Test Readiness Review

INFERNO

INtegrated Flight-Enabled Rover For Natural disaster Observation

Customer: Barbara Streiffert, Jet Propulsion Laboratory
Faculty Advisor: Jelliffe Jackson

Adam Archuleta, Devon Campbell, Tess Geiger,
Thomas Jeffries, Kevin Mulcair, Nick Peper,
Kaley Pinover, Esteben Rodriguez, Johnathan Thompson
• Project Context
  • CONOPS
  • Levels of Success
  • FBD
  • Baseline Design
  • Critical Project Elements
• Schedule
• Test Readiness
  • Flight Testing
  • Thermal Testing
  • SP Comms Testing
• Financial Status
PROJECT CONTEXT
Design and create an aerial sensor package delivery system for future integration with a natural disaster observation system.
CONCEPT OF OPERATIONS

Legend

GS – Ground Station
MGS – Mobile Ground Station
MR – Mother Rover
CD – Child Drone
SP – Sensor Package

- Movement
- Deployment
- Sensor Data
- Video and Picture Data
- Commands from GS/MGS

Project Context

Schedule

Flight

Thermal

SP Comms

Financial
Levels of Success Status:
Currently on track to meet Level 4 Success

Level 4
• 10 m/s translational flight
• Landing and deployment within 5 m of LOI on command
• Fully autonomous flight except during final landing
• Time stamped video transmitted at 720 p 30 fps
• >= 90% wireless data transmission from SP to GSMRS at 200 m
• Data retransmission possible
• Data transmission and reception GUI on GSMRS
• Final landing within designated area with 80% confidence
FUNCTION BLOCK DIAGRAM: SYSTEM LEVEL

INFERNO FBD LEGEND
- Electrical Power
- Communication Link
- Physical Interface
- INFERNO System Test Equipment
- INFERNO System Deliverables

Observed Environment
- Child Drone
  - GS Commands and Child Drone Position (915 MHz)
  - External Power
- Ground Station / Mother Rover Simulator (GSMRS)
  - GS Commands and Child Drone Position (915 MHz)
  - Imagery Data (5.8 GHz)
  - Comm Handshake and Temperature Data (900 MHz)
- Sensor Package
  - Deployment Mechanism Connection
  - Ambient Temperature
  - Observed Environment
  - GPS Signal (1572.42 MHz)

Project Context
- Schedule
- Flight
- Thermal
- SP Comms
- Financial

5/9/2016
BASELINE DESIGN: INFERNO SYSTEM

INTEGRATED INFERNO SYSTEM

GSMRS

Project Context  Schedule  Flight  Thermal  SP Comms  Financial

5/9/2016
## CRITICAL ELEMENTS

<table>
<thead>
<tr>
<th>Critical Element</th>
<th>Mission Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem Integration</td>
<td>Full mission success is unachievable without compatible integration.</td>
</tr>
<tr>
<td>Software Integration</td>
<td>Responsible for command and execution of all systems.</td>
</tr>
<tr>
<td>Power Limitations</td>
<td>Subsystems must be able to function for mission duration on limited power supplies.</td>
</tr>
<tr>
<td>Communications</td>
<td>Subsystems must be able to send and receive commands and data to ensure mission success and safety.</td>
</tr>
<tr>
<td>Scheduling</td>
<td>High number of tests with complicated scheduling procedures are critical to verifying models and requirements</td>
</tr>
</tbody>
</table>

