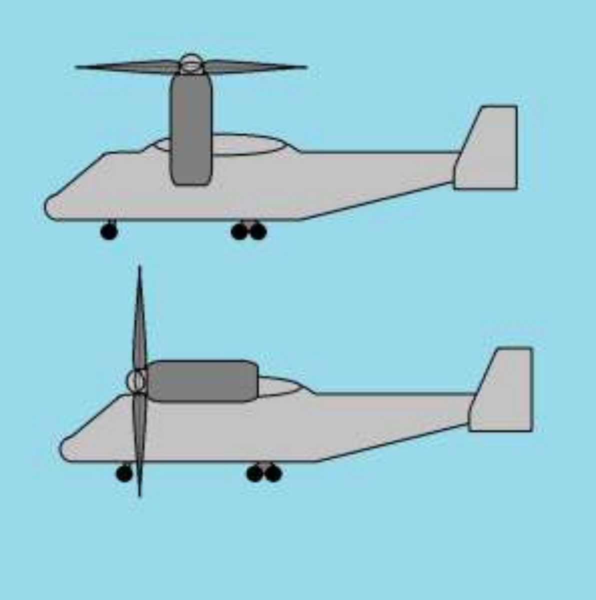


Figure 3.1.6-1: Diagram of Fixed Wing/ Rotor Hybrid

Table 3.1.6-1: Pros and Cons of Fixed Wing/Rotor Hybrid

Advantages	**Disadvantages**
• Allows for vertical takeoff and landing • Hover ability for easy reconnaissance and SP deployment • Higher flight speeds than rotor	• Mechanically very complex • Lower endurance than fixed wing • Complex system integration • Complex controls

3.1.7 Ballistic Rocket

The last design option considered was a ballistic rocket (see Fig. 3.1.7-1). The general idea of this design is that a rocket would be launched from the MR (**FR 3.0**) — likely protected by some sort of blast shield — to the location of interest (**FR 5.0**). The SP would be somehow contained in or carried with the rocket (**DR 5.1**), thus allowing for rapid deployment. However, there are also many disadvantages to this design option. There are many safety hazards associated with rocket malfunction, such as: significant damage to the SP, loss of the SP, significant damage to the MR, etc. Along these same lines of disadvantages, obtaining a COA will likely be impossible. Additionally, one of the primary mission requirements is the collection of imagery and video data (**FR 6.0, 7.0**), which, if possible at all, would be very limited and likely of poor quality due to the speed of the rocket. For these numerous reason, rockets were quickly ruled out as being an infeasible design option.

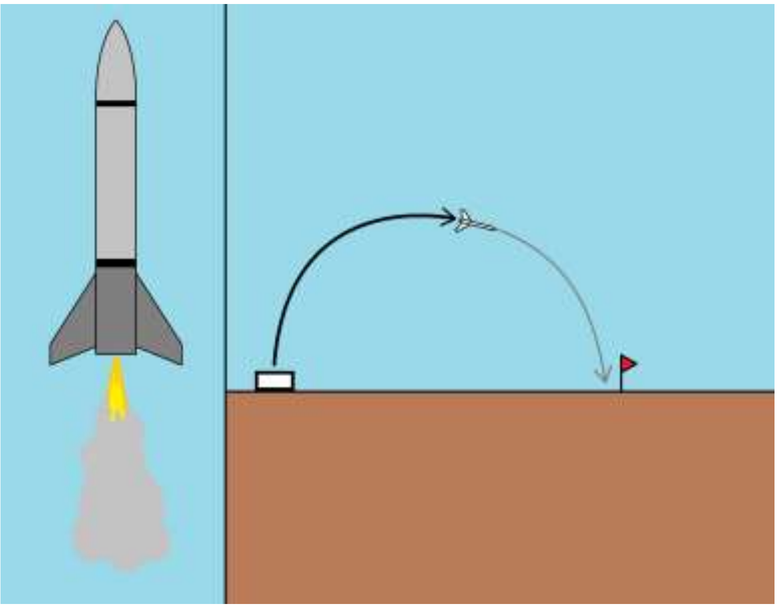


Figure 3.1.7-1: Diagram of Ballistic Rocket

Table 3.1.7-1: Pros and Cons of Ballistic Rocket

Advantages	Disadvantages
• Speed • Vertical takeoff from the MR	• Non-reusable • Safety concerns • COA will be much harder/impossible to obtain • Highly unstable • Limited reconnaissance and imaging • Difficult to correctly deploy sensor package in location of interest • Risk of damaging MR

3.2 Deployment Method

A key factor that will drive the design of both the CD and SP is the method of deployment, i.e. how the SP is delivered from the CD to the ground. As stated in **FR 5.0**, **DRs 5.2** and **5.3**, the CD will not only need to deploy the SP, but will need an accurate method for doing so. Four alternative deployment system designs are presented here: Parachute, Freefall, Winch, and Landing.

3.2.1 Parachute

The Parachute concept for sensor deployment, as its name suggests, would involve the SP dropping from the CD, then retard the fall with a parachute. The key benefits to this mode are that it is mechanically simple, has the ability to drop the SP from any altitude above that required for the parachute to deploy, and places the SP relatively gently on the ground (reducing its survivability requirements).

Among other potential downsides, parachutes are difficult to predict in their behavior. Requirement **DR 5.3** states that the SP must remain within 5 meters of the desired GPS location; however, parachutes are susceptible to wind (potentially causing the SP to drift away from the target during descent) and the device could easily become stuck in trees or other vegetation high above the ground, thus not meeting requirement **FR 5.0**. Additionally, the parachute could land on top of the sensor, potentially interfering with data collection and transmission as required by **FR 11.0** and **12.0**.

Figure 3.2.1-1 below demonstrates two different versions of the parachute deployment method. The first requires the parachute to deploy after release, while the second uses a potentially large housing aboard the CD to pre-deploy the parachute, adding mass but reducing the altitude required for deployment. Table 3.2.1-1 addresses the advantages and disadvantages of the concept.

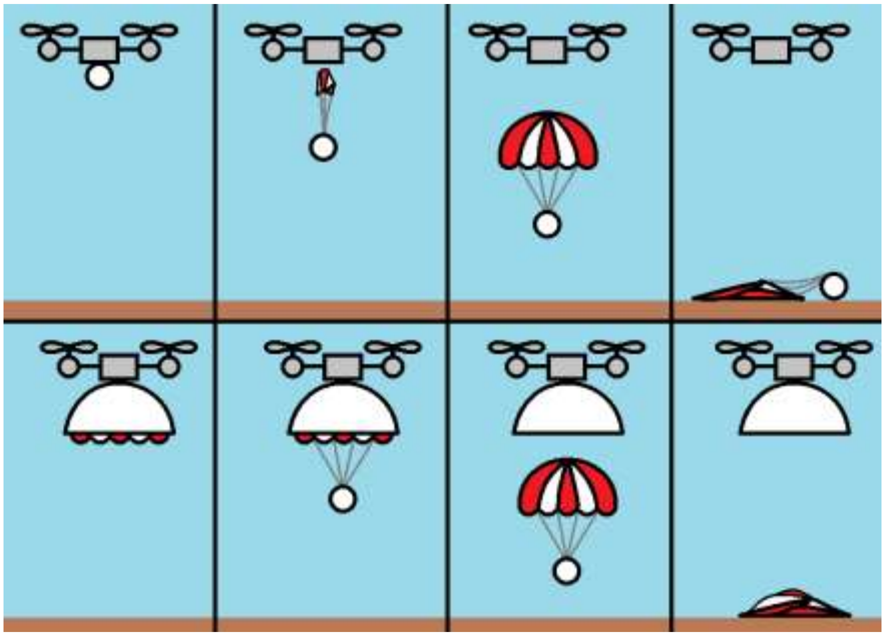


Figure 3.2.1-1: Parachute Sensor Deployment Concept

Table 3.2.1-1: Pros and Cons of "Parachute" Sensor Deployment Concept

Advantages	**Disadvantages**
• Soft landing of SP—lower survivability requirements • May help to orient the SP in a specific direction on the ground • May be mechanically simple	• Parachute could land on sensor and interfere with data collection and transmission • Rotary-wing downwash could interfere with parachute deployment • Requires minimum altitude for deployment • Parachute could become stuck in vegetation or on drone • Difficult to land accurately—easily disturbed by wind • May be difficult to model

3.2.2 Freefall

The Freefall concept of deployment would, like the Parachute, involve releasing the SP from the CD during flight. In this case, however, the SP would fall uncontrolled, impacting the ground at a high speed. This system would be extremely simple and reliable mechanically, and would allow more precise positioning of the sensor regardless of wind or vegetation, satisfying requirement **DR 5.3**.

