Preliminary Design Review

CHIMERA

CHIId drone deployment MEchanism and Retrieval Apparatus

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Customer: Barbara Streiffert, Jet Propulsion Laboratory

Advisor: Jelliffe Jackson
Mission Statement

CHIMERA (CHIld drone deployment MEchanism and Retrieval Apparatus) will support the autonomous deployment, landing, and securing of the INFERNO unmanned aerial system and act as a communications relay to assist firefighters in the monitoring and mitigation of wildfires.
Wildfire containment and mitigation efforts are a primary concern for those living in or near wildfire-prone regions of the United States.

Autonomous vehicle systems are an active area of research and development for a wide range of applications.

An **autonomous drone** and **mother rover** surveying system can support long-range missions.

Such systems will be able to **perform reconnaissance** operations and **assist firefighters** that are unable to reach remote locations of interest.
Project Heritage

INFERNO

INtegrated Flight Enabled Rover for Natural disaster Observation

- 2015-2016 JPL sponsored senior design project
- Semi-autonomous drone capable of delivering temperature-sensing package to wildfire area of interest
- CHIMERA will utilize existing INFERNO hardware shown:

INFERNO Capabilities:
- **Mission Duration**: 13.5 minutes
- **Fully Autonomous Takeoff**
- **10 m/s Translational Flight**
- **Video/Imaging**: 720p at 30fps
- **Sensor Package**: >90% transmission of SPS data
Definitions

- **Alight:** To descend from the air and settle
- **Charge:** Transfer of electricity from MRS battery to CDS battery
- **Deploy:** The CDS vertically ascends from DSS
- **Disarm:** CDS is no longer capable of flight
- **Drive:** MRS motors are initiated on axle, propelling MRS in a forward direction
- **Land:** CDS alights with all four feet on DSS
- **Mission:** The CDS is deployed from the DSS, flies to area of interest, drops SPS, returns to MRS, and lands on DSS
- **Secure:** DSS electromagnets are activated, restraining CDS on the DSS
Acronyms

- **CDS**: Child Drone System
- **COM**: Communication System
- **CRG**: Charging System
- **DSS**: Drone Securing System
- **GND**: Ground Station
- **MRS**: Mother Rover System
- **SPS**: Sensor Package System
- **SRS**: Sensor Package Release System
- **WLS**: Wheel Locking System

**FOV**: Landing Camera Diagonal Field of View

- \( P_R \) = Power received
- \( P_T \) = Transmitted Power
- \( G_T \) = Transmit Gain
- \( G_R \) = Received Gain
- \( L_S \) = Space Loss
- \( L_L \) = Line Loss
Concept of Operations

Deployment

Command: MRS to Drive
GND → MRS

Re-Deploy

Release SPS

Command: Deploy
GND → MRS → CDS

Transmit SPS Data
GND ← SPS

Transmit CDS Video
GND ← CDS

End of CONOPS

Landing

Command: Charge
GND → MRS → CRG

Charging

Re-Deploy

Command: Re-Deploy
GND → MRS → CDS
Functional Block Diagram: System Level
## Functional Requirements

<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Description</th>
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<td>The CDS shall autonomously land on DSS.</td>
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<td>The CDS shall autonomously deploy from the DSS.</td>
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<td>The DSS shall secure the CDS using electromagnets.</td>
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### Autonomous Landing

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<td>The CDS shall land within a 1.1 by 1.1 m² area.</td>
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<td>DR 1.2</td>
<td>The CDS shall land within 15 minutes of deployment.</td>
</tr>
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<td>DR 1.3</td>
<td>The CDS shall autonomously land under 3 minutes after landing command is sent.</td>
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<td>The CDS shall deploy to a minimum height of 1 m above the DSS.</td>
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### Securing

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<td>DR 9.1</td>
<td>The CRG shall charge the CDS battery one time by a minimum of 1 Volt.</td>
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<td>DR 9.2</td>
<td>The CRG shall adjust CDS orientation on DSS for maximum landing yaw error of 45°.</td>
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Baseline Design

1. Image Recognition (Autonomous Landing)
2. Securing System
3. Wheel Locking System
4. Wheeled MRS
5. Charging System
6. Communication System

Critical Project Elements
Autonomous Landing
Autonomous Landing

0:40
- CDS uses GPS to get MRS in FOV of camera

1:10
- IRS finds center of DSS platform and sends position command

2:50
- CDS descends at constant rate while maintaining DSS in center of image
- Camera no longer sees full image
  - Last position is commanded
- Landing accuracy relies on accuracy of accelerometer in Pixhawk.
- Landing timeline TBR (flight testing)

Pattern width matches FOV of camera

GPS <= 5 m
Assumptions:

- After platform fills camera FOV, accurate position can no longer be determined
- **Camera height** is z-position of CDS legs
- CDS offset from center and wind effects accounted for with 20% design margin
- Max camera **resolution** error of 1 pixel
- **Constant** descent rate
- Camera mounted on CDS geometric center

**Known Pixhawk Error**

- Gyro error: 0.1 [deg/s]
- Accelerometer error: 1.11 x 10^{-3} g [m/s^2]
Landing Feasibility

- Sensitivity parameters:
  - Camera FOV
  - Descent rate, \( z \)
  - Platform pattern width

- Requirements for feasibility:
  - Land within a radius of 55 cm. (FR 1.0, DR 1.1)
  - Land with yaw error less than 45°. (FR 9.0, DR 9.2)

![Graph showing landing feasibility with different pattern widths and yaw errors.](image)
Landing Feasibility

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  - Descent rate, \( \dot{z} \)
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- FEASIBLE by analysis
Image Recognition Feasibility

- Find center of **four** different **hues** to get center of MRS platform.
  - Color **thresholding**, **shape detection**, and **image masking** can improve performance.

- Convert **pixel offset** of MRS platform from center of image to distance using **known dimensions** of platform.