**Project Context**

- Schedule
- Flight
- Thermal
- SP Comms
- Financial
SCHEDULE
SCHEDULE OVERVIEW

Project Context

Schedule

Flight

Thermal

SP Comms

Financial

Critical Path

Deliveryable

Expected

Margin

Test

Behind Schedule

NO

Expected Margin

Critical Path

Deliverable

Test

Behind Schedule

Project Context

Schedule

Flight

Thermal

SP Comms

Financial

Critical Path

Deliveryable

Expected

Margin

Test

Behind Schedule

2/26 Flight

3/1 Image Quality

3/12 Performance Test

3/5 Image Transmission

3/31 CD Performance

3/7 Power

3/25 Thermal

3/31 SP Performance

4/8 System Validation

No Major Schedule Slippage
TEST READINESS
TEST READINESS:
CHILD DRONE OVERVIEW

Project Context

Schedule

Flight

Thermal

SP Comms

Financial

5/9/2016
TEST READINESS: CHILD DRONE FLIGHT TEST

• **PURPOSE**
  • Ensure CD capable of controlled, manual flight by pilot
  • Adjust control gains for optimal responsiveness

• **TESTED MODEL**
  • Child Drone power model

• **KEY DATA**
  • Flight time
  • Current draw/charge consumption
  • Proportional roll/pitch angle/rate gains

<table>
<thead>
<tr>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endurance</td>
</tr>
</tbody>
</table>

**5/9/2016**
CHILD DRONE FLIGHT TEST: POWER MODEL

- Manufacturer specs available relating current to thrust for 11” and 12” props
- Polynomial fit to current-thrust curves
  \( T_{11} = f(I) \quad T_{12} = g(I) \)
- Thrust curves scaled linearly from 11” and 12” to 13”
  \( T_{13}(I) = 2T_{11}(I) - T_{12}(I) \)
- Min/max current scaled linearly from 11” and 12” to 13”
  \( I_{13,\text{min}} = 2I_{12,\text{min}} - I_{11,\text{min}} \)
  \( I_{13,\text{max}} = 2I_{12,\text{max}} - I_{11,\text{max}} \)

<table>
<thead>
<tr>
<th>Config</th>
<th>Mass (g)</th>
<th>Propulsion (A)</th>
<th>Other (A)</th>
<th>Total (A)</th>
<th>Endurance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Test</td>
<td>2450</td>
<td>24.7</td>
<td>0.18</td>
<td>24.9</td>
<td>19.1</td>
</tr>
<tr>
<td>Full System</td>
<td>2600</td>
<td>26.6</td>
<td>0.38</td>
<td>27.0</td>
<td>17.8</td>
</tr>
</tbody>
</table>

Project Context

Schedule

Flight

Thermal

SP Comms

Financial

5/9/2016
CHILD DRONE FLIGHT TEST: TEST SETUP

- Conducted at RIFLE (RECUV)
  - CD flown through piloted maneuvers and hover
- Data Collection
  - 3DR Power Module outputs 0 – 3.3 V signal to Pixhawk
  - Pixhawk samples through 12-bit ADC at 10 Hz
  - Pixhawk records telemetry to flash memory while propulsion is armed

| Total Current | 3DR Power Module | Pixhawk | Range: 0 – 60 A
|              |                  |        | Error: ±2 A
|              |                  |        | Resolution: 14.6 mA
| Time         | Pixhawk          |        | Sample Rate: 10 Hz
| Charge Consumed | Pixhawk        |        | Error: integral dependent

Data

Project Context  Schedule  Flight  Thermal  SP Comms  Financial
CHILD DRONE FLIGHT TEST DATA REDUCTION

**Data**

<table>
<thead>
<tr>
<th>Data</th>
<th>Propulsion (A)</th>
<th>Other (A)</th>
<th>Total (A)</th>
<th>Endurance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>24.7</td>
<td>0.18</td>
<td>24.9</td>
<td>19.1</td>
</tr>
<tr>
<td>Recorded</td>
<td>18.9</td>
<td>0.50</td>
<td>19.4</td>
<td>24.7 ± 0.1</td>
</tr>
</tbody>
</table>

**Project Context**

- Schedule
- Flight
- Thermal
- SP Comms
- Financial

5/9/2016
THERMAL CHAMBER TEST

- **Purpose**
  - Verify SP temperature sensor range, accuracy, precision, sample rate and storage.

- **Model**
  - Sensor package internal temperature remains between 1.1 – 4.4 ºC above ambient temperature.

### Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Value</th>
<th>DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>10 – 47.8 ºC</td>
<td>1.1.1</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 2.78 ºC</td>
<td>1.1.1</td>
</tr>
<tr>
<td>Sample Frequency</td>
<td>1 Hz</td>
<td>1.1.3</td>
</tr>
<tr>
<td>Storage</td>
<td>3600 data points</td>
<td>1.1.2</td>
</tr>
</tbody>
</table>
THERMAL CHAMBER TEST: MODEL

\[ q_{\text{generated}} = q_{\text{conduction}} + q_{\text{convection}} \]

\[ q_{\text{conduction}} = \frac{k}{\ell} A(T_S - T_\infty) \]

\[ q_{\text{convection}} = \overline{h} A(T_S - T_\infty) \]

- Major Assumptions:
  - 1D heat transfer
  - Vertical plate free convection
  - Steady state
  - Uniform internal SP temp

**Results:**
- In the operational temperature range (10-47.8 °C), SP internal temperature remains within 3.3 °C above ambient
- Upper and lower bound determined by typical free convection coefficients for air
  - 1.1-4.4 °C
Equipment
- Thermal Chamber
- K type thermocouples
- Data Acquisition module
- Computer with LabView GUI
  - Equipment provided by ASEN staff

SP running and operational but will transmit no data during test (XBee Idle)

### Data

| Temperature Sensor Baseline | K type thermocouple | Range: 0 – 1260 °C  
|                           |                     | Error: ± 2.2 °C  
|                           |                     | Resolution: 7.5*10^-5 °C
| SP Temperature Sensor      | LM34CA              | Range: -48 – 120 °C  
|                           |                     | Error: ± 3 °C  
|                           |                     | Resolution: 0.04 °C
Temperature of Sensor compared to ambient < 2.78 °C

1 Hz Data Collected for 1 hour

Internal SP temperature compared to ambient temperature is between 1.1 - 4.4 °C

DR 1.1.1 is verified

DR 1.1.1 is not verified

DR 1.1.2 and 1.1.3 are verified

DR 1.1.3 is not verified

Thermo model verified

Thermo model not verified

Validated SP Operation and Thermo Model
Purpose
- Verify SP communications model at various distances from GSMRS

Requirements
- Range: 200 m (DR 5.3)
- Success Rate: 90% (DR 5.3.1)

Model
- Sensor package/GSMRS wireless link has ~50 dB link margin at 200 m and ~56 dB at 100 m

Level 4 success requires ≥ 90% packet reception at 200 meters
Governing Equation:
- Power Received = Power Transmitted + Transmitter Gain + Receiver Gain - Losses

Assumptions:
- Ambient conditions free of rain/snow/fog
- Line of sight transmission
- Isotropic emission from antenna

Predictions:
- Received signal strength at:
  - 200 m: ~50 dB
  - 100 m: ~56 dB
  - 50 m: ~62 dB
- Communication model cannot predict packet loss rate
- Previous testing predicts ~95 % packet success rate at 200 m

Verification:
- Measure received signal strength at GSMRS using XCTU software and compare with model
- Post-testing download data from SP memory, compare with received data at GSMRS and compare with previous testing
SP COMMUNICATIONS TEST: TEST SETUP

- **Equipment**
  - Laptop with XCTU software

- **Data**
  - Ambient Temperature Data
  - Timestamping

- **Procedure**
  - Place SP at measured distances from GSMRS
  - Take data at SP and transmit to GSMRS
  - Compare SP data with received GSMRS data

---

Test Distances

- 50 m
- 100 m
- 200 m

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[Project Context Schedule Flight Thermal SP Comms Financial]
**Summary:**
- Testing performed at South Campus
- Empirical data compared with model and previous testing

- **Packet reception greater than 90% at 200 meters**
  - YES
    - DR 5.3.1 is validated
  - NO
    - DR 5.3.1 not validated
    - Drop to level 3 success