Because of the uncontrolled descent, the sensor would have to be designed to survive and continue to function following hard impacts with the ground. Additionally, this would limit the altitude at which the SP could be deployed if not designed to withstand terminal velocity impact.

Figure 3.2.2-1 and Table 3.2.2-1 illustrate the Freefall concept and explore its characteristics.

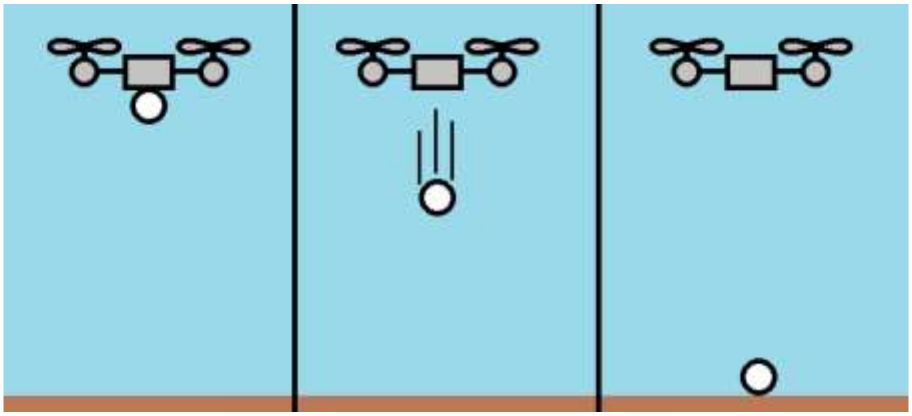


Figure 3.2.2-1: Freefall Sensor Deployment Concept

Table 3.2.2-1: Pros and Cons of "Freefall" Sensor Deployment Concept

Advantages	Disadvantages
• Precise location of drop • Mechanically simple • Low weight	• Hard landing of SP—greater survivability requirements • SP could bounce/roll away from target upon landing—must be deployed on flat and/or soft terrain • Difficult to orient SP in a specific direction on the ground • Dictates a maximum deployment altitude

3.2.3 Winch

A Winch would allow the CD to provide a highly-controlled method of deploying the SP from an airborne platform. The SP would be attached to the end of a spooled cable on the CD. At the target, the SP would be slowly lowered to the ground. Upon reaching the ground, the SP would be released, the cable reeled in, and the CD could return to the MR. This would allow very precise positioning and orientation of the SP on the ground (**DR 5.3**), low survivability requirements of the SP, and the ability to "cancel" deployment and retrieve the SP at any point prior to release.

Despite the level of control the Winch method offers, it has many downsides. The mechanism itself would be very complex, power hungry, and – perhaps most importantly – heavy. Additionally, the cable could become stuck on vegetation or other obstacles, resulting in the CD becoming stuck or crashing.

Figure 3.2.3-1 and Table 3.2.3-1 illustrate the Winch method and list its pros and cons.

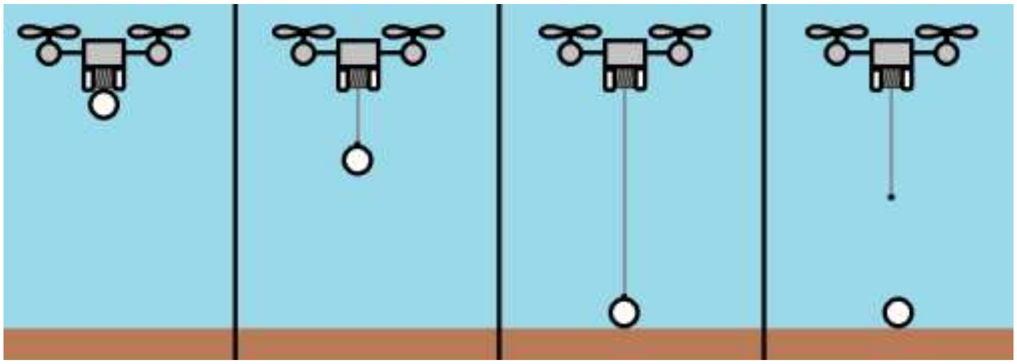


Figure 3.2.3-1: Winch Sensor Deployment Concept

Table 3.2.3-1: Pros and Cons of "Winch" Sensor Deployment Concept

Advantages	Disadvantages
• Soft landing of SP—lower survivability requirements • Precise placement of SP • Easy to place the SP in a specific orientation on the ground • Can cancel deployment and reel in the SP prior to release	• Mechanically complex • Heavy • Long deployment time • May be power-intensive • Cable could cause CD to become irretrievably stuck on vegetation • Cable length dictates a maximum deployment altitude

3.2.4 Landing

The Landing method of deployment is likely the simplest out of those evaluated herein. In this case, the CD itself would land at the target, place the SP on the ground, and then fly away. Its chief advantages are highly accurate positioning and orientation of the SP (**DR 5.3**), little-to-no impact force on the SP, and low weight (**DR 4.2**). Additionally, it could utilize the same exact mechanism as the Freefall concept, providing a design fallback in case the SP is not able to be made to survive Freefall impact.

The most significant drawback to the Landing concept is its limitation to operational flexibility—the SP could only be deployed where the CD is capable of landing. As such, the SP could not be deployed on sloped or heavily vegetated terrain. Additionally, it would increase the time required for deployment, and could reduce the overall endurance of the CD because of the power required for landing and takeoff, potentially restricting the ability to meet requirement **DR 4.2**.

Figure 3.2.4-1 and Table 3.2.4-1 visualize and discuss the Landing methodology.

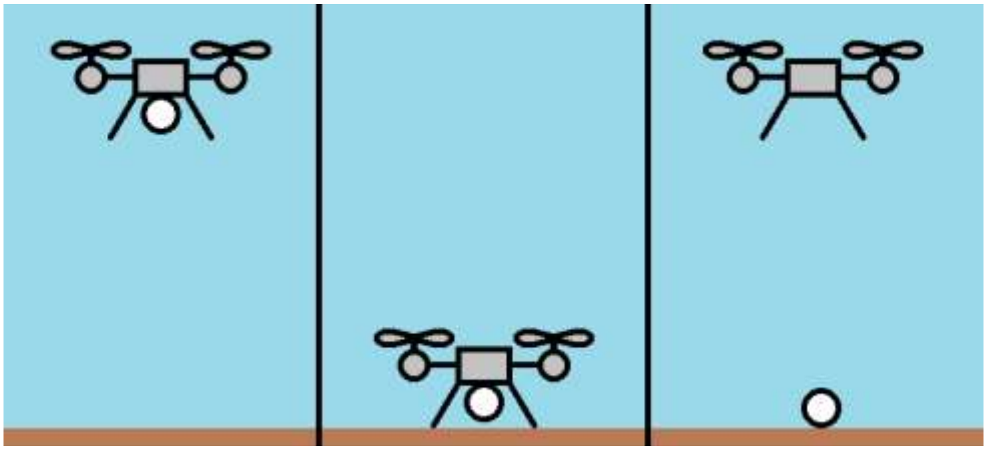


Figure 3.2.4-1: Landing Sensor Deployment Concept

Table 3.2.4-1: Pros and Cons of "Landing" Sensor Deployment Concept

Advantages	Disadvantages
• Soft landing of SP—lower survivability requirements • Very accurate placement and orientation of SP on ground • Mechanically simple • Low weight	• Prevents the SP from being deployed where Child cannot land—must be deployed on flat, non-vegetated terrain • Long deployment time • Descent, landing, and ascent could be power-intensive

3.3 Sensor Attachment

Due to the fact that the project definition requires delivering a SP to a remote GPS location (**FRs 4.0** and **5.0**), the necessity of an attachment device for the SP to the CD is obvious. There were a large number of designs that were in consideration for the attachment device, all of the choices along with their advantages and disadvantages are presented below.

