INFERNO
INtegrated Flight-Enabled Rover For Natural disaster Observation

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

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Thomas Jeffries, Kevin Mulcair, Nick Peper,
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• Project Purpose and Objectives
• Design Description
• Test Overview
• Test Results
• Systems Engineering
• Project Management
PROJECT PURPOSE AND OVERVIEW
Wildfires in 2015 [1]
- 68,151 fires
- 10,125,149 acres burned
- Over $2 billion spent

Human Danger
- 2013 Yarnell Hill Fire
  - 19 firefighters killed

[1] National Interagency Fire Center
Design and create an **aerial, sensor package delivery system** for future integration with a natural disaster observation system.
FIRE TRACKER SYSTEM

Legend

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS</td>
<td>Ground Station</td>
</tr>
<tr>
<td>MGS</td>
<td>Mobile Ground Station</td>
</tr>
<tr>
<td>MR</td>
<td>Mother Rover</td>
</tr>
<tr>
<td>CD</td>
<td>Child Drone</td>
</tr>
<tr>
<td>SP</td>
<td>Sensor Package</td>
</tr>
</tbody>
</table>

- **Movement**: Black lines
- **Deployment**: Purple lines
- **Sensor Data**: Orange lines
- **Video and Picture Data**: Blue lines
- **Commands to Child**: Green lines

INFERNO

Project Context  Design Solution  V&V  Systems and Management

5/9/2016
INFERNO SYSTEM

Project Context  Design Solution  V&V  Systems and Management

5/9/2016
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.
## Levels of Success

<table>
<thead>
<tr>
<th>Level</th>
<th>Child Drone</th>
<th>Imaging</th>
<th>Sensor</th>
<th>GSMRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flies at Loaded Weight</td>
<td>Time stamped video 420p at 30fps</td>
<td>Wired Communication</td>
<td>Stationary Workbench</td>
</tr>
<tr>
<td></td>
<td>Lands Safely</td>
<td>Wired communication</td>
<td>Time Stamped 1 Hz 8 bit</td>
<td>Wired transmission and reception</td>
</tr>
<tr>
<td></td>
<td>Simulated Deployment</td>
<td>8MP pictures taken</td>
<td>Temperature Collection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manually Piloted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10 minute flight time</td>
<td>Wireless communication</td>
<td>Establish wireless communication</td>
<td>Wireless transmission and reception</td>
</tr>
<tr>
<td></td>
<td>Translational Flight</td>
<td>Time stamped video 720p at 30fps</td>
<td>Store 1 hour of data</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>15 minutes flight time</td>
<td>Time stamped video recorded 1080p at 30fps</td>
<td>&gt;50% Data Transmission</td>
<td>Portable simulator</td>
</tr>
<tr>
<td></td>
<td>5 m/s Translational Flight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deploys SP within 10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manual takeoff/landing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10 m/s Translational Flight</td>
<td>Time stamped video transmitted 720p at 30fps</td>
<td>&gt;90% Data Transmission</td>
<td>Data transmission and reception GUI</td>
</tr>
<tr>
<td></td>
<td>Deploys SP within 5 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fully autonomous takeoff</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Critical Elements

<table>
<thead>
<tr>
<th>Critical Element</th>
<th>Mission Influence</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem Integration</td>
<td>Mission failure without successful operation of each subsystem</td>
<td>• Maintained ICDs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Integrated components early</td>
</tr>
<tr>
<td>Power Limitations</td>
<td>Mission profile can’t be executed without required endurance</td>
<td>• Modeled power draw</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Budgeted mass</td>
</tr>
<tr>
<td>Software</td>
<td>All systems require SW: mission failure if any system’s SW fails</td>
<td>• Team strength &amp; knowledge with SW</td>
</tr>
<tr>
<td>Communications</td>
<td>All systems must communicate: mission failure if any system fails to communicate</td>
<td>• Performed link budget analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Performed communication tests</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Necessary for verification and validation of requirements and mission profile</td>
<td>• Maintained testing schedule</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Designated scheduler</td>
</tr>
</tbody>
</table>

### Project Context

- Design Solution
- V&V
- Systems and Management
SYSTEM DESIGN

Integrated INFERNO System

Child Drone

Imaging System

Sensor Package

GSMRS (Simulator)

Project Context  Design Solution  V&V  Systems and Management

5/9/2016
New antenna bought for 3DR radio to increase gain for ground communications.