- **Received signal strength greater than minimum required power received**
  - YES
    - DR 5.3 is validated
  - NO
    - DR 5.3 not validated
    - Drop to level 3 success

**Level 4 Success**
FINANCIAL STATUS
FINANCIAL STATUS: BUDGET

Summary: Under budget with margin allocated for testing incidental costs

Margin Allocation
- Additional Child Drone batteries and propellers / GoPro Incidental test equipment / replacement components in case of testing failure
- Future logistic costs (printing, report binding, etc.)
## FINANCIAL STATUS: PROCUREMENT

### PROCURED (As of 2/21/2016)

**CHILD DRONE**
- Airframe (arms, landing legs, baseplate)
- Propulsion Subsystem (motors, speed controllers, propellers)
- Power Distribution and Battery
- Flight Controller, GPS Unit
- Communication Hardware (X8R, ImmersionRC Transmitter, 3DR Radio Set)
- Imaging Mount Manufacturing and GoPro
- Linear Actuator
- Connectors for interface compatibility

### GSMRS
- Communication Links (Taranis, ImmersionRC Uno Receiver, 3DR Radio Set)
- ImmersionRC Uno Battery
- MissionPlanner GS Software

### SENSOR PACKAGE
- Communication Hardware (XBees, Antennas)
- LM34CA Temperature Sensors
- Structural Materials (Polycarbonate, Foam)
- PCB Mounting Standoffs
- GM62238-PCB Batteries (x3)

<table>
<thead>
<tr>
<th>Remaining Procurement Item</th>
<th>Procurement Plan</th>
<th>Total Cost</th>
<th>Estimated Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement Parts</td>
<td>Order</td>
<td>~$1000</td>
<td>As Needed</td>
</tr>
</tbody>
</table>
SUMMARY

51.43% COMPLETE

502 HOURS REMAINING

READY FOR TESTING
QUESTIONS
• Levels of Success
• CONOPS
• Functional Block Diagrams
• Requirements
• Human Factors Testing
• Mass and Power Model Updates
• Exhaust Stability Model
• Tensile Strength Testing
• SP Structures
• SP Electronics
LEVELS OF SUCCESS

Level 1
• Manually controlled CD flight with simulated payload
• Simulated deployment
• Time-stamped video collected at 420 p at 30 fps

• 8 MP still images taken at 5 second intervals
• Wired communications (SP, Imaging, CD, GSMRS)
• Time stamped temp data at 1 Hz, 8 bit resolution

Level 2
• 10 minute fully loaded flight duration
• Landing and deployment on command
• Wireless communications (SP, Imaging, CD, GSMRS)

• Time-stamped video collected at 720 p at 30 fps
• SP-GSMRS handshake at 200 m
• SP storage of 1 hour of temperature data
LEVELS OF SUCCESS

Level 3

• 15 minute fully loaded flight duration
• 5 m/s translational flight
• Landing and deployment within 10 m of LOI on command
• Time stamped video collected at 1080 p at 30 fps

• >50% wireless data transmission from SP to GSMRS at 200 m
• Final landing within designated area with 50% confidence

Level 4

• 10 m/s translational flight
• Landing and deployment within 5 m of LOI on command
• Fully autonomous flight except during final landing
• Time stamped video transmitted at 720 p 30 fps
• >= 90% wireless data transmission from SP to GSMRS at 200 m

• Data retransmission possible
• Data transmission and reception GUI on GSMRS
• Final landing within designated area with 80% confidence
The CD takes off from the GSMRS using autopilot.
The CD flies to a GPS waypoint up to 200 meters away using autopilot. The CD then maintains its commanded position to 5 meter accuracy.
Using autopilot, the CD lands and deploys the SP which begins collecting and storing 1 hour of data.
The CD returns to hover using autopilot. It may be commanded to capture video and/or still images at any time. This data is transmitted to the GSMRS.
The CD returns to the GSMRS after a 15 minute maximum flight duration using autopilot.
The CD lands on the GSMRS under pilot control and the SP begins transmitting to the GSMRS.
FUNCTION BLOCK DIAGRAM: SENSOR PACKAGE
## REQUIREMENTS