3.3.1 Claw Design

The first attachment device of interest is a claw design. This design choice allows many different version of a 'claw' but the general idea is shown in Fig. 3.3.1-1 with some advantages and disadvantages tabled below. The claw adds the capability for many different shapes and sizes of SPs to be designed; it also has the advantage of being power efficient unlike some of the other choices. The claw is a relatively lightweight solution but could prove to be relatively unreliable depending on the exact design. Some possible designs are shown in Figure 3.3.1-1. A list of advantages and disadvantages is given in Table 3.3.1-1.

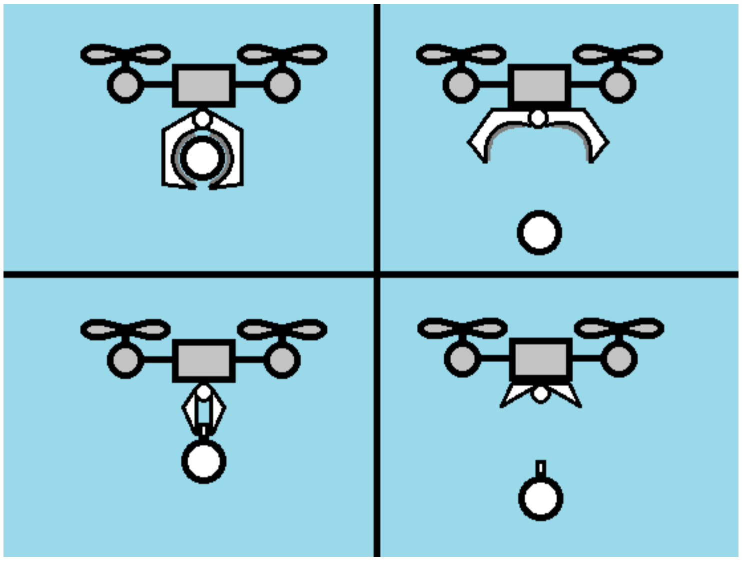


Figure 3.3.1-1: Claw Concept of Sensor Attachment

Table 3.3.1-1: Pros and Cons of Claw Attachment

Advantages	**Disadvantages**
• Simple Mechanical Design • Small Power Draw	• Reliability dependent on SP design • Creates a large amount of drag while carrying the SP

3.3.2 Housing Design

The next design choice is that of a housing. This design, similar to the claw, adds the capability for a diverse selection of SP designs but is also much more mechanically complex and will likely have more adverse effects on the child drone during flight due to the additional mass and power consumption (discussed below). One of the main concerns with this option is the interference with the CD landing gear and the potential power draw of keeping the housing shut during SP transport. As shown in Figure 3.3.2-1 the housing would likely need to include a "door" which is where the major downfalls of this design choice originate; the necessity to keep the door shut during flight and re-shutting it after deployment add significant power draw and mass concerns to the system (**DR 4.2**) and could interfere with the flight of the vehicle itself (**FRs 3.0, 4.0,** and **10.0**). This system does however provide a very secure transport mechanism for the sensor package. A list of advantages and disadvantages is given in Table 3.3.2-1.

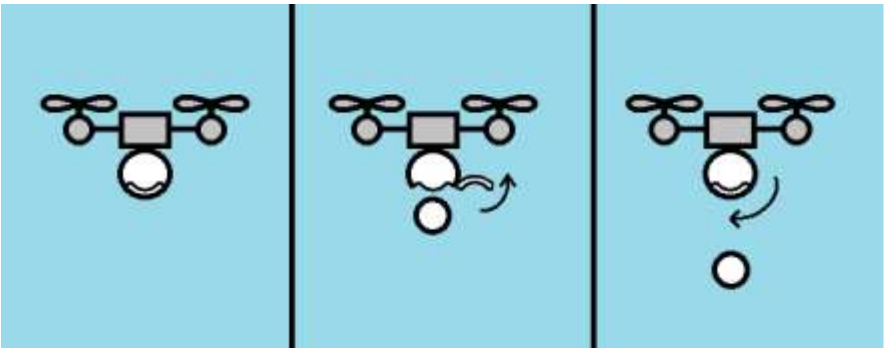


Figure 3.3.2-1: Housing Concept of Sensor Attachment

Table 3.3.2-1: Pros and Cons of Housing Attachment

Advantages	Disadvantages
• Potential for low drag design • Secure transport and deployment of SP	• Complicated Mechanical Design • Large Mass

3.3.3 Torque Magnet

The next design is a torque magnet. A torque magnet functions by rotating two diametrically polarized magnets 180° thus aligning their magnetic poles to generate a powerful magnetic field. This type of magnet requires no power to remain on and can be deactivated with a relatively small torque from an onboard actuator. These magnets would be a low mass (**DR 4.2**), low cost, and effective attachment design for the SP (**DR 5.0**). The main worry associated with this attachment device is the complication with magnets and electronics that is known to occur. There is also some concern regarding the motor that will be needed to torque the device itself to release the magnet. One possible design is shown in Fig. 3.3.3-1. A list of advantages and disadvantages is given in Table 3.3.3-1.

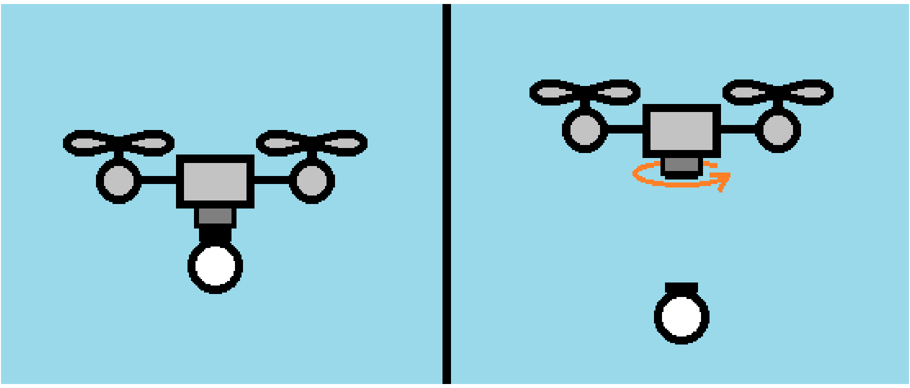


Figure 3.3.3-1: Torque Magnet Concept of Sensor Attachment

Table 3.3.3-1: Pros and Cons of Torque Magnet Attachment

Advantages	Disadvantages
• Secure hold of SP • Simple Mechanical Design • Small mass • Low profile design when SP is not attached	• Negative affect on electrical components • Short term high power requirement

3.3.4 Tilt Deploy

The next design option considered by the team was that of a Tilt deploy SP release. This design choice is envisioned as being a "compartment" mounted on the top of the flight vehicle that could then drop the sensor package over the side of the CD upon arrival at the LOI. This design option is very limited by the choice of flight vehicle because it has no practical ability to function with a LTA vehicle and could cause complications with a rotor vehicle (**FR 3.0, 4.0,** and **10.0**). This device, however, requires little to no power draw and is extremely low in mass (**DR 4.2**). A list of advantages and disadvantages is given in Table 3.3.4-1.

Table 3.3.4-1: Pros and Cons of Tilt Deploy Attachment

Advantages	Disadvantages
• No landing interference from mechanism • Simple mechanical design	• Possible rotor interference • Will not work with LTA vehicle design • Stability effects on vehicle • Accidental deployments possible

3.3.5 Pull Pin

Perhaps one of the most obvious design options is that of a simple pull pin. This is a design in which the SP would be secured to the CD via an attachment point held together by a pin. Using a small servo motor to release the pin would cause the SP to drop at a desired location. This design also allows for a secure transport connection (**FR 5.0** and will have low power draw and low mass (**DR 4.2**) in comparison to the claw and housing designs. One possible design is shown in Figure 3.3.5-1. A list of advantages and disadvantages is given in Table 3.3.5-1.