### GSMRS Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Controller</td>
<td>FrSky Taranis XRD+</td>
</tr>
<tr>
<td>CD Telemetry Transceiver</td>
<td>3DR Radio V2: 900 MHz</td>
</tr>
<tr>
<td>SP Telemetry Transceiver</td>
<td>XBee-Pro XSC S3B: 900 MHz</td>
</tr>
<tr>
<td>Video Receiver</td>
<td>ImmersionRC Uno: 5.8 GHz</td>
</tr>
<tr>
<td>Cost</td>
<td>$403</td>
</tr>
</tbody>
</table>

**Project Context**

**Design Solution**

**V&V**

**Systems and Management**

5/9/2016
CHILD DRONE
**Child Drone Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe</td>
<td>Lumenier QAV500 V2</td>
</tr>
<tr>
<td>Flight Controller</td>
<td>3DR Pixhawk</td>
</tr>
<tr>
<td>Telemetry Transceiver</td>
<td>3DR Radio V2: 900 MHz</td>
</tr>
<tr>
<td>RC Transceiver</td>
<td>Taranis X8R: 2.4 GHz</td>
</tr>
<tr>
<td>Video Transmitter</td>
<td>ImmersionRC: 5.8 GHz</td>
</tr>
<tr>
<td>Drone Mass</td>
<td>2520 g</td>
</tr>
<tr>
<td>Cost</td>
<td>$1847</td>
</tr>
</tbody>
</table>

**Camera Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>GoPro Hero 3 Black</td>
</tr>
<tr>
<td>Image Quality</td>
<td>8.5 MPixels</td>
</tr>
<tr>
<td>Photo Rate</td>
<td>0.2 Hz</td>
</tr>
<tr>
<td>Video Quality</td>
<td>1080p @ 30 fps</td>
</tr>
<tr>
<td>FOV</td>
<td>118.2° H x 69.5° V</td>
</tr>
<tr>
<td>Mass</td>
<td>78 g</td>
</tr>
<tr>
<td>Cost</td>
<td>$370</td>
</tr>
</tbody>
</table>

- Purchased COTS LC Filter for video transmitter to replace in-house design
- New antenna bought for 3DR radio to increase gain for ground communications
FUNCTIONAL BLOCK DIAGRAM: CHILD DRONE

INFERNO FBD LEGEND

- Electrical Power
- Communication Link
- Command / Data Signal
- Physical Interface

Project Context  Design Solution  V&V  Systems and Management

5/9/2016
SENSOR PACKAGE
SENSOR PACKAGE DESIGN

Structural Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Mass</td>
<td>180 g</td>
</tr>
<tr>
<td>Baseplate Material</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>Housing Material</td>
<td>Extruded Polystyrene Foam</td>
</tr>
<tr>
<td>Attachment Piece</td>
<td>3D printed ABS plastic</td>
</tr>
<tr>
<td>Cost</td>
<td>$146</td>
</tr>
</tbody>
</table>

Electrical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td>XBee-Pro XSC S3B: 900 MHz</td>
</tr>
<tr>
<td>Antenna</td>
<td>900 MHz dipole</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>PIC18F67K22</td>
</tr>
<tr>
<td>Battery</td>
<td>450 mAh LiPo</td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>LM34CA</td>
</tr>
<tr>
<td>Cost</td>
<td>$221</td>
</tr>
</tbody>
</table>

Project Context

Design Solution

V&V

Systems and Management
FUNCTION BLOCK DIAGRAM: SENSOR PACKAGE

- **Project Context**: Ambient Temperature
- **Design Solution**:
  - LM34A Temperature Sensor
  - PIC18f67k22 Microcontroller
  - Xbee XSC S3B
- **V&V**: Comm Handshake and Temperature Data (900 MHz)

- **Systems and Management**

**INFERNO FBD LEGEND**
- Electrical Power
- Communication Link
- Command / Data Signal
- Physical Interface
TEST RESULTS
TEST OUTLINE

- Child Drone
  - Endurance Test
  - Communications Test
  - Landing Test
  - Validation Test
  - GPS Test
  - Airspeed Test
- Sensor Package
  - Thermal Test
  - Communication Test
CHILD DRONE TESTING
CHILD DRONE ASSEMBLY/TEST FLOW

Project Context    Design Solution    V&V    Systems and Management

CD Deployment Interface Manufacturing
CD Deployment Electrical Assembly
CD Bus Assembly
CD Camera Mount Manufacturing
CD Camera Assembly
CD Video Transmitter Assembly

CD Deployment Assembly
CD Pixhawk Software Configuration
CD Image Quality Test
CD Camera Activation Prototyping
CD Image Transmission Test

GSMRS Mission Planner Integration

CD Flight Test
CD Comms Test
CD Imaging Integration
CD Video Transmission Test

CD Deployment Integration

CD Subsystem Integration

CD Landing Tests
CD Endurance Test
CD Airspeed Test
CD Mission Test

LEGEND
Manufacturing/Assembly
Test
Complete
Partial Completion
Canceled

5/9/2016
CHILD DRONE ENDURANCE TEST

Project Context
Design Solution
V&V
Systems and Management

LEGEND
- Manufacturing/Assembly
- Test
- Complete
- Partial Completion
- Canceled