- Testing method: Flight simulation software, pilot override option

- **FEASIBLE** by demonstration

Angle: $-62$
Dist: 234
Autonomous Landing: Image Recognition Flowchart

**Project Overview**

**Autonomous Landing**

**Securing**

**Charging**

**Communication**

**Conclusion**

**GND**

User Commands
Land

>= 2Hz

Video Camera

Preprocessing:
- Shadow Removal
- Glare Removal
- Masking

Color Thresholding

Shape Detection

Find Centers and Calculate Mask

Calculate Relative Position Vector

Pixhawk

<= 10 Hz

CDS

Image Processing

JPL

CHIMERA
Hardware/Software Components

- Camera module
  - Higher FOV preferred
- Companion computer on INFERNO
- IRS prototyped from Python libraries
- Pixhawk flight controller (already equipped)
  - MAVLink communication protocol
- DSS pattern for recognition

Project Overview

Autonomous Landing

Securing

Charging

Communication

Conclusion
Securing
Securing

- Modifications to CDS:
  - Replace rubber feet with high carbon steel

- Design of DSS:
  - High carbon steel across DSS platform
  - 3 electro-permanent magnets

Steel feet

Magnet placement under DSS Platform
Magnetic Securing Feasibility

- Maximum securing force needed: \( \sim 80 \text{ N} \)
- Maximum magnetic force available: \( 200 \text{ N} \)
- Assumptions:
  - External force: \( 10 \text{ N} \)
  - Coefficient of friction for steel on steel \( (0.5-0.8) \)
- FR 3.0, DR 3.1
- FEASIBLE by analysis
Charging
Charging Mechanism on DSS

- Charge bars positioned on either side of DSS
- Motors will slide charging bars onto CDS
- Once CDS is disarmed charging will initiate

**Future Work:** Ensure quality copper contact, INFERNO stability, safety precautions
Copper plate on two faces of CDS
Bracket and support structure will be attached to CDS legs
Bracket does not interfere with SPS deployment or GoPro FOV
INFERNO baseline mass: **2520 g**
Estimated added mass: **521 g**
Estimated final mass: **3041 g**
Maximum allowable mass for 15 minute flight: **3530 g**
FEASIBLE by analysis
Charging Schematic

- FEASIBLE by analysis
- FR 9.0, DR 9.1

MRS
- MRS Processor
- Current Limit Detector
- MRS Charging Battery 28-33.6V

CDS
- CDS Battery 14-16.8V
- Cell Balancer
Communication
Link Margin Analysis

- Link Margin for INFERNO Child Drone System Video Transmission

- Immersion RC Video Tx/Rx (600 mW)
- 5.8 GHz at Data Rate of 2500 kbps
- Max: 700 meter distance
- FR 5.0, 6.0, 7.0, 8.0

**Feasible** by analysis

<table>
<thead>
<tr>
<th></th>
<th>Immersion RC (5.8 GHz)</th>
<th>Transmitter (INFERNO)</th>
<th>Receiver (GND)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Transmitted ($P_T$)</td>
<td>-2 dBW</td>
<td>-2 dBW</td>
<td></td>
</tr>
<tr>
<td>Gain Transmit ($G_T$)</td>
<td>1 dBi</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Gain Received ($G_R$)</td>
<td>N/A</td>
<td>10 dbi</td>
<td></td>
</tr>
<tr>
<td>Space Loss ($L_S$)</td>
<td>-105 dB</td>
<td>-105 dB</td>
<td></td>
</tr>
<tr>
<td>Additional Error (Line Loss) ($L_L$)</td>
<td>-0.5 dB</td>
<td>-0.5 dB</td>
<td></td>
</tr>
<tr>
<td>Power Received (Actual) ($P_R$)</td>
<td>-109 dB</td>
<td>-99 dB</td>
<td></td>
</tr>
<tr>
<td>Power Received (Minimum) ($P_{R, min}$)</td>
<td>-118 dB</td>
<td>-117 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Link Margin</strong></td>
<td><strong>9 dB</strong></td>
<td><strong>18 dB</strong></td>
<td></td>
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</tbody>
</table>
Conclusion
## Verification and Validation

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<tr>
<th>Functional Requirement</th>
<th>Testing</th>
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<tr>
<td>FR 1.0</td>
<td><strong>Demonstration and Visual Inspection</strong> – CDS landing will be demonstrated and visually inspected</td>
</tr>
<tr>
<td>FR 2.0</td>
<td><strong>Test and Demonstration</strong> – CDS deployment will be demonstrated and height will be measured.</td>
</tr>
<tr>
<td>FR 3.0</td>
<td><strong>Test and Demonstration</strong> – CDS will be secured to the MRS using electromagnets.</td>
</tr>
<tr>
<td>FR 4.0</td>
<td><strong>Test and Demonstration</strong> – The ability for MRS to drive forward will be demonstrated and the distance will be measured.</td>
</tr>
<tr>
<td>FR 5.0</td>
<td><strong>Test and Demonstration</strong> – Data will be transmitted at a horizontal range of 200 m.</td>
</tr>
<tr>
<td>FR 6.0</td>
<td><strong>Test and Demonstration</strong> – Data will be received at a horizontal range of 500 m.</td>
</tr>
<tr>
<td>FR 7.0</td>
<td><strong>Test and Demonstration</strong> – SPS data will be received from a horizontal distance of 700 m.</td>
</tr>
<tr>
<td>FR 8.0</td>
<td><strong>Test and Demonstration</strong> – Video will be received over a maximum range of 700 m.</td>
</tr>
<tr>
<td>FR 9.0</td>
<td><strong>Test</strong> – Battery voltage will be measured.</td>
</tr>
</tbody>
</table>
Charging - Safety

- **Safety Procedure for Operating High voltage**
  - De-energize equipment before working
  - Touch circuit with back of your hand first
  - Keep one hand in your pocket
  - Wear rubber shoes

- **Charging Tests**
  - Unit testing will occur throughout design and manufacturing process
  - Controlled, away from equipment
  - Fire precautions (CO₂ fire extinguisher, BBQ grill, etc.)
Facilities and Resources

- **Required Facilities**
  - RIFLE: RECUV Indoor Flight Environment
  - Boulder South Campus (flight testing)
  - Flat, open area
    - 10 m radius for MRS
    - 700 m open area for COM testing

- **Required Resources**
  - Pilot
  - Spectrum analyzer (COM testing)
  - Multimeter
Wheel Locking Mechanism

- **Problem:** If the CDS lands on (or deploys from) the MRS with a horizontal velocity component, the MRS could move.

- **Solution:** Prevent the wheels from moving by applying a horizontal force to each wheel.