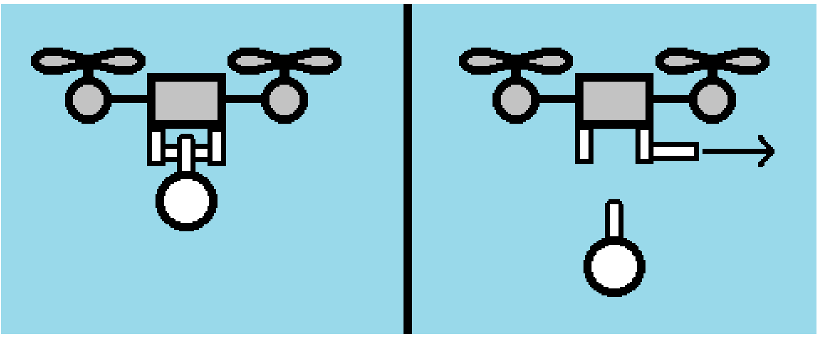


Figure 3.3.5-1: Pull Pin Concept of Sensor Attachment

Table 3.3.5-1: Pros and Cons of Pull Pin Attachment

Advantages	Disadvantages
• Small power draw • Simple mechanical design	• SP must be designed with pin mechanism, limiting the SP design

3.3.6 Burn Wire

The final design option considered by the team was a burn wire. A burn wire attachment scheme has the potential to integrate with many different SP designs and would allow for versatile mounting positions. One major advantage of the burn wire is that it would be the lightest (**DR 4.2**) of all of the design options. However, it may be difficult to keep the SP fixed during flight; depending on the exact design, this method of attachment could allow for significant movement of the SP during transport. One possible design is shown in Fig. 3.3.6-1. A list of advantages and disadvantages is given in Table 3.3.6-1.

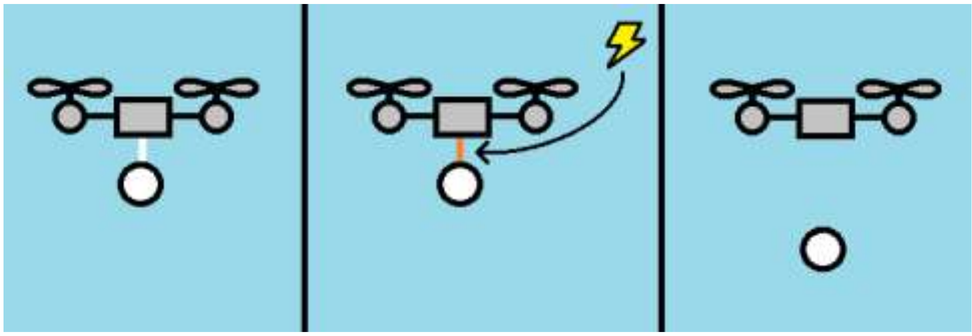


Figure 3.3.6-1: Burn Wire Concept of Sensor Attachment

Table 3.3.6-1: Pros and Cons of Burn Wire Attachment

Advantages	Disadvantages
• Low mass • Simple mechanical design • Small power draw	• Not reusable • Less secure than other options

4 Trade Study Process and Results

4.1 Aircraft Selection

4.1.1 Design Criteria and Weighting Explanation

Table 4.1-1: Design Criteria Weighting and Rationale

Criteria	Weight	Driving Requirements	Description and Rationale
Position-Hold Capability	20%	FR 4.0 DR 4.1.1 FR 5.0, DR 5.3	The main functional purpose of the CD is to deliver the SP to a commanded location with a 5 meter accuracy. In order to accomplish and verify this requirement during operation, the CD is required to hold its position within the 5 meter tolerance long enough to confirm its GPS location with the GS before deploying the SP. A design that is able to hold its position accurately will increase the confidence in the SP's deployment location and thus the reliability of the data received. This criterion is weighted the heaviest because it most directly affects the ability for the INFERNO system to accomplish its main goal of gathering temperature data at a precise location.
Cost	17%	N/A	After initial research, it is clear that the cost of the CD, whether COTS or custom-built, will dominate the budget for the INFERNO project. Many COTS systems have a cost above half of the project's current total budget. Keeping the CD cost low will be

			essential to ensuring that enough budget remains to purchase other essential components for other aspects of the INFERNO system.
Procurement	17%	N/A	Due to the high costs and unavailability of some alternatives, purchasing a fully COTS CD will likely not be possible for this project. Most of the aircraft design alternatives will require purchasing and integrating multiple components to construct a system capable of meeting all of the requirements. This criterion quantifies the anticipated difficulty in obtaining and integrating these components for each design by accounting for commercial availability, manufacturability, design heritage, and ease of integration.
Ease of Takeoff and Landing	10%	FR 3.0 FR 10.0, DR 10.1	Another main requirement of the INFERNO system is that the CD must be capable of taking off from and landing on the MR. Although the MR may be modified in order to more easily accomplish this task, the design of the CD will greatly facilitate or complicate this process. This criterion is given a lighter weight than other mission-critical criteria here due to the flexibility in the MR design.
Size	10%	FR 3.0, DR 3.1, DR 3.1.1, DR 3.1.2 FR 10.0	The size of the CD will greatly affect the CD’s ability to integrate with the MR which is also tied closely with the takeoff and landing criteria. This criterion considers both the footprint of the design and the overall size of the aircraft since both will have implications on the takeoff and landing of the CD as well as MR locomotion within the scope of the FireTracker system.
Payload Capacity	8%	FR 5.0, DR 5.1, DR 5.1.1, DR 5.1.2 FR 6.0, DR 6.1.4, DR 6.1.5 FR 7.0, DR 7.1.2, DR 7.1.3	In order for the CD to deliver its payload to a remote location, it must be capable of flying for a sufficient amount of time while the SP is still attached. Preliminary research indicates that most design options will be capable of carrying payload weights matching or exceeding the team’s presupposed values. For these reasons, this criterion is given a below-average weight.
Stability and Control	8%	FR 2.0, DR 2.6, DR 2.7 FR 4.0, DR 4.1, DR 4.1.1, DR 4.2.3 FR 5.0 FR 10.0, DR 10.1	In order to achieve the highest levels of success for this project, the CD is required to be capable of travelling to commanded locations using autopilot functionality. This, coupled with the need for the system to be stable in flight even with an experienced pilot in control, drives the need for a stable aircraft.

Endurance	5%	DR 4.2, DR 4.2.1, DR 4.2.2, DR 4.2.4, DR 4.3	The CD is required to endure mission durations of 20 minutes including traveling with the payload, deployment, reconnaissance, and returning to the MR. This criterion is given a lower weighting because an endurance of 20 minutes is not critical to primary mission success and most of the designs can be augmented with additional power to ensure this requirement is met.
Flight Speed	5%	DR 4.2.3, DR 4.2.3.1	In order for the INFERNO system to be useful, the CD must be capable of reaching its intended target within a reasonable time. The CD is required to achieve a wind speed of 10 m/s. This criteria is given a lower weighting because a mission duration of 20 minutes requires a much lower flight speed than 10 m/s, thus it is not critically important to primary mission success.

4.1.2 Trade Study

Table 4.1-2: Aircraft Design Trade Study

		Rotor		**Fixed Wing**		**LTA**	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**
Position-Hold Capability	20%	5.00	1.00	1.00	0.20	4.00	0.60
Cost	17%	2.00	0.34	4.00	0.68	5.00	0.85
Procurement	17%	4.00	0.17	5.00	0.85	2.00	.034
Ease of Takeoff and Landing	10%	5.00	0.50	1.00	0.10	2.00	0.20
Size	10%	5.00	0.20	3.50	0.35	1.00	0.10
Payload Capacity	8%	2.00	0.16	4.00	0.32	2.00	0.16
Stability and Control	8%	4.00	0.32	5.00	0.40	2.00	0.16
Endurance	5%	2.00	0.10	3.00	0.15	5.00	0.25
Flight Speed	5%	3.50	0.175	5.00	0.25	1.00	0.05
Total	**100%**	**3.78**		**3.30**		**2.71**	

The trade study shown in Table 4.1-2 above shows the numerical analysis of each alternative design and the final weighted totals for each. These totals provide a relative indication of which system is best for the baseline design.

The first system analyzed was the rotor-based aircraft design. This system has strengths in its ability to easily hold its position with greater accuracy than the other designs and in its ability to more easily integrate with the MR due to its small size and vertical takeoff and landing capability. These strengths resulted in scores of 5 in the position-hold, takeoff/landing, and size categories. Rotor systems are also widely available on the commercial market and have a comprehensive heritage both in the literature and among CU's faculty, however, the cost for many of these systems is quite high, especially COTS models. The rotor aircraft received poor scores in the payload capacity, endurance, and flight speed criteria due to the more restrictive limitations on available power and payload mass imposed on rotor aircraft than the other designs.