<table>
<thead>
<tr>
<th>FR 1.0</th>
<th>The system shall collect 1 Hz ambient temperature data at ground level for 60 minutes at the LOI.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DR 1.1</strong></td>
<td>The system shall contain a disposable sensor package capable of collecting 1 Hz ambient temperature data for 60 minutes.</td>
</tr>
<tr>
<td><strong>DR 1.1.1</strong></td>
<td>The sensor package shall contain a sensor capable of measuring temperature between 10°C and 47.8°C with a minimum accuracy of ±2.78°C.</td>
</tr>
<tr>
<td><strong>DR 1.1.2</strong></td>
<td>The sensor package shall be capable of operating continuously for a minimum of 60 minutes.</td>
</tr>
<tr>
<td><strong>DR 1.1.2.1</strong></td>
<td>The sensor package shall contain a power system capable of sustaining operations for 60 minutes.</td>
</tr>
<tr>
<td><strong>DR 1.1.2.2</strong></td>
<td>The sensor package shall have a minimum storage capacity of 10.8 kilobytes.</td>
</tr>
<tr>
<td><strong>DR 1.1.3</strong></td>
<td>The sensor package shall contain a CDH system capable of sampling the temperature sensor at a minimum frequency of 1 Hz.</td>
</tr>
<tr>
<td><strong>DR 1.2</strong></td>
<td>The system shall be capable of carrying a disposable sensor package a minimum horizontal range of 200 meters to the LOI.</td>
</tr>
<tr>
<td><strong>DR 1.2.1</strong></td>
<td>The system shall contain a drone with a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td><strong>DR 1.2.2</strong></td>
<td>The system shall contain a drone with a minimum airspeed of 10 meters per second.</td>
</tr>
<tr>
<td><strong>DR 1.3</strong></td>
<td>The system shall deploy a disposable sensor package at the LOI with a maximum error of 5 horizontal meters.</td>
</tr>
<tr>
<td><strong>DR 1.3.1</strong></td>
<td>The drone shall be capable of holding translational position at the LOI with a maximum horizontal error of 5 meters.</td>
</tr>
<tr>
<td><strong>DR 1.3.2</strong></td>
<td>The drone shall possess a deployment system capable of deploying the sensor package to the LOI with a maximum horizontal error of 5 meters.</td>
</tr>
</tbody>
</table>
# REQUIREMENTS

<table>
<thead>
<tr>
<th>FR 2.0</th>
<th>The system shall collect 1080P aerial video at 30 fps for 15 minutes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 2.1</td>
<td>The drone shall carry an imaging system capable of capturing 1080P video at 30 fps for 15 minutes.</td>
</tr>
<tr>
<td>DR 2.1.1</td>
<td>The imaging system shall have a minimum FOV of 90°.</td>
</tr>
<tr>
<td>DR 2.1.2</td>
<td>The imaging system shall have a maximum mass of 200 g.</td>
</tr>
<tr>
<td>DR 2.1.2</td>
<td>The imaging system shall have a minimum storage capacity of 1.35 GB.</td>
</tr>
<tr>
<td>DR 2.2</td>
<td>The drone shall have a minimum flight endurance of 15 minutes.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FR 3.0</th>
<th>The system shall collect 8MP aerial pictures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 3.1</td>
<td>The drone shall carry an imaging system capable of capturing 8MP pictures.</td>
</tr>
<tr>
<td>DR 3.1.1</td>
<td>The imaging system shall have a minimum storage capacity of 1.35 GB.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FR 4.0</th>
<th>The system shall wirelessly receive commands at a minimum horizontal range of 200 meters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 4.1</td>
<td>The drone shall possess a communication system capable of receiving commands at a minimum horizontal range of 200 meters.</td>
</tr>
</tbody>
</table>
### REQUIREMENTS