- **Determining if necessary through analysis and test.**
### Budget

#### Project Overview

**Design Margin: 1.2**

#### Summary

<table>
<thead>
<tr>
<th>System</th>
<th>System Cost</th>
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<tbody>
<tr>
<td>Administrative</td>
<td>$192.00</td>
</tr>
<tr>
<td>MRS Manufacturing</td>
<td>$1,310.40</td>
</tr>
<tr>
<td>WLS Manufacturing</td>
<td>$254.40</td>
</tr>
<tr>
<td>GND Manufacturing</td>
<td>$207.60</td>
</tr>
<tr>
<td>DSS Manufacturing</td>
<td>$1,298.40</td>
</tr>
<tr>
<td>CDS Upgrades</td>
<td>$543.60</td>
</tr>
<tr>
<td>CDS Replacement Parts</td>
<td>$127.20</td>
</tr>
<tr>
<td>Testing and Safety</td>
<td>$288.00</td>
</tr>
<tr>
<td>Remaining Funds</td>
<td>$778.40</td>
</tr>
<tr>
<td><strong>Budget</strong></td>
<td><strong>$5,000.00</strong></td>
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#### CHIMERA Budget Breakdown

- **Remaining Funds**: 16%
- **Administrative**: 4%
- **Testing and Safety**: 6%
- **MRS Manufacturing**: 25%
- **WLS Manufacturing**: 5%
- **GND Manufacturing**: 4%
- **CDS Replacement Parts**: 2%
- **CDS Upgrades**: 11%
- **DSS Manufacturing**: 26%
## Conclusion

### Preliminary Design Summary

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<tr>
<th>Critical Project Element</th>
<th>Design Solution</th>
<th>Feasible?</th>
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<tr>
<td>Autonomous Landing</td>
<td>Image Recognition</td>
<td>Yes</td>
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<tr>
<td>Securing</td>
<td>Electromagnets</td>
<td>Yes</td>
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<tr>
<td>Charging</td>
<td>Conduction Brackets</td>
<td>Yes</td>
</tr>
<tr>
<td>Communications</td>
<td>Rx/Tx Connection</td>
<td>Yes</td>
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QUESTIONS?
References

References (Software)

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- Design Requirements (CRG)
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- AI&T Charts
- Budget
Concept of Operations

Mission

1. MRS Travel
2. Deploy CDS
3. CDS Mission (drop SPS)
4. CDS Return
5. CDS Redocking
6. MRS travel, CDS recharge
7. CDS Redeploy

- MRS Travel:
- Deploy CDS:
- CDS Mission (drop SPS):
- CDS Return:
- CDS Redocking:
- MRS travel, CDS recharge:
- CDS Redeploy:

functionality inherited from INFERNO

video, telemetry, control
wireless communications
up to 500m up to 200m

Project Overview Autonomous Landing Securing Charging Communication Conclusion
# Design Requirements

## Securing

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<td>DR 4.1</td>
<td>The MRS shall remain stationary during the entire CDS mission.</td>
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Design Requirements

**Communication**

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<td>The DSS COM shall wirelessly transmit video at 720p at 30 fps.</td>
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<td>DR 7.2</td>
<td>The DSS COM shall wirelessly transmit 5 minutes of video</td>
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<tr>
<td>DR 7.3</td>
<td>The DSS COM shall wirelessly transmit CDS telemetry.</td>
</tr>
<tr>
<td>DR 8.1</td>
<td>The GND COM shall wirelessly receive video at 720p at 30 fps.</td>
</tr>
<tr>
<td>DR 8.2</td>
<td>The GND COM shall wirelessly receive 5 minutes of video</td>
</tr>
<tr>
<td>DR 8.3</td>
<td>The GND COM shall wirelessly receive data from the SPS.</td>
</tr>
</tbody>
</table>
## Design Requirements

### Charging

<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 9.0</td>
<td>The CRG shall autonomously increase the CDS battery voltage.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 9.1</td>
<td>The CRG shall charge the CDS battery one time by a minimum of 1 Volt.</td>
</tr>
<tr>
<td>DR 9.2</td>
<td>The CRG shall adjust CDS orientation on DSS for maximum landing yaw error of 45°.</td>
</tr>
</tbody>
</table>
Functional Block Diagram: Mother Rover System
Functional Block Diagram: Ground Station

FROM MRS: GPS data from CDS, video feed from CDS, GPS data of MRS

FROM SPS: Temperature data

TO MRS: Command CDS video on/off, command CDS autonomous land, command autonomous charge, command CDS to GPS waypoint

LEGEND
- - - - Wired Command
— — Wireless Command
— — — Wireless Data Transmission
— — — — Physical Interface
Functional Block Diagram: Child Drone System
Functional Block Diagram: Sensor Package System

Sensor Package System

CDH
Data Handling

Science
Temperature Sensor

COM

EPS

SRS

TO GND: Temperature data

Securement and release from CDS

LEGEND

Wired Data Transmission

Wireless Data Transmission

Physical Interface

Powered by EPS
Landing Feasibility

- Assumptions:
  - After **platform fills camera FOV**, accurate position can no longer be determined
  - **Camera height** is z-position of CDS legs
  - **CDS offset from center** and **wind effects** accounted for with **10% design margin**
  - Error due to camera **resolution** is a max of 1 pixel
  - **Constant** descent rate
  - Camera mounted on **geometric center** of CDS

- Knowns (from Pixhawk spec sheet):
  - Pixhawk gyro error: **0.1 [deg/s]**
  - Pixhawk accelerometer error: **$1.11 \times 10^{-3} \text{ g} [\text{m/s}^2]$**
Software Architecture

- **ROS** – Robot Operating System
- **Libraries and packages**
- Easy *communication* and *message-passing* between processes
- **Nodes** are medium through which information is *streamed* and are written in **C++ or Python**:
  - **Topic** - Named buses over which nodes exchange messages
  - **Publisher** - Sends messages *to* specified topic
  - **Subscriber** - Receives messages *from* specified topic.
  - **Master** - Acts as *communications hub* to route information between nodes.
- Allows easy message customization to send:
  - **Sensor** data
  - **Control** or **actuator** commands
  - **State** and **planning** information
Software Architecture

ROS Packages Available

- **Mavros**
  - **MAVLink** extendable communication node
  - **Driver** for various autopilots with MAVLink protocol
    - Set **Mode**
    - Arm **drone**
    - Command local **position**

- **Camera Packages**
  - Standard USB cameras
  - OpenCV with cameras
  - Raspberry Pi camera module

- **Motor Drivers**
  - Serial Roboteq motor controllers
  - Various brushed DC motor devices

**Diagram Description**

- **IRS Sends Position Vector to Mavros node**
- **Mavros Node**: Publishes position message to topic defined by mavros package
- **mavros/setpoint_position/local**: Mavros uses MAVLink protocol to send message to flight control
- **PX4 Flight Stack Flight Control Software**
# Autonomous Landing

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight</th>
<th>Image Recognition</th>
<th>Differential GPS</th>
<th>Sonar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Required</td>
<td>35%</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Performance/Effectiveness</td>
<td>35%</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Complexity</td>
<td>15%</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>15%</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td><strong>4.35</strong></td>
<td><strong>4.15</strong></td>
<td><strong>3.30</strong></td>
</tr>
</tbody>
</table>
### Autonomous Landing Metric Levels