CD Deployment Interface Manufacturing
CD Deployment Electrical Assembly
CD Bus Assembly
CD Camera Mount Manufacturing
CD Camera Assembly
CD Video Transmitter Assembly
CD Deployment Assembly
GSMRS Mission Planner Integration
CD Pixhawk Software Configuration
CD Flight Test
CD Comms Test
CD Imaging Integration
CD Video Transmission Test
CD Subsystem Integration
CD Endurance Test
CD Landing Tests
CD Airspeed Test
CD Mission Test

5/9/2016
- Verify flight endurance requirements *(FR 2.0)*
- Characterize drone thrust-power curves
- Determine mass/power budget

**Endurance Test**

<table>
<thead>
<tr>
<th>Endurance</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>15</td>
</tr>
<tr>
<td>Target</td>
<td>18</td>
</tr>
<tr>
<td>Predicted</td>
<td>17.8</td>
</tr>
<tr>
<td>Tested</td>
<td>23.1 ± 1.4</td>
</tr>
</tbody>
</table>

**Project Context**

**Design Solution**

**V&V**

**Systems and Management**

**MN3508KV700 Current vs. Thrust**

**Current vs. Time**

- Initial Model
- Tested Power
CHILD DRONE ENDURANCE TEST

- Design model extrapolated from manufacturer specs
- Analytical model from PDR more accurate

Observed Endurance vs. Analytical Model

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Observed (min)</th>
<th>Modeled (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2450</td>
<td>25.5 ± 0.9</td>
<td>26.0</td>
</tr>
<tr>
<td>2520</td>
<td>24.5 ± 0.1</td>
<td>24.9</td>
</tr>
<tr>
<td>2700</td>
<td>23.1 ± 1.4</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Possible Alternate System Configurations

<table>
<thead>
<tr>
<th>Endurance (min)</th>
<th>Maximum Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>3530</td>
</tr>
<tr>
<td>18</td>
<td>3130</td>
</tr>
<tr>
<td>20</td>
<td>2910</td>
</tr>
<tr>
<td>25</td>
<td>2515</td>
</tr>
</tbody>
</table>

- Further testing required for full model verification

Project Context | Design Solution | V&V | Systems and Management
CHILD DRONE COMMUNICATIONS TEST

Project Context

Design Solution

V&V

Systems and Management
• Verify comm requirements (FRs 4.0, 5.0) and model
• Characterize comm performance and interference sources

• CD moved from 50-500 m from GSMRS
• Measured telemetry:
  • Signal strength (RSSI)
  • Noise power

---

**Signal vs. Noise (0-500 m)**

Signal
Noise
Receiver Sensitivity

**Signal vs. Noise (200-300 m)**

Signal
Noise
Receiver Sensitivity

---

**Noise Comm Loss Example**

**Ground-Level Comm Loss**

---

**Project Context**

**Design Solution**

**V&V**

**Systems and Management**
Model overestimated link budget by ~5-8 dB
Ground effects and noise caused most comm loss

**Predicted vs. Observed Link Budgets**

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Predicted (dB)</th>
<th>Observed (dB)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>47</td>
<td>43.2 ± 0.7</td>
<td>-8.1</td>
</tr>
<tr>
<td>100</td>
<td>41</td>
<td>34.7 ± 0.7</td>
<td>-15.4</td>
</tr>
<tr>
<td>200</td>
<td>35</td>
<td>30.0 ± 0.5</td>
<td>-14.2</td>
</tr>
<tr>
<td>300</td>
<td>32</td>
<td>24.2 ± 0.4</td>
<td>-24.4</td>
</tr>
<tr>
<td>500</td>
<td>27</td>
<td>21.6 ± 0.4</td>
<td>-20.0</td>
</tr>
</tbody>
</table>

Acceptable communication except during deployment
Possible Solutions
- Higher gain antennas
- More powerful communication system
- Additional testing

Project Context  Design Solution  V&V  Systems and Management

5/9/2016
CHILD DRONE LANDING TEST

- CD Deployment Interface Manufacturing
  - CD Deployment Assembly
    - GSMRS Mission Planner Integration
      - CD Flight Test
        - CD Comms Test
          - CD Subsystem Integration
            - CD Landing Tests
              - CD Endurance Test
                - CD Mission Test
      - CD Pixhawk Software Configuration
        - CD Flight Test
          - CD Comms Test
            - CD Subsystem Integration
              - CD Landing Tests
                - CD Endurance Test
                  - CD Mission Test
- CD Bus Assembly
  - CD Image Quality Test
    - CD Imaging Integration
      - CD Video Transmission Test
        - CD Subsystem Integration
          - CD Landing Tests
            - CD Endurance Test
              - CD Mission Test
- CD Camera Mount Manufacturing
  - CD Camera Activation Prototyping
    - CD Image Quality Test
      - CD Imaging Integration
        - CD Video Transmission Test
          - CD Subsystem Integration
            - CD Landing Tests
              - CD Endurance Test
                - CD Mission Test
- CD Camera Assembly
  - CD Image Transmission Test
    - CD Imaging Integration
      - CD Video Transmission Test
        - CD Subsystem Integration
          - CD Landing Tests
            - CD Endurance Test
              - CD Mission Test
- CD Video Transmitter Assembly