The second system analyzed was the fixed wing aircraft design. This system received high scores for its stability and flight speed; however, the aircraft's inability to hold its exact position or easily takeoff from and land on a small surface such as the MR resulted in scores of 1 in both categories. Similarly to the rotor design, fixed wing aircraft are readily available on the commercial market while remaining relatively cheap in comparison to the rotor aircraft, thus this design was given high scores for procurement and cost. Fixed wing aircraft are often larger than rotor aircraft, however, they have a smaller vertical size, and thus this design received a medium score of 3.5 for size. Finally, fixed wing aircraft can carry relatively large payloads and fly for longer than average rotor aircraft designs, thus the fixed wing aircraft received a score of 4 for payload and 3 for endurance.

The final system analyzed was the lighter than air design. The strengths of a lighter than air design include significantly reduced power requirements and its ability to hold position accurately. However, lighter than air vehicles are highly susceptible to environmental effects such as wind, so it received a score of 2 in both stability and ease of takeoff and landing. Based on preliminary analyses, shown in Appendix A, lighter than air vehicles capable of carrying payloads of expected weight are much larger than either rotor aircraft or fixed wing aircraft which could have a significant impact on integration with the MR. Lighter than air vehicles also have a significantly lower airspeed than both other designs which would most likely mean that this design could not achieve the 10 m/s flight speed requirement. Finally, lighter than air vehicles do not have nearly the level of heritage that rotor and fixed wing aircraft do, thus more of the vehicle would need to be designed and acquired separately than for the other two designs. This resulted in a score of 2 for procurement, however, the materials required for a lighter than air vehicle are expected to cost less than those for either of the other designs since expensive COTS components such as airframes and multiple rotors are not required.

4.2 Deployment Method Selection

Once the base aircraft design had been determined, the team proceeded to consider various methods of deploying the sensor package. The selection of a deployment scheme also required a trade study. This section details that trade study process including trade metrics chosen, respective weighting, and the process of assigning values for each metric.

4.2.1 Design Criteria and Weighting Explanation

Table 4.2-1: Design Criteria Weighting and Rationale

Criteria	Weight	Driving Requirements	Description and Rationale
SP Survivability	15%	FR 5.0 FR 11.0, DR 11.1 FR 12.0, DR 12.1 FR 13.0, DR 13.1	The main purpose of the SP is to record and transmit temperature data back to the MR. In order to accomplish and verify this, the SP must not be damaged in any way upon deployment and impact with the ground. Possible methods of disabling the SP could come from damaging the hardware casing or losing the ability to transmit the data to the MR due to loose components after impact. As a result, survivability was weighted at 15% because of its critical contribution to the INFERNO system.
Position Accuracy	15%	DR 4.2.3	The main functional purpose of the CD is to deliver the SP to a commanded location with a 5 meter accuracy. This trade study examines deployment methods for which the

		FR 5.0, DR 5.3, DR 5.4 FR 11.0	deployment location and landing location could differ. Since the locational accuracy of the SP is a driving customer requirement, our team has also given position accuracy critical mission status, and a 15% weighting.
SP Orientation	10%	DR 4.2.3 FR 5.0 FR 11.0 FR 12.0 FR 13.0	Although the shape of the SP is currently in development, temperature sensor and radio transmitter orientation is important to system performance. While not a critical mission element, properly orienting the transmitter will increase the likelihood of successful data transmission to the MR. Additionally, orienting the temperature sensor properly will ensure ambient air temperature is recorded rather than ground temperature. These considerations led to a 10% weighting.
Hazard Avoidance	15%	FR 5.0, DR 5.3, DR 5.4 FR 11.0 FR 12.0 FR 13.0	A driving requirement for the SP is the collection and transmission of ambient air temperature at ground level. As this is a customer defined requirement, ensuring the SP reaches ground level is a critical mission element, earning the weight of 15%. Hazard avoidance encompasses many aspects for this project. Deployment of the SP must have the ability to avoid getting the SP stuck in trees, stranded in bushes, hooked on boulders, or submerged in water.
Mechanical Complexity	10%	FR 5.0, DR 5.1, DR 5.2	Mechanical complexity and system integration is highly important to the success of the project. Even though complexity is not defined in the mission statement or requirements, it influences risk and reliability of the associated system. Because of this, the deployment mechanism must be reliable enough to deploy the payload upon command, failure of which could lead to a mission failure. As a result, mechanical complexity was given a weight of 10%.
Power Draw	15%	DR 4.2	Power concerns are of the highest importance for the INFERNO system. Available power determines the overall flight endurance of the CD and which deployment methods are conceivable. With the power being such a limited resource for this mission, it was also deemed a critical mission element and received a weight of 15%.
Altitude Limitations	5%	FR 4.0 FR 5.0	Altitude Limitations received the lowest weight at 5%. Nevertheless, altitude limitations are still important to design element selection. Possible trade study solutions have certain altitude restrictions for their success. For example, the winch can only be as high above the ground as the length of the cable holding the SP. However, the CD is still able to change altitude quickly and easily, thus lowering the weight of this design criterion.
Mass	15%	DR 4.2, DR 4.2.1, DR 4.2.2,	As with many flying vehicles, component mass has a major influence on system performance and capability.

		DR 4.2.3, DR 4.2.3.1, DR 4.2.4 DR 5.2	With the INFERNO project especially, mass is a driving factor in selection due to the CD's lift and carry capabilities. Mass effects are coupled with many other factors, including flight endurance, power draw, and altitude limitations. Because of these implications, mass was also deemed a critical mission element and received a weight of 15%.

4.2.2 Trade Study

Table 4.2-2: Deployment Method Trade Study

		Parachute		Free Fall		Winch		Land CD	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**	**R**	**W**
SP Survivability	15%	3.50	0.525	2.00	0.30	4.00	0.60	5.00	0.75
Position Accuracy	15%	1.00	0.15	3.50	0.525	4.00	0.60	5.00	0.75
SP Orientation	10%	2.50	0.25	1.00	0.10	4.00	0.40	5.00	0.50
Hazard Avoidance	15%	1.00	0.15	4.00	0.60	2.50	0.375	1.00	0.15
Mechanical Complexity	10%	3.00	0.30	5.00	0.50	1.00	0.10	5.00	0.50
Power Draw	15%	5.00	0.75	5.00	0.75	1.00	0.15	2.00	0.30
Altitude Limits	5%	4.00	0.20	3.00	0.15	2.00	0.10	1.00	0.05
Mass	15%	3.50	0.525	5.00	0.75	1.00	0.15	5.00	0.75
Total	**100%**	**2.85**		**3.68**		**2.475**		**3.75**	

Selection of a deployment method was performed using a numerical trade study, as shown in Table 4.2-2. The totals for each system provide a relative suggestion as to which system accomplishes SP deployment most appropriately.

The first system analyzed for SP deployment was the parachute. This option scores a 3.5 for SP survivability. This is higher than freefall because of the reduction in shock the SP will receive upon impact. However, the parachute scores lower than both the winch and landing methods; since the SP would be attached to the parachute, wind could drag the SP around and could damage it. Additionally, the parachute could end up covering the SP, altering the gathered temperature data or even blocking the signal from the SP transmitter. The parachute scored the lowest value of 1 for position accuracy due to the unpredictability of an uncontrolled descent. Given a light breeze, the parachute could drift off course, violating the 5 meter accuracy requirement. Similar to survivability, the orientation of the SP upon reaching the ground could be influenced by wind or the parachute itself. Fortunately, the orientation of the landing would have some predictability (it wouldn't be upside down). These considerations led to a value of 2.5 for orientation. Understandably, with any breeze blowing the parachute off course or even natural drift from the parachute, it is hard to determine precisely where the SP will travel. Additionally, the cables and structure of the parachute could easily become intertwined with trees and bushes. With this in mind, the parachute was given a 1 for hazard avoidance. Devising a method to store the parachute to ensure reliable deployment has given the team reason to assign the mechanical complexity a value of 3. This value serves as a midpoint for the remaining systems: while more mechanically complex than freefall, a parachute is less complex than using a winch. The parachute, like freefall, requires very little power. Once the system is released from the CD, no additional power is needed, meriting a rating of 5. The parachute allows for almost any drop height and thus received the highest value of 4 in this section. The only limitation is that the CD must deploy the SP from high enough that the parachute has enough time to inflate. However, the team rationalized that if the drop height is not sufficient to open the parachute, the shocks encountered upon landing would also be small. The parachute is a relatively low mass solution for deployment; although much lighter than the winch, the parachute still has more mass than a landing or freefall would require. As such, a value of 3 was assigned for the trade study.