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Required</td>
<td>&gt; 100 hrs</td>
<td>50 -100 hrs</td>
<td>25 – 50 hrs</td>
<td>10 – 25 hrs</td>
<td>&lt; 10 hrs</td>
</tr>
<tr>
<td>Performance/ Effectiveness</td>
<td>Performance does not meet requirements; accuracy is unacceptable</td>
<td>Performance is relatively poor; accuracy is below expectations</td>
<td>Performs with a moderate level of accuracy; Autonomous landing meets expectations</td>
<td>Performs to a relatively high degree of accuracy; Autonomous landing goes beyond what is required</td>
<td>Autonomous landing system performs to the highest level of accuracy</td>
</tr>
<tr>
<td>Complexity</td>
<td>Requires in-house manufacturing and assembly with custom design; rewriting all of open source code to meet expectations</td>
<td>Requires in-house manufacturing and assembly with custom design; most source code needs to be modified</td>
<td>System is a mix of manufactured and purchased components; some source code needs to be modified</td>
<td>System uses off the shelf components with assembly required; little source code needs to be modified</td>
<td>System is “plug and play” with all off the shelf components; source code needs no modifications</td>
</tr>
<tr>
<td>Cost</td>
<td>&gt; $1000</td>
<td>$500 - $1000</td>
<td>$250 - $500</td>
<td>$100 - $250</td>
<td>&lt; $100</td>
</tr>
</tbody>
</table>
Autonomous Landing Software Flow

Ground Station
- User Commands Land
- Publisher Node (Bool)

Subscriber Node (Bool)
- If True:
  - Video Camera
  - Color Thresholding
  - Preprocessing: Shadow Removal, Glare Removal, Masking
  - Find Centers and Calculate Mask
  - Calculate Relative Position Vector
  - Publisher Node (Pose)
- If False:
  - Do Nothing

Pixhawk Setup
- Subscriber Node (Bool)
- Node = OFFBOARD
  - If True:
  - Service Client: Set Mode Client
  - Service Server: mavros/set_mode
- Node = POSCTRL
  - If True:
  - Service Client: Arming Client
  - Service Server: mavros/cmd/arming

PX4 Flight Stack
- OFFBOARD Position Control
- Arm Control
- Mode Control

Topic: /mavros/setpoint_position/local
MAVLink

Image Processing Loop
- Video Camera
Autonomous Landing Backup: Approach View

- \( z = \frac{y}{2 \tan\left(\frac{\text{FOV}_y}{2}\right)} \); \( y = 10 \) (GPS accuracy of \( \pm 5m \))

- Height required to see image on approach to MRS

- \( \% = \frac{y_p^2}{x \times y} \times 100 \); \( x = 2 \times z \times \tan\left(\frac{\text{FOV}_H}{2}\right) \)

- Percent of picture filled by image on MRS
  - Must be >0.25% (TBR – testing) for recognition

- Using Rpi Camera: Platform image fills 0.27% of picture
  - **FEASIBLE**
Autonomous Landing Backup: Landing Model Derivation (Position)

- Equations:
  - \[ \text{equation} \]

- Assumptions:
  - After \text{platform fills camera FOV}, accurate position can no longer be determined
  - \text{Camera height} is z-position of CDS legs
  - \text{CDS offset from center} and \text{wind effects} accounted for with \text{10\% design margin}
  - Error due to camera \text{resolution} is a max of \text{1 pixel}
  - \text{Constant} descent rate
  - Camera mounted on \text{geometric center} of CDS

- Known Parameters:
Autonomous Landing Backup: Landing Model Derivation (Position)

- \( x_{\text{error,accelerometer}} = \int_0^{t_{\text{land}}} a_{\text{error}} \, dt^2; \ t_{\text{land}} = \frac{z}{\dot{z}} \)

- \( z = \frac{1.1 \cdot y_p}{2 \cdot \tan(\theta)} \); \( \theta = \frac{\text{FOV}}{2} \), 1.1 \( y_p \) = platform image width with 10\% margin

- \( x_{\text{error,pixel}} = 2 \cdot z \cdot \frac{\tan(\theta)}{n} \); \( n = \# \text{of pixels} \)

- \( x_{\text{error,quad geometry}} = d; \ d = \text{distance from geometric center to leg of INFERNO} \)

- \( x_{\text{error}} = d + \frac{1.1 \cdot y_p}{n} + 0.0013611 \cdot \left( \frac{1.1 \cdot y_p}{\dot{z} \cdot \tan(\theta)} \right)^2 \)
Autonomous Landing Backup: Landing Model Derivation (Yaw)

- Equations:
  - \( \theta = \int \omega dt \)
  - \( d = r \times t \) \((distance = rate \times time)\)

- Assumptions are the same as Position Derivation

- Known Parameters:
  - \( \textit{gyro error}: 0.1 \frac{deg}{s} \)
  - \( \psi_{error} = \int_{0}^{t_{\text{land}}} 0.1 \times dt \); \( t_{\text{land}} = \frac{z}{\dot{z}}, z = \frac{1.1 \times y_p}{2 \times \tan(\theta)} \)
  - \( \psi_{error} = 0.05 \times \frac{1.1 \times y_p}{\dot{z} \times \tan(\theta)} \) \((degrees)\)
Estimated Flight Time from CDS Modifications

- INFERNO Nominal Mass: 2520 g
- Estimated Mass Addition: 521 g
  - Steel feet (x4): 18.6 g (74.4 g)
  - IRS: 75 g
  - Charging (x2): 186 g (372 g)
- Estimated Final Mass: 3041 g
- Estimated Endurance: 18.2 min

*All values TBR (component selection)
Charging Modifications to CDS

- Blinky Battery Balancer
  - Low Cost: ~$35
  - Low mass: 0.014 kg
  - Balances 4s LiPo Batteries while they charge