<table>
<thead>
<tr>
<th>FR 5.0</th>
<th>The system shall wirelessly transmit data at a minimum horizontal range of 200 meters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 5.1</td>
<td>The drone shall possess a communication system capable of transmitting position data at a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td>DR 5.2</td>
<td>The drone shall possess a communication system capable of transmitting video data with a minimum Cooper-Harper modified quality level of 2 at a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td>DR 5.2.1</td>
<td>The imaging communication system shall be capable of transmitting video data with a minimum Cooper-Harper modified quality level of 2.</td>
</tr>
<tr>
<td>DR 5.3</td>
<td>The sensor package shall possess a communication system capable of transmitting data at a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td>DR 5.3.1</td>
<td>The sensor package shall possess a communication system capable of transmitting 90% of measured data a minimum horizontal range of 200 meters.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FR 6.0</th>
<th>The system shall be able to land under piloted control in a 1.10 m long by 1.10 m wide landing bay with 80% confidence.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 6.1</td>
<td>The system shall have a maximum footprint of 0.730 m long by 0.730 m wide.</td>
</tr>
<tr>
<td>DR 6.2</td>
<td>The drone shall land in the designated landing area with 80% confidence.</td>
</tr>
</tbody>
</table>
• No automated landing on GSMRS
• Piloted control
• Cannot predict the effects of flight on the transmitted image
  • Dr. Frew: We don’t have the time, expertise, or resources to build a model
• Using human factors testing
• Backup plan: Use a COTS gimbal
  • 2000 Hz control frequency
  • 0.1° pointing accuracy
Benefits of Human Factors Analysis

- Analyze complete functionality of imaging system (vibrations, lag, resolution)
- Cooper Harper criteria is industry standard for pilot-aircraft interface analysis
- Utilization of multiple pilots provides accurate metrics on controllability and operator strain
TEST READINESS: CHILD DRONE PERFORMANCE TEST

Is the drone controllable?

Yes

Is controllability satisfactory without improvements?

Yes

No

Deficiencies Warrant Improvement

No

Deficiencies Require Improvement

Is controllability obtainable without intolerable strain?

Yes

No

Is the drone controllable?

Yes

No

Improvement Mandatory

Pilot Interaction

No Improvement Required

Yes

Deficiencies

Warrant Improvement

Excellent, highly desirable

Pilot strain is not a factor

1

Good, negligible deficiencies

Minimal pilot strain is required

2

Minor but tolerable deficiencies

Desired performance requires moderate pilot strain

3

Moderately unpleasant deficiencies

Adequate performance requires considerable pilot strain

4

Major deficiencies

Maintaining control requires considerable pilot strain

5

Major deficiencies

Maintaining control requires maximum pilot strain

6

Major deficiencies

Control will be lost

7
### Component Mass Changes since CDR

<table>
<thead>
<tr>
<th>Component</th>
<th>New Mass [g]</th>
<th>Change since CDR [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Child Drone Bus</td>
<td>2216</td>
<td>+177</td>
</tr>
<tr>
<td>Imaging System</td>
<td>186</td>
<td>-57</td>
</tr>
<tr>
<td>Deployment System</td>
<td>48</td>
<td>+9</td>
</tr>
<tr>
<td>Sensor Package</td>
<td>150</td>
<td>+16</td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td><strong>2600</strong></td>
<td><strong>+145</strong></td>
</tr>
<tr>
<td>Margin vs. MTOW</td>
<td><strong>1077</strong></td>
<td>-145</td>
</tr>
<tr>
<td>Margin vs. Max Thrust</td>
<td><strong>2653</strong></td>
<td>-145</td>
</tr>
</tbody>
</table>

- **Structure Changes**
  - Added GPS mast (+16 g)
  - Added X8R mast (+24 g)
  - New SP baseplate (+16 g)
  - Added perfboard (+22 g)
- **Component Changes**
  - New Video Transmitter (-57 g)
- **Cabling**
  - Never estimated in previous mass budgets (+146 g)