The second deployment option analyzed for this trade study is freefall from the CD. Freefall received the lowest survivability score of all of the deployment methods due to the fact that the freefall method contains the highest forces and shocks upon impact. Not only will the shocks be the greatest, but attitude during descent will be unknown, leading to more crash landing concerns. Our team chose a value of 2 instead of 1 because of the possibility of constructing a sensor package capable of handling the impact forces. Dropping the SP provides reasonable accuracy. The only real concern regarding position accuracy is the possibility that the SP could bounce or roll upon reaching the ground. A value of 3.5 was assigned for this trade study. This value is higher than that of the parachute because it will not be influenced by the wind nearly as significantly, but lower than the winch or landing methods because of the possibility of rolling or bouncing. Dropping the SP received the lowest score of 1 for orientation control due to the uncontrolled spinning during descent and the bouncing and rolling upon impact. A strong attribute of dropping the SP is that the “flight path” can be predicted quite well, thus resulting in accurate placement and enhance hazard avoidance. As a result, the SP can be dropped so as to avoid trees, bushes, boulders, and water with ease. A value of 4 was assigned instead of 5 accounting for the risk that, after landing, the SP bounces or rolls such that it encounters a hazard. Dropping the SP requires minimal mechanical complexity. Similar to landing the CD, very few mechanisms are required to accomplish this. As a result, the value of 5 was assigned. Another advantage of the freefall method is that minimal power is required. Similar to the parachute, once the SP is released, no additional power is required to get the SP to the ground. For this reason, a value of 5 was given for the trade study. The height at which the SP is released will have major implications on survivability and position accuracy. The higher the drop height, the more shock the SP encounters upon impact and the less accurate the position will be. However, in contrast to the winch, there is no “maximum” height for a drop and as such, this method received a 3.Because the freefall method requires no additional mass to be added to the CD it received a value of 5.

The third system analyzed for this trade study is a winch used to lower the SP to the ground. Using a winch to lower the SP to the ground has several advantages and disadvantages. Our team assigned a survivability value of 4 for the winch primarily due to its ability to set the SP on the ground safely with negligible shock, leading to a low probability of damaging the SP. However, a value of 5 was not earned due to concerns (like the parachute) of the SP being dragged while still attached to the winch, which could potentially damage the SP and render it unusable. Lowering the SP by winch allows for the SP to be placed softly in any position desired by the operator. This trait is very advantageous because it does not run the risk of bouncing and rolling, and wind influences are minimized. However, wind still influences the winch more than landing the CD, so a value of 4 was assigned for winch position accuracy. Another advantage of the winch is that the SP would be placed on the ground with a very predictable orientation. A value of 4 was assigned instead of a 5 because the SP still has the possibility of being dragged by the winch cable before it is detached, thereby changing the final orientation. Hanging the SP by a winch cable from the CD could introduce significant hazard avoidance problems. Even though the SP would be lowered directly below the CD, a winch cable would have the potential to strike trees and bushes. Because of this, a value of 2.5 was assigned. Complexity of the winch and integration with the CD remove from the feasibility of using a winch for deployment. A value of 1 was given here because of the many difficulties associated with adding a winch to the system. Examples include: multiple motors on board the CD for reeling the cable in and out, a hold and release mechanism at the end of the cable, and a stable housing for the winch assembly. The winch also received a score of 1 in the power draw criteria. Not only would the winch assembly require ample amounts of power for reeling the SP out and the cable back in, but the CD would have to hover while this process was carried out. Using a cable to lower the SP to the ground imposes an altitude restriction for deployment. Since the cable is finite in length, the deployment altitude has a ceiling that cannot be broken. A score of 2 was assigned rather than 1 because the CD does not have to land to perform the deployment. Mass is one of the most influential factors in aircraft design. A high mass limits the flight time, flight speed, and agility of the flight system. Additionally, it adds to power requirements. Using a winch would considerably influence the mass budget of the entire INFERNO project. The winch, cables, and motor assembly yielded a score of 1 in this category.

The final "system" analyzed for this trade study was a landing scheme for directly setting the SP on the ground. Landing the CD received the highest SP survivability score of 5 due to the fact that there is essentially no impact involved for the SP upon landing. This method guarantees the SP experiences negligible shock upon landing, is placed on a safe surface, and is not dragged around by attachments (parachute or winch cable). Again with exemplary performance and a value of 5, landing the CD guarantees the proper position of the SP. The SP would not have the opportunity to bounce or roll, and can be set anywhere the operator chooses. Since the SP will be lightly placed on the ground, orientation can be easily predicted and planned for. By landing the CD in a safe location, the risk of the SP tipping or rolling due to a boulder becomes negligible, and tumbling in freefall and bouncing upon landing are also irrelevant. Landing the CD was given a value of 5 in this trade study for the reliability involved in the method. A primary concern with landing the CD for the deployment of the SP it that many SP deployment locations are ruled out. This deployment method removes the possibility of sloped or heavily vegetated terrain for data collection. Because of this, a value of 1 for this trade study was applied. The CD requires little to no extra equipment for landing at the LOI due to the fact that the CD will already have to be able to land on the MR. For this reason, a value of 5 was assigned to the landing method for the trade study. A value of 2 was assigned for this category because of the high power requirements to safely land the CD with the SP still attached and the additional power required to take off and reach a safe altitude again. A value of 1 was not assigned because the power requirement is not as strenuous as that of the winch system. A consequence of landing the CD is that all high altitude deployments are ignored. The CD would not be able to deploy the SP above any obstacle, and would have to safely reach ground level to deploy the system. Similar to the hazard avoidance logic, a value of 1 was assigned for altitude limitations. A benefit with landing the CD compared to using the winch or parachute is that this method requires no additional mass. This is the driving reason behind a value of 5 for the mass criteria.

4.3 Attachment Selection Trade Study

Once the aircraft type and deployment method trade studies had been completed, the team studied different methods to attach and release the SP. This section shows the criteria used for evaluation and their relative weights. This section also provides explanations for the values assigned to each possible system.

4.3.1 Design Criteria and Weighting Explanation

Table 4.3-1: Design Criteria Weighting and Rationale

Criteria	Weight	Driving Requirements	Description and Rationale
Mechanical Complexity	20%	FR 5.0, DR 5.1, DR 5.2	Mechanical complexity refers to the difficulty of designing and fabricating the system. This is given an average weighting because increasing complexity requires more design and testing time to be spent on the system. This is time that is preferred to be spent on CPEs. However, these systems are small enough that they are not an insurmountable burden.
Power Draw	25%	DR 4.2	Power Draw refers to the amount of power required to operate the system throughout the mission duration. This includes take off, traveling, deployment, reconnaissance, return, and landing. This category is given an above average weighting because the power consumed directly affects the ability of the CD to complete its mission. Drawing substantial power will reduce the endurance of the CD.
Mass	25%	FR 4.0, DR 4.2, DR 4.2.1, DR 4.2.2, DR 4.2.3.1, DR 4.2.4 DR 5.2	Mass refers to the overall mass of the attachment system. This includes any mechanisms, electronics, and mountings that may be required. This is given an above average weighting because the mass of the system directly affects the power required to operate the CD. Large amounts of mass can result in reduced endurance, range, and speed.
Effects on CD	20%	FR 3.0, DR 3.1, CD 3.1.2 FR 4.0, DR 4.1.1, DR 4.2 FR 10.0	An effect on the CD refers to how carrying the SP with the attachment system affects the flight, stability, and control of the CD. This includes aerodynamic concerns, instability, and possible movement of the SP within the attachment. This is given an average weighting because extreme effects on the CD will compromise the entire mission. However, most effects are expected to be mild enough to be overcome.
Cost	10%	N/A	Cost refers to the monetary cost of the system. This includes any COTS products, as well as any parts that must be bought for the creation and testing of each system. This is given a below average weighting because the overall cost of the attachment system is expected to be very low in comparison to other costs in the project.