- Recharge circuit:
Required Docking Force Model

- **Assumptions:**
  - CDS can be modeled as a point mass
  - Air resistance/drag is negligible
  - All forces are acting on the CDS' center of mass
  - All forces are instantaneous
  - Gravity is constant
  - Applied force acts vertically
  - Docking force acts perpendicular to platform

\[
\begin{align*}
\Sigma F_x &= f \cos(\alpha) + D \sin(\alpha) - N \sin(\alpha) = 0 \\
f &= f_{max} = \mu N \\
D \sin(\alpha) &= N \left( \sin(\alpha) - \mu \cos(\alpha) \right) \\
D &= N \left( 1 - \mu \cot(\alpha) \right) \\
\Sigma F_y &= A - mg - D \cos(\alpha) + f \sin(\alpha) + N \cos(\alpha) = 0 \\
D \cos(\alpha) &= A - mg + N \left( \mu \sin(\alpha) + \cos(\alpha) \right) \\
N &= -\frac{\sin(\alpha)}{\mu} \left( A - mg \right) \\
D &= \frac{\sin(\alpha)}{\mu} \left( mg - A \right) \left( 1 - \mu \cot(\alpha) \right)
\end{align*}
\]
Securing

Magnetic Securement Component Feasibility

• Electro-permanent magnet
• Low power draw: ~50 mW nominal
• Compact form factor
• Low cost: ~$54

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_max</td>
<td>200 [N]</td>
</tr>
<tr>
<td>V_supply</td>
<td>5.0 [V]</td>
</tr>
<tr>
<td>I_steady</td>
<td>10 [mA]</td>
</tr>
<tr>
<td>I_peak</td>
<td>1000 [mA]</td>
</tr>
<tr>
<td>mass</td>
<td>65 [g]</td>
</tr>
</tbody>
</table>

Power Budget: MRS Power Supply

- **Power Supply**
  - Chemistry: Lithium Polymer
  - Nominal Voltage: 14.8V
  - Minimum Voltage: 14V
  - Capacity: 10Ah
  - Maximum Constant Discharge Current: 100A
  - Maximum Peak Discharge Current: 200A
  - Maximum Discharge: 70%

- **Power Regulation**
  - 5V Linear Regulator
    - Minimum Voltage: 7V
  - 3.3V Linear Regulator
    - Minimum Voltage: 5V
  - 12V Linear Regulator
    - Minimum Voltage: 14V
## Power Budget: MRS Power Consumption

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Motor</td>
<td>12</td>
<td>30</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Actuator</td>
<td>0.4</td>
<td>1</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Antenna</td>
<td>0.4</td>
<td>1</td>
<td>4</td>
<td>3.3</td>
</tr>
<tr>
<td>Processor</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>13.3</strong></td>
<td><strong>33</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Power Budget: MRS Battery Lifetime

\[ T_{\text{avg}} = \left( \frac{C}{I_{\text{Lavg}}} \right) D_{\text{max}} = \left( \frac{10Ah}{13.3A} \right) 0.7 = 0.7h = 30\text{min} \]

\[ I_{\text{Lmax}} \leq I_{\text{Omax}} = 33A \leq 100A \]

\[ T_{\text{min}} = \left( \frac{C}{I_{\text{Lmax}}} \right) D_{\text{max}} = \left( \frac{10Ah}{33A} \right) 0.7 = 0.7h = 20\text{min} \]

\[ V_{\text{reg min}} \leq V_{\text{batt min}} = 14V \leq 14V \]

- \( D_{\text{max}} = \text{Max Discharge} \)
- \( I_{\text{Lavg}} = \text{Average Load Current} \)
- \( I_{\text{Lmax}} = \text{Max Load Current} \)
- \( C = \text{Capacity} \)
- \( T_{\text{avg}} = \text{Average Time} \)
- \( T_{\text{min}} = \text{Minimum Time} \)
- \( I_{\text{Omax}} = \text{Max Constant Output Current} \)
- \( V_{\text{reg min}} = \text{Minimum Input Voltage} \)
- \( V_{\text{batt min}} = \text{Minimum Output Voltage} \)
Power Budget: MRS Power Supply

- **Power Supply**
  - Chemistry: Lithium Polymer
  - Nominal Voltage: 14.8V
  - Minimum Voltage: 14V
  - Capacity: 10Ah
  - Maximum Constant Discharge Current: 100A
  - Maximum Peak Discharge Current: 200A
  - Maximum Discharge: 70%

- **Power Regulation**
  - 5V Linear Regulator
    - Minimum Voltage: 7V
  - 3.3V Linear Regulator
    - Minimum Voltage: 5V
  - 12V Linear Regulator
    - Minimum Voltage: 14V
Motor Torque Model

Assumptions:
- Rubber-concrete contact between the wheel and road.
- The inclination of the surface is zero degrees.
- Air resistance is negligible.
- Motor efficiency is 65%
Motor Torque Model

\[ f = F_{\text{req}} = F_a + F_r \]
\[ F_a = ma \]
\[ F_r = \left( \frac{W}{4} \right) C_{rr} \quad (C_{rr} \text{ is the coefficient of rolling resistance}) \]
\[ F_a = m \left( \frac{v}{t} \right) \]
\[ F_{\text{req}} = m \left( \frac{v}{t} \right) + \left( \frac{mg}{4} \right) C_r \]
\[ T_{\text{req}} = \left( \frac{100}{e} \right) F_{\text{req}} R \quad (T_{\text{req}} = \text{required torque, } e = \text{efficiency}) \]

\[ T_{\text{req}} = \left\{ m \left( \frac{v}{t} \right) + \left( \frac{mg}{4} \right) C_r \right\} \left( \frac{100}{e} \right) R \]

- \( F_r = \) rolling resistance
- \( R = \) radius
- \( N = \) normal force
- \( F_a = \) acceleration force
- \( W = \) weight
- \( f = \) frictional force
Motor Torque Model Results

Required torque for each wheel motor for various radii versus the total mass of the CHIMERA system.
Motor Torque Feasibility

Current System Parameters
- Mass = 100 kg (based on SolidWorks model)
- Wheel Diameter = 10 inches (0.127 m).
- Assume motor efficiency = 65%.
- Maximum velocity of MRS = 0.5 m/s
- Time to accelerate to maximum speed = 1 s
- Result: Motor torque must be greater than or equal to 3.16 Nm and the motor must rotate at least 37.5 RPMs.