### Component Charge Usage

<table>
<thead>
<tr>
<th>Component</th>
<th>Current [A]</th>
<th>Charge Used [mAh]</th>
<th>Change [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion @ Hover</td>
<td>26.6</td>
<td>6,650</td>
<td>+460</td>
</tr>
<tr>
<td>Flight Electronics</td>
<td>0.18</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td>Video Transmitter</td>
<td>0.20</td>
<td>50</td>
<td>-125</td>
</tr>
<tr>
<td>Deployment System</td>
<td>0.04</td>
<td>~0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>26.0</strong></td>
<td><strong>6,745</strong></td>
<td><strong>+335</strong></td>
</tr>
<tr>
<td>Margin vs. Endurance</td>
<td>6.0</td>
<td>1,255</td>
<td>-335</td>
</tr>
</tbody>
</table>

**Summary**

- Mass increase primarily due to structure changes and cabling
- 29% margin vs. MTOW
- 15.7% margin vs. endurance
### GIMBAL OFF-RAMP: MASS/POWER BUDGETS

#### Component

<table>
<thead>
<tr>
<th>Component</th>
<th>New Mass [g]</th>
<th>Change [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging System and Transmitter</td>
<td>317</td>
<td>+131</td>
</tr>
<tr>
<td>Total Mass</td>
<td>2731</td>
<td>+131</td>
</tr>
<tr>
<td>Margin vs. MTOW</td>
<td>946</td>
<td>-131</td>
</tr>
<tr>
<td>Margin vs. Max Thrust</td>
<td>2528</td>
<td>-131</td>
</tr>
</tbody>
</table>

#### Margin vs. MTOW

- 946 g
- -131 g

#### Margin vs. Max Thrust

- 2528 g
- -131 g

#### Summary:

- Cost manageable within project margin
- Margin vs MTOW reduced to 25%
- Charge margin reduced to 9.5%
- Additional Pixhawk/EPS integration

### Tarot T-2D

- **Cost:** $190
- **Mass:** 200 g
- **Power:** 200-500 mA @ 12 V
- **Accuracy:** 0.1°
### Component Mass Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>New Mass [g]</th>
<th>Change [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Guards x4</td>
<td>200</td>
<td>+200</td>
</tr>
<tr>
<td>Total Mass</td>
<td>2800</td>
<td>+200</td>
</tr>
<tr>
<td>Margin vs. MTOW</td>
<td>877</td>
<td>-200</td>
</tr>
<tr>
<td>Margin vs. Max Thrust</td>
<td>2453</td>
<td>-200</td>
</tr>
</tbody>
</table>

### Component Charge Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Current [A]</th>
<th>Charge Used [mAh]</th>
<th>Change [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion @ Hover</td>
<td>29.0</td>
<td>7,250</td>
<td>+600</td>
</tr>
<tr>
<td>Other</td>
<td>0.39</td>
<td>95</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>29.4</td>
<td>7,345</td>
<td>+600</td>
</tr>
<tr>
<td>Margin vs. Endurance</td>
<td>2.6</td>
<td>655</td>
<td>-600</td>
</tr>
</tbody>
</table>

### Summary:
- Cost manageable within project margin
- Adds considerable manufacturing time
- Margin vs MTOW reduced to 24%
- Charge margin reduced to 8%
- Large change in MOI will affect the gains for the Pixhawk

### BLADE GUARDS:

- **Mass**: ~50 g each
- **Assembly Time**: 8 hr
- **MOIs**:
  - $\Delta I_x = 34\%$
  - $\Delta I_y = 36\%$
  - $\Delta I_z = 42\%$