4.3.2 Trade Study

Table 4.3-2: Aircraft Design Trade Study

		Claw		**Housing**		**Torque Magnet**		**Pull Pin**		**Burn Wire**	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**	**R**	**W**	**R**	**W**
Mechanical Complexity	20%	2.00	0.40	2.00	0.40	3.00	0.60	3.00	0.60	4.00	0.80
Power Draw	25%	3.00	0.75	2.00	0.50	3.00	0.75	4.00	1.00	3.00	0.75
Mass	25%	2.00	0.50	1.00	0.25	3.00	0.75	4.00	1.00	5.00	0.25
Effects on CD	20%	3.00	0.60	4.00	0.80	4.00	0.80	4.00	0.80	3.00	0.60
Cost	10%	3.00	0.30	2.00	0.20	3.50	0.35	3.00	0.30	5.00	0.50
Total	**100%**	**2.55**		**2.15**		**3.25**		**3.70**		**3.90**	

The trade study shown in Table 4.3-2 above shows the numerical analysis of each SP attachment design as well as the final weight totals for each. These totals provide a relative indication of which system or systems are worth carrying through to the preliminary design phase.

The first system analyzed was the claw. This system received poor scores in mechanical complexity and mass. This is because the claw would require multiple, custom manufactured physical components, as well as one or more servos to operate the claw. These additional parts would add more weight to the system as well. The claw received a medium score in power draw and cost. This is because power will be needed to operate the required motors. The claw will also require attachments to the CD and will be located beneath the drone. This resulted in an average score in the effects on CD category. Finally, the cost associated with the claw are not expected to be expensive, but must be accounted for.

The second system analyzed was the housing mechanism. This system is the heaviest of the investigated systems, resulting in the lowest score in mass. The extra material and fabrication associated with a full housing system resulted in a low score in mechanical complexity and cost. Additionally, the SP housing will require power to open, close, and maintain control over the release mechanism. This led to the system receiving a low score in power draw. The system was given a higher score in effects on CD because the housing could be designed aerodynamically in order to reduce effects on the CD. The extra material and fabrication will require additional costs, resulting in a poor value in the cost category.

The third system analyzed was the Torque Magnet. This system has average to above average scores in all categories. The magnet is fairly simple to design, and likely only requires a single motor. This leads to threes in mechanical complexity, power draw, and mass. The system is smaller, and shouldn’t interfere with the CD as much resulting in a four in the effects on CD category. Finally, the magnet is inexpensive, and the additional components required are minimal.

The fourth system analyzed was the pull pin. This system is lightweight, requires minimal power, and is unlikely to affect the CD much. This results in the system scoring well in mass, power draw, and effects on CD. The system is also mechanically simple compared to the claw and the housing, but does require a motor to release the SP. This led to a 3 in the mechanical complexity category. Finally, this system is expected to have an average cost associated with it.

The final system analyzed was the burn wire. The material needed for burn wires is lightweight and costs little. This results in the highest possible score in mass and cost. This system does not require any moving parts, reducing the complexity of the system. The burn wire requires a large current for a very short period during the SP release, but requires no power before or after. Together these result in an average score in the power draw category. The burn wire scored the worst in the effects on the CD category. This is due to the relatively loose attachment, which could cause the SP to sway and affect the motion of the CD.

5 Selection of Baseline Design

After careful consideration of the trade study results, the INFERNO team selected a baseline design. Perhaps the most important decision made was the choice to use a rotor aircraft for the CD. The rotor vehicle was the highest rated choice in the aircraft type trade study by a reasonable margin. Nine different categories were analyzed, and the rotor aircraft was the highest rated overall by 0.4. A sensitivity analysis was performed by changing the weights of the relative categories, and the rotor aircraft remained the highest rated in the vast majority of cases. This is due to the high number of categories analyzed. Each individual category weighting has a small effect on the overall score. Additionally, because of the heritage of rotor aircraft at CU and in the literature, the team will have ample sources to consult throughout the design process.

The INFERNO team intends to carry both the drop and landing SP deployment types through CDD. This is because both methods scored significantly higher than the competition, but neither distinguished itself from the other. Additionally, these methods are complimentary, with each serving as a possible backup for the other. The team intends to design the SP to survive a drop deployment, but the CD for a landing deployment. This adds redundancy to the system, reducing the chance of mission failure. If the CD is unable to land, the sensor package can be dropped. However, if the sensor package can't survive a particular drop, the child drone can land and lightly drop the SP.

Additionally, the INFERNO team intends to carry three separate SP attachment designs through CDD. The attachment trade study resulted in two tiers of results: the claw and housing mechanisms scored similarly to each other, though lower than all other options, while the torque magnet, pull pin, and burn wire all scored similar higher results. These options are easily and cheaply prototyped, and deserve further investigation before a final choice is made.

The INFERNO project will require many additional trade studies moving forward. The next set of trade studies the team expects include, but are not limited to: the particular vehicle selection, the communications hardware used, the design of the sensor package, the choice of imaging system, as well as the micro-controller platform selection. These trade studies will be critical for the preliminary design, but could not be completed before the selection of a baseline design.

6 References

[1] *Wildfires – Annual 2012*. NOAA National Centers for Environmental Information, Jan. 2013. Web. Accessed 28 Sep. 2015. <https://www.ncdc.noaa.gov/sotc/fire/201213>.

[2] *State Annual and Seasonal Time Series*. NOAA National Centers for Environmental Information, Dec. 2013. Web. Accessed 28 Sep. 2015. <https://www.ncdc.noaa.gov/temp-and-precip/state-temps/>.

[3] *Record Highest Temperatures by State*. NOAA National Centers for Environmental Information, Dec. 2003. Web. Accessed 28 Sep. 2015. <http://www.ncdc.noaa.gov/oa/pub/data/special/maxtemps.pdf>.

[4] *Average Wind Speeds*. Western Regional Climate Center, Dec. 2006. Web. Accessed 28 Sep. 2015. <http://www.wrcc.dri.edu/htmlfiles/westwind.final.html#COLORADO>.

[5] *Average Relative Humidity USA*. Steven L. Horstmeyer, 2008. Web. Accessed 28 Sep. 2015. <http://www.shorstmeyer.com/wxfaqs/humidity/rh.html>.

[6] *Density and Buoyancy*. Georgia State University, unknown date. Web. Accessed 28 Sep. 2015. <http://hyperphysics.phy-astr.gsu.edu/hbase/class/phscilab/dens.html>.

A Lighter-than-Air Vehicle Size Modeling

A.1 Spherical/Weather Balloon-Type

A key analysis done to determine the practicality of a lighter-than-air CD was to determine the size required for a payload of any reasonable size.

For a lighter-than-air vehicle of any type, the buoyant force of the lifting gas, F_{buoy}, must be equal the combined weight of the gas, W_{He}, and weight of the structure and payload, W_{PL}:

$$F_{buoy} = W_{He} + W_{PL}$$

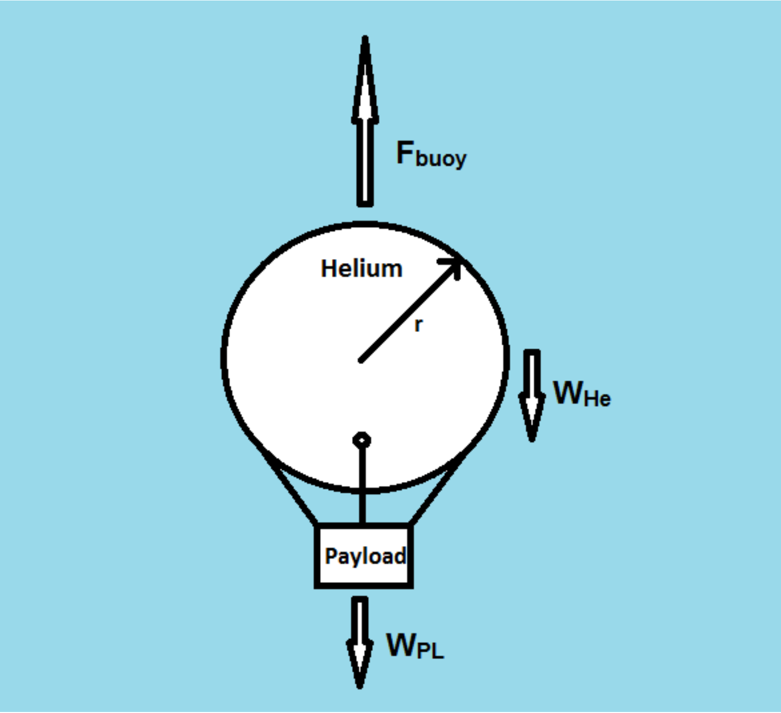


Figure A.1-1 Forces Acting on a Weather Balloon-Type Lighter-than-Air Vehicle

The buoyant force is equal to the weight of the air displaced by the balloon,[6] while the weights of the lifting gas (in this case, helium) and payload are equal to their mass times gravitational acceleration:

$$F_{buoy} = \rho_{air} g V_{ball}$$
$$W_{He} = \rho_{He} g V_{ball}$$
$$W_{PL} = m_{PL} g$$

where ρ_{air} and ρ_{He} are the densities of air and helium, and V_{ball} is the volume of the balloon. Combining these terms together, and assuming a spherical balloon shape with negligible material thickness, the force balance equation simplifies to find the required balloon radius, r, for a given mass and gas densities:

$$\frac{4}{3}\pi r^3 \rho_{air} g = m_{PL} g + \frac{4}{3}\pi r^3 \rho_{He} g$$
$$\frac{4}{3}\pi r^3 (\rho_{air} - \rho_{He}) = m_{PL} g$$

$$r = \left[\frac{3}{4\pi}\left(\frac{m_{PL}}{\rho_{air} - \rho_{He}}\right)\right]^{1/3}$$

Using a standard atmosphere model, the density, pressure (P_{air}), and temperature (T_{air}) of ambient air can be found for a given altitude. In turn, assuming the pressure and temperature of the helium are equal to the ambient air, the helium density can be found through ideal gas relations:

$$\rho_{He} = \frac{P_{air}}{R_{He}T_{air}}$$

where R_{He} is the specific gas constant of helium. Using an altitude of 1600 m for the standard atmosphere model (corresponding roughly to Boulder, Colorado local altitude), yields the following values for air density, pressure, and temperature:

$$\rho_{air} = 1.0746 \text{ kg/m}^3$$

$$P_{air} = 83.524 \text{ kPa}$$

$$T_{air} = 277.75 \text{ K}$$

Plugging these values in yields the following radius, diameter (d), and volume for a spherical balloon with a payload/structure mass of 2 kg:

$$r = 0.8087 \text{ m}$$

$$d = 2r = 1.6174 \text{ m}$$

$$V_{ball} = 2.2153 \text{ m}^3$$

These values likely exclude compatibility with the Mother Rover.

A.2 Blimp-Type

The size of a blimp-type vehicle can also be analyzed, assuming ellipsoidal proportions according to Fig. A.2-1:

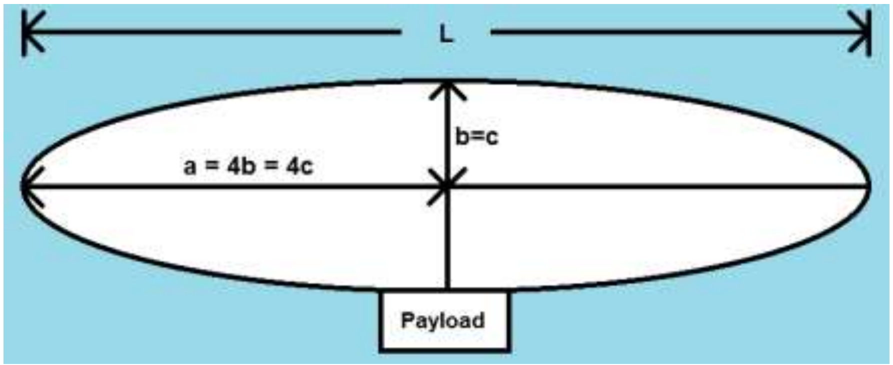


Figure A.2-1 Proportions of Ellipsoidal Blimp-Type Vehicle

The volume of an ellipsoidal vehicle like this can be calculated by:

$$V_{blimp} = \frac{4}{3}\pi abc$$

Since $a = 4b = 4c$, and the length $L = 2a$, the equation simplifies to:

$$V_{blimp} = \frac{\pi L^3}{96}$$

Rearranging this equation allows us to solve for the length, width (w), and height (h) of the blimp as a function of its volume:

$$L = \left[\frac{96}{\pi} V_{blimp}\right]^{1/3}$$

$$w = h = \frac{L}{4}$$

Since the volume required is the same as the balloon-type vehicle in Section A.1, the same volume can be plugged in to find the dimensions required for a blimp-type vehicle to lift a 2 kg payload/structure:

$$L = 4.0755 \text{ m}$$

$$w = h = 1.0189 \text{ m}$$

Though this reduces the height required for the vehicle, it substantially increases the length, and remains impractical for integration with the MR.

B Sensor Package Drop Test Force Modeling

In order to better characterize the feasibility of simply dropping the SP during deployment, the forces acting on the SP during a worst-case impact had to be understood. This analysis began by making a few assumptions about the physical characteristics of the SP. Assuming a metal sphere landing on concrete, a coefficient of drag of 0.5 was assumed along with a coefficient of restitution of 0.8. Using the values along with air density and gravitational acceleration approximating that of Boulder, estimates for the terminal velocity of SP designs with varying radii and masses were computed:

$$V_{terminal} = \sqrt{\frac{2mg}{C_d \rho \pi r^2}}$$

Next, assuming that the center of mass of the SP moves 1 cm during the impact, the following equation for the average force on the SP can be derived from the Work-Energy relation:

$$W_{tot} = KE_1 + KE_2$$

$$W_{tot} = F_{avg}(2\text{d}) = \frac{1}{2} m V_{terminal}^2 + \frac{1}{2} m (eV_{terminal})^2$$

$$F_{avg} = \frac{m}{2d}\left(V_{terminal}^2 + (eV_{terminal})^2\right)$$

Applying this equation to the range of SP designs produces the plot shown in Fig B.1-1 below.

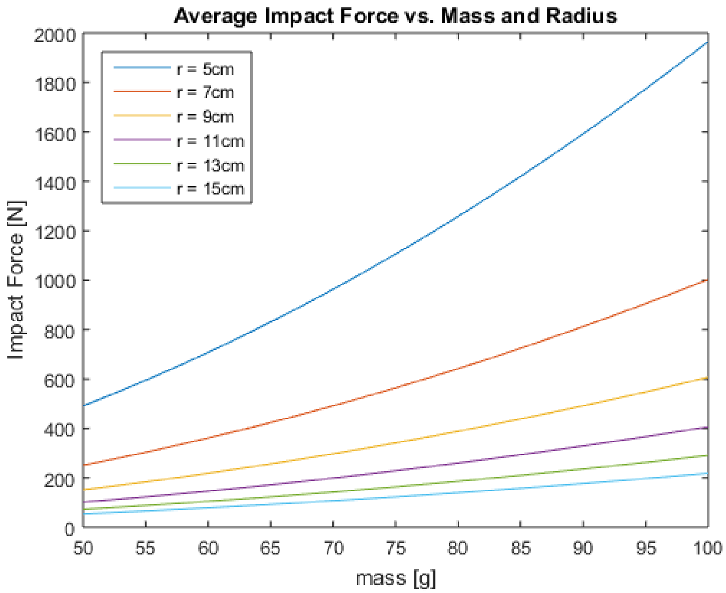


Figure B.1-1 Predicted Average Impact Force for Varied SP Design Values

As seen in Fig B.1-1, depending on the design values, the average impact force varies from a minimum value of 54.6 N to a maximum value of 1966 N. While neither value is negligible in the final SP design, an extremely high impact force would drive much of the work necessary to design the SP for maximum survival chance, while a much lower impact force would allow for more leniencies in the SP design. This result effectively shows that there are SP designs which would experience survivable impact forces if dropped from the CD during deployment, validating the method as feasible.