- The motor shown in the figure on the right provides 3.73 Nm of torque at 60 RPMs
- Feasible
Wheel RPM Model
Wheel Locking Force Model

**Assumptions:**

- The mass of the MRS is evenly distributed amongst the four wheels.
- The impact force of the CDS landing on the platform acts on all four wheels equally.
- Rubber-concrete contact between wheel and ground.
- Rubber-rubber contact between wheel and brake.
Wheel Locking Force Model

\[
\sum F_x = 0 = A - \frac{F}{4} + f_1 \\
\sum F_y = 0 = N - \frac{W}{4} - f_2 \\
\sum M_0 = 0 = f_1 R - f_2 R \\
\]

\[
\begin{align*}
A &= \frac{F}{4} - f_1 \\
f_2,\text{max} &= \mu_{s,2}A \\
f_1,\text{max} &= \mu_{s,2}N \\
\end{align*}
\]

\[
\begin{align*}
\mu_{s,2}A &= \mu_{s,1}N \rightarrow N = \frac{\mu_{s,2}A}{\mu_{s,1}} \\
\frac{\mu_{s,2}A}{\mu_{s,1}} &= \frac{W}{4} + \frac{F}{4} - A \rightarrow A \left(\frac{\mu_{s,2}}{\mu_{s,1}} + 1\right) = W + \frac{F}{4}, \\
\end{align*}
\]

\[
A = \frac{W + F}{\frac{\mu_{s,2}}{\mu_{s,1}} + 1}
\]
Wheel Locking Force Model

The force needed to be applied to keep the system static versus the horizontal impact force of the CDS.
Wheel Locking Feasibility

Worst case scenario:
- The mass of the MRS system is 100 kg (SolidWorks).
- Impact force:
  - CDS mass: 3.04 kg
  - Maximum speed: 13.8 m/s
  - Impact time = 0.05 s
  - CDS hits the MRS horizontally.
  - Impact force = m(v/t) = 839 N
- The required force from the actuators is 185 N.
- This $30 linear actuator can provide 100 N to 2500 N of force.
- Feasible.
Drive and WLS
## Communication Overview

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FR 5.0</strong></td>
<td>The COM shall wirelessly transmit data at a minimum horizontal range of 200 meters at 915 MHz.</td>
</tr>
<tr>
<td><strong>FR 6.0</strong></td>
<td>The COM shall wirelessly receive data at a minimum horizontal range of 500 meters 915 MHz.</td>
</tr>
<tr>
<td><strong>FR 7.0</strong></td>
<td>The COM shall wirelessly receive SPS data at a minimum horizontal distance of 700 meters at 900 MHz.</td>
</tr>
<tr>
<td><strong>FR 8.0</strong></td>
<td>The COM shall wirelessly receive video at a maximum horizontal range of 700 meters at 5.8 GHz.</td>
</tr>
</tbody>
</table>
Communication Assumptions

Assumptions

Primary Loss: Free Space Path Loss with no environmental interference (Rain/Snow)

All distances are open space with elevated ground station to avoid Fresnel affect

Min. Design Margin = 6 dB

Average temperature for July in Colorado is reference temperature (303 K)

Possible max distance analyzed for feasibility
Communication Methodology
Backup Slide

**Nomenclature**

- $P_t$: Power Transmitted
- $G_t$: Receiving Antenna Gain
- $G_r$: Transmitting Antenna Gain
- $L_s$: Free Space Loss
- $P_r$: Power Received
- $k$: Boltzmann’s Constant
- $L_r$: Line Loss
- $d_r$: Receive Antenna Diameter
- $NF$: Noise Figure
- $T_0$: Reference Temperature
- $N_0$: Noise Power
- $T_s$: System Noise Temperature
- $E_b/N_0$: Bit Energy to Noise Ratio

**System Noise Temp. [k]**: $T_s = \frac{T_a}{L_r} + T_0 \left(1 - \frac{1}{L_r}\right) + T_0(NF - 1)$

**Receive Antenna Gain [dB]**: $10\log\left(\frac{d_r^2g^2\eta}{\lambda^2}\right)$

**Signal to Noise Ratio [dB-Hz]**: \( \frac{(P_r)}{(N_0)} \)

**System Noise Power [dB]**: $N_0 = 10\log(k \ast T_s)$

**Power Received [dB]**: $P_r = P_t + G_t + G_r - L_s - Fade Margin$

**Minimum Signal to Noise Ratio [dB-Hz]**:

\[
\left(\frac{P_r}{N_0}\right)_{\text{min}} = \text{Bit Rate} + \text{Design Margin} + \frac{E_b}{N_0}
\]

**Link Margin [dB]**: \( \left(\frac{P_r}{N_0}\right) - \left(\frac{P_r}{N_0}\right)_{\text{min}} \)

- Values for above calculations obtained from data sheets and literature

Reference: The spreadsheet and math was updated from INFERNO JPL Senior Project
Link Margin Analysis

- Xbee transmitter and receiver
- 915 MHz at Data Rate of 9600 bps
- Max: 700 meter distance

**Xbee-Pro 900 HP (900 MHz)**

<table>
<thead>
<tr>
<th></th>
<th>Transmitter (SPS)</th>
<th>Receiver (GND)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Transmitted</td>
<td>-6 dBW</td>
<td>-6 dBW</td>
</tr>
<tr>
<td>Gain Transmit</td>
<td>1 dBi</td>
<td>N/A</td>
</tr>
<tr>
<td>Gain Received</td>
<td>N/A</td>
<td>.1225 dBi</td>
</tr>
<tr>
<td>Space Loss</td>
<td>-88 dB</td>
<td>-88 dB</td>
</tr>
<tr>
<td>Additional Error</td>
<td>-.5 dB</td>
<td>-.5 dB</td>
</tr>
<tr>
<td>(Line Loss)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Received (Actual)</td>
<td>-105 dB</td>
<td>-105 dB</td>
</tr>
<tr>
<td>Power Received (Minimum)</td>
<td>-142 dB</td>
<td>-142 dB</td>
</tr>
<tr>
<td><strong>Link Margin</strong></td>
<td><strong>37 dB</strong></td>
<td><strong>37 dB</strong></td>
</tr>
</tbody>
</table>
Link Margin Analysis

- Link Margin for INFERNO Child Drone System Data Transmission

- 3DR Transmitter and Receiver
- 915 MHz at Data Rate of 250 kbps
- Max: 700 meter distance
- NOTE: Same system will be used for GND to MRS across distance of 500 meters.