**Cost**: ~$35

May 9, 2016
### BLADE GUARDS AND GIMBAL: MASS/POWER BUDGETS

<table>
<thead>
<tr>
<th>Component</th>
<th>New Mass [g]</th>
<th>Change [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging System and Transmitter</td>
<td>317</td>
<td>+131</td>
</tr>
<tr>
<td>Blade Guards x4</td>
<td>200</td>
<td>+200</td>
</tr>
<tr>
<td>Total Mass</td>
<td>2931</td>
<td>+331</td>
</tr>
<tr>
<td><strong>Margin vs. MTOW</strong></td>
<td>746</td>
<td>-331</td>
</tr>
<tr>
<td><strong>Margin vs. Max Thrust</strong></td>
<td>2322</td>
<td>-331</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Current [A]</th>
<th>Charge Used [mAh]</th>
<th>Change [mAh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion @ Hover</td>
<td>30.8</td>
<td>7,700</td>
<td>+1,050</td>
</tr>
<tr>
<td>Gimbal</td>
<td>0.40</td>
<td>100</td>
<td>+100</td>
</tr>
<tr>
<td>Other</td>
<td>0.39</td>
<td>95</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31.6</strong></td>
<td><strong>7,895</strong></td>
<td><strong>+1,150</strong></td>
</tr>
<tr>
<td><strong>Margin vs. Endurance</strong></td>
<td><strong>0.4</strong></td>
<td><strong>105</strong></td>
<td><strong>-1,150</strong></td>
</tr>
</tbody>
</table>

**Summary:**
- Cost manageable within project margin
- Margin vs MTOW reduced to 20%
- Charge margin reduced to 1.3%
- Would require larger battery to maintain flight endurance

5/9/2016
SP STABILITY
EXHAUST ANALYSIS

\[ mg \]

\[ \frac{1}{2} \rho v^2 \]

5/9/2016
Exhaust velocity $V_e = \sqrt{\frac{2F_{prop}}{\rho A_{prop}}}$

Lift force $F = \frac{1}{2} \rho v_e^2 A_{SP}$

- Baseplate area $A_{SP} = 0.0274 \text{ m}^2$
- SP weight $mg = 1.45 \text{ N}$

<table>
<thead>
<tr>
<th>Throttle</th>
<th>Exhaust Velocity [m/s]</th>
<th>Dynamic Pressure [Pa]</th>
<th>Lift Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>12.0</td>
<td>75.6</td>
<td>2.07</td>
</tr>
<tr>
<td>70%</td>
<td>14.2</td>
<td>106</td>
<td>2.90</td>
</tr>
<tr>
<td>100%</td>
<td>16.9</td>
<td>150</td>
<td>4.10</td>
</tr>
</tbody>
</table>
Tensile Strength Testing

- Instron machine used to determine Young's Modulus and failure stress
- ASTM D638 Standard with Type 1 specimen used for tests

<table>
<thead>
<tr>
<th></th>
<th>Failure Stress (MPa)</th>
<th>Young's Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested</td>
<td>12.87</td>
<td>1.82</td>
</tr>
<tr>
<td>Specified</td>
<td>33</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Design Issues Addressed

<table>
<thead>
<tr>
<th>Issues</th>
<th>Design Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittle Material</td>
<td>Switch from Acrylic to Polycarbonate</td>
</tr>
<tr>
<td>Possible Flipping Due to Downdraft</td>
<td>Increased Radius and Added Outer Ring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>Polycarbonate</td>
</tr>
<tr>
<td><strong>Radius</strong></td>
<td>125 mm (+ 25%)</td>
</tr>
<tr>
<td><strong>Surface Area</strong></td>
<td>27,574 mm$^2$ (+ 63%)</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>78.8 g (+ 24%)</td>
</tr>
</tbody>
</table>
SENSOR PACKAGE: STRUCTURE – HOUSING

- Permanently Joined Foam Housing
  - Manufactured

- PCB Mounting
  - Prototyped

- Foam - Standoff - Screw Interface
  - 10 mm
  - 10 mm
  - 13 mm
• Reprint will take 12 days if necessary