<table>
<thead>
<tr>
<th></th>
<th>3DR (915 MHz)</th>
<th>Transmitter (GND &amp; CDS)</th>
<th>Receiver (GND &amp; CDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Transmitted</td>
<td>-10 dBW</td>
<td>-10 dBW</td>
<td></td>
</tr>
<tr>
<td>Gain Transmit</td>
<td>1 dBi</td>
<td>1 dBi</td>
<td></td>
</tr>
<tr>
<td>Gain Received</td>
<td>.125 dBi</td>
<td>.125 dBi</td>
<td></td>
</tr>
<tr>
<td>Space Loss</td>
<td>-89 dB</td>
<td>-89 dB</td>
<td></td>
</tr>
<tr>
<td>Additional Error</td>
<td>-.5 dB</td>
<td>-.5 dB</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Received</td>
<td>-109</td>
<td>-109</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Received</td>
<td>-128 dB</td>
<td>-128 dB</td>
<td></td>
</tr>
<tr>
<td>(Minimum)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Link Margin</strong></td>
<td><strong>19 dB</strong></td>
<td><strong>19 dB</strong></td>
<td></td>
</tr>
</tbody>
</table>
AI&T Diagrams
MRS AI&T Diagram
DSS AI&T Diagram
CDS AI&T Diagram
GND AI&T Diagram
## Budget: MRS Manufacturing

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Description</th>
<th>Unit Cost</th>
<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4ft x 8ft .031 thick 3003 Aluminum sheet</td>
<td>MRS Bed Material</td>
<td>$74.00</td>
<td>2</td>
<td>0%</td>
<td>$74.00</td>
</tr>
<tr>
<td>Cold Finish Aluminum BAR Rectangle 2024 T351 2 feet</td>
<td>MRS Bed Struts</td>
<td>$11.00</td>
<td>2</td>
<td>0%</td>
<td>$11.00</td>
</tr>
<tr>
<td>ATR Wheel and Shaft Set Pair 8mm bore - 10 inch Traction Lug</td>
<td>Pairs of Wheels</td>
<td>$95.00</td>
<td>2</td>
<td>0%</td>
<td>$190.00</td>
</tr>
<tr>
<td>Multistar High Capacity 46 10000mAh Multi-Rotor Lipo Pack</td>
<td>Battery</td>
<td>$59.00</td>
<td>3</td>
<td>0%</td>
<td>$177.00</td>
</tr>
<tr>
<td>High Torque DC Servo Motor 60RPM With UART/LCR/PPM Drive</td>
<td>Motor</td>
<td>$29.00</td>
<td>2</td>
<td>0%</td>
<td>$118.00</td>
</tr>
<tr>
<td>Stepper Mounting Bracket</td>
<td>Motor Mounting Bracket</td>
<td>$6.00</td>
<td>4</td>
<td>0%</td>
<td>$14.00</td>
</tr>
<tr>
<td>DX2E 2Ch DSMR Surface Radio w/SR310</td>
<td>Remote Control Transmitter</td>
<td>$60.00</td>
<td>1</td>
<td>0%</td>
<td>$60.00</td>
</tr>
<tr>
<td>SR310 DSMR 3-Channel Sport Receiver</td>
<td>Remote Control Receiver</td>
<td>$45.00</td>
<td>1</td>
<td>0%</td>
<td>$45.00</td>
</tr>
<tr>
<td>Raspberry Pi Model 2</td>
<td>Data Handling Computer</td>
<td>$46.00</td>
<td>1</td>
<td>0%</td>
<td>$46.00</td>
</tr>
<tr>
<td>Xbee PRO-900HP, Part Number: 602-1301-ND</td>
<td>Communication to GND</td>
<td>$39.00</td>
<td>1</td>
<td>0%</td>
<td>$39.00</td>
</tr>
<tr>
<td>3DR Radio Set: 900KHz Duct Antenna RP-SMA</td>
<td>Communication to GND</td>
<td>$100.00</td>
<td>1</td>
<td>0%</td>
<td>$100.00</td>
</tr>
<tr>
<td></td>
<td>Miscellaneous Communication Hardware</td>
<td>$100.00</td>
<td>1</td>
<td>0%</td>
<td>$100.00</td>
</tr>
<tr>
<td></td>
<td>Miscellaneous Hardware and electronics</td>
<td>$100.00</td>
<td>1</td>
<td>0%</td>
<td>$100.00</td>
</tr>
</tbody>
</table>

**Mother Rover System Total** | **$1,092.00**
### Budget: CDS Upgrades

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Description</th>
<th>Unit Cost</th>
<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1215 Carbon Steel, Rod, 1&quot; Diameter, 1' Length</td>
<td>Magnetic inserts for CDS Securement</td>
<td>$10.00</td>
<td>1</td>
<td>0%</td>
<td>$10.00</td>
</tr>
<tr>
<td>E-CAM50IMX6 - 5MP MIPI iMX6 Camera Board</td>
<td>Autonomous Landing Imaging System</td>
<td>$69.00</td>
<td>1</td>
<td>0%</td>
<td>$69.00</td>
</tr>
<tr>
<td>Hummingboard- Gate</td>
<td>Autonomous Landing Onboard Computer</td>
<td>$83.00</td>
<td>1</td>
<td>0%</td>
<td>$83.00</td>
</tr>
<tr>
<td>Xbee PRO-900HP, Part Number: 602-1301-ND</td>
<td>CDS to GND Antenna</td>
<td>$39.00</td>
<td>1</td>
<td>0%</td>
<td>$39.00</td>
</tr>
<tr>
<td>Super-Conductive 101 Copper, Rectangular Bar, 1/16&quot; x 1&quot;, 4' Length</td>
<td>Conductive Panels for Autonomous Charge</td>
<td>$28.00</td>
<td>2</td>
<td>0%</td>
<td>$56.00</td>
</tr>
<tr>
<td>White Delrin ² Acetal Resin Rectangular Bar, 3/4&quot; Thick x 1-1/2&quot; Width</td>
<td>Mounting for Conductive Panels</td>
<td>$13.00</td>
<td>2</td>
<td>0%</td>
<td>$26.00</td>
</tr>
<tr>
<td>Type 316 Stainless Steel Socket Head Cap Screw, 4-40 Thread, 7/8&quot; Length, packs of 25</td>
<td>Securement of Conductive Panels</td>
<td>$12.00</td>
<td>2</td>
<td>0%</td>
<td>$24.00</td>
</tr>
<tr>
<td>Raspberry Pi Model 2</td>
<td>Data Handling Computer for Image Recognition System</td>
<td>$46.00</td>
<td>1</td>
<td>0%</td>
<td>$46.00</td>
</tr>
<tr>
<td>–</td>
<td>Miscellaneous Hardware and Electrical Components</td>
<td>$100.00</td>
<td>1</td>
<td>0%</td>
<td>$100.00</td>
</tr>
</tbody>
</table>

**Child Drone System Upgrades Total: $453.00**
### Budget: DSS Manufacturing

#### Manufacturing - Docking and Securement System

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Description</th>
<th>Unit Cost</th>
<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multipurpose 5061 Aluminum, 1/4&quot; Thick, 12&quot; x 48&quot;</td>
<td>Bed Fabrication Material</td>
<td>$83.00</td>
<td>2</td>
<td>0%</td>
<td>$166.00</td>
</tr>
<tr>
<td>General Purpose Low-Carbon Steel, Sheet, .075&quot; Thick, 24&quot; x 48&quot;</td>
<td>Magnetic panels for securement of CDS</td>
<td>$76.00</td>
<td>2</td>
<td>0%</td>
<td>$152.00</td>
</tr>
<tr>
<td>Super-Conductive 101 Copper, Rectangular Bar, 1/16&quot; x 1&quot;, 4' Length</td>
<td>Panels for CDS Autonomous Charging</td>
<td>$28.00</td>
<td>2</td>
<td>0%</td>
<td>$56.00</td>
</tr>
<tr>
<td>White Delrin® Acetal Resin Rectangular Bar, 3/4&quot; Thick x 1-1/2&quot; Width</td>
<td>Mounting for CRG Panels</td>
<td>$13.00</td>
<td>2</td>
<td>0%</td>
<td>$26.00</td>
</tr>
<tr>
<td>OpenGrab EPM v3</td>
<td>Magnet</td>
<td>$54.00</td>
<td>3</td>
<td>0%</td>
<td>$162.00</td>
</tr>
<tr>
<td>DC 12V 0.07A 8.86RPM High Torque Gearbox Electric Motor 37mm</td>
<td>Motor</td>
<td>$13.00</td>
<td>4</td>
<td>0%</td>
<td>$52.00</td>
</tr>
<tr>
<td>Actobotics 48T Aluminum Hub Gear (0.5&quot;)</td>
<td>Motor Gear</td>
<td>$13.00</td>
<td>4</td>
<td>0%</td>
<td>$52.00</td>
</tr>
<tr>
<td>70 Tooth Timing Belt</td>
<td>Gear Track</td>
<td>$3.00</td>
<td>10</td>
<td>0%</td>
<td>$30.00</td>
</tr>
<tr>
<td>Multistar High Capacity 4S 10000mAh Multi-Rotor Lipo Pack</td>
<td>DSS Battery</td>
<td>$59.00</td>
<td>2</td>
<td>0%</td>
<td>$118.00</td>
</tr>
<tr>
<td>Multistar High Capacity 4S 10000mAh Multi-Rotor Lipo Pack</td>
<td>CRG Battery</td>
<td>$59.00</td>
<td>2</td>
<td>0%</td>
<td>$118.00</td>
</tr>
<tr>
<td>- Miscellaneous Hardware and Electrical</td>
<td>$150.00</td>
<td>1</td>
<td>0%</td>
<td>$150.00</td>
<td></td>
</tr>
</tbody>
</table>

**Docking and Securement System Total** $1,082.00
# Budget: GND & WLS Manufacturing

## Manufacturing: Ground Station

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Description</th>
<th>Unit Cost</th>
<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 MHz 5dBi Rubber Duck Antenna</td>
<td>Communication to SP</td>
<td>$23.00</td>
<td>1</td>
<td>0%</td>
<td>$23.00</td>
</tr>
<tr>
<td></td>
<td>Miscellaneous Software</td>
<td>$50.00</td>
<td>1</td>
<td>0%</td>
<td>$50.00</td>
</tr>
<tr>
<td></td>
<td>Hardware/Electronics</td>
<td>$100.00</td>
<td>1</td>
<td>0%</td>
<td>$100.00</td>
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</table>

**Ground Station Total** $173.00

## Manufacturing: Wheel Locking System

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Description</th>
<th>Unit Cost</th>
<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston Gear D1418KRH</td>
<td>Worm Gear, 14.5 Degree</td>
<td>$45.00</td>
<td>2</td>
<td>0%</td>
<td>$86.00</td>
</tr>
<tr>
<td>Worm Gear, 0.750” Pressure</td>
<td>Angle, 10 Pitch, 1.25 PD, RH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actobotics 48T Aluminum</td>
<td>Motor Gear</td>
<td>$13.00</td>
<td>2</td>
<td>0%</td>
<td>$26.00</td>
</tr>
<tr>
<td>Hub Gear (0.5”)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Miscellaneous Hardware</td>
<td>$100.00</td>
<td>1</td>
<td>0%</td>
<td>$100.00</td>
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</table>

**Wheel Locking System Total** $212.00
Budget: Administrative & Testing

---

### Replacements: Child Drone System

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Description</th>
<th>Unit Cost</th>
<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemfan T-Type CF Prop 13x5.5</td>
<td>Propellers (pair)</td>
<td>$14.00</td>
<td>2</td>
<td>0.00%</td>
<td>$28.00</td>
</tr>
<tr>
<td>Lumener 80A ESC</td>
<td>Elec. Speed Controllers</td>
<td>$25.00</td>
<td>1</td>
<td>0.00%</td>
<td>$25.00</td>
</tr>
<tr>
<td>Polou 12V, 2.2A Step-Down Reg</td>
<td>Voltage Regulator</td>
<td>$10.00</td>
<td>1</td>
<td>0.00%</td>
<td>$10.00</td>
</tr>
<tr>
<td>Polou 5V, 1A Step-Down Reg</td>
<td>Voltage Regulator</td>
<td>$8.00</td>
<td>1</td>
<td>0.00%</td>
<td>$8.00</td>
</tr>
<tr>
<td>Polou 5V Step-Up Reg</td>
<td>Voltage Regulator</td>
<td>$5.00</td>
<td>7</td>
<td>0.00%</td>
<td>$35.00</td>
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**Testing Total** $106.00

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### Testing and Safety

<table>
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<tr>
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<th>Description</th>
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<th>Quantity</th>
<th>Discounts</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Fire Extinguisher</td>
<td>Electrical Fire Extinguisher</td>
<td>$150.00</td>
<td>1</td>
<td>0%</td>
<td>$150.00</td>
</tr>
<tr>
<td>Bushnell Velocity Speed Gun</td>
<td>Speedometer for MRS testing</td>
<td>$90.00</td>
<td>1</td>
<td>0%</td>
<td>$90.00</td>
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</table>

**Testing Total** $240.00

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### Administrative

<table>
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<th>Discounts</th>
<th>Total Cost</th>
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</thead>
<tbody>
<tr>
<td>Printing</td>
<td>$160.00</td>
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<td>0%</td>
<td>$160.00</td>
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</tbody>
</table>

**Administrative Total** $160.00
What is a Chimera?

Offspring of Typhon (giant, last son of Gaia) and Echidna (She-Viper).

Head of a lion, body (and head) of a goat, and snake tail.

Defeated by Bellerophon with the help of Pegasus.