LEGEND
- Manufacturing/Assembly
- Test
- Complete
- Partial Completion
- Canceled

Project Context | Design Solution | V&V | Systems and Management

5/9/2016
• Verify piloted landing capability \((FR 6.0)\)
• Characterize landing pad size

**Actual Landing Test**

### Landing Locations with Footprint Confidence

- **80%**
- **95%**

<table>
<thead>
<tr>
<th>Pad Size</th>
<th>Dimensions (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>110 x 110 *</td>
</tr>
<tr>
<td>Measured (Visual)</td>
<td>79 x 79</td>
</tr>
<tr>
<td>Measured (Video)</td>
<td>Future Testing Required</td>
</tr>
</tbody>
</table>

* 80% Confidence
1) Takeoff
2) Deploy SP
3) Imaging TGT1
4) Imaging TGT2
5) Imaging TGT3
6) Landing

Project Context Design Solution V&V Systems and Management
CHILD DRONE GPS TESTING

- Verify GPS receiver accuracy
- Verify ability to deploy SP within 5 m of target (FR 1.0)

### Accuracy

<table>
<thead>
<tr>
<th></th>
<th>Mean Error (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>---</td>
<td>5</td>
</tr>
<tr>
<td>HDOP</td>
<td>$0.70 \pm 0.0007$</td>
<td>$0.82 \pm 0.0007$</td>
</tr>
<tr>
<td>Measured</td>
<td>$0.38 \pm 0.04$</td>
<td>$1.56 \pm 0.04$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.79 \pm 0.04$</td>
<td>$2.38 \pm 0.04$</td>
</tr>
</tbody>
</table>

---

**Project Context**

**Design Solution**

**V&V**

**Systems and Management**

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5/9/2016
**CHILD DRONE AIRSPEED TESTING**

- Verify 10 m/s airspeed requirement *(FR 1.0)*
- Characterize power consumption vs. airspeed

- **Airspeed vs. Groundspeed (Wind = 3.1 m/s E)**

  - Groundspeed
  - Airspeed

- **Airspeed vs. Current (Wind = 3.1 m/s E)**

  - Airspeed
  - Current (A)

<table>
<thead>
<tr>
<th>Airspeed</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>10</td>
</tr>
<tr>
<td>Tested</td>
<td>13.8</td>
</tr>
</tbody>
</table>

- CD exceeds airspeed requirement
- Further testing required for full performance characterization
SENSOR PACKAGE TESTING
SENSOR PACKAGE THERMAL TEST

- Verify SP sensor accuracy and range (FR 1.0)

Thermal Chamber Setup

Thermocouples

Sensor Package

Recorded Data

Thermal Test Raw Data

Hold at 10°C for 30 minutes
Ramp to 47.8°C in 30 minutes
Hold at 47.8°C for 30 minutes

Project Context  Design Solution  V&V  Systems and Management
Sensor Error

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.78°C</td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>1.74 ± 1.74</td>
</tr>
<tr>
<td>Max Measured</td>
<td>3.48</td>
</tr>
</tbody>
</table>

- Mean required thermal sensor accuracy verified
  - Max required thermal sensor accuracy not verified
- Thermal sensor range verified

Primary Test: Hold at 47.8°C

- Calibrate SP software to account for sensor bias
- Use more accurate sensor
**SENSOR PACKAGE COMMUNICATIONS TEST**

- Verify sensor package comm link up to 200m away (*FRs 4.0, 5.0*)
- Verify accuracy of wirelessly received data (*FR 5.0*)

**Testing Setup at South Campus:**
- Place SP at measured distance from GSMRS
- Collect and timestamp temperature data of ambient air
- Transmit temperature data to GSMRS
- Repeat at new distance from GSMRS
- Data collected and transmitted for 5 minutes at 50m, 100m and 200m each
- GSMRS placed 1m AGL to simulate antenna mast
SENSOR PACKAGE COMMUNICATIONS TEST

- Comms link drops significantly at ground level
- Antenna mast may be required for Mother Rover

Received Data Accuracy Results

**Predicted vs. Observed Link Budgets**

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Predicted (dB)</th>
<th>Observed (dB)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>63</td>
<td>59</td>
<td>6.78</td>
</tr>
<tr>
<td>100</td>
<td>57</td>
<td>53</td>
<td>7.04</td>
</tr>
<tr>
<td>200</td>
<td>51</td>
<td>44</td>
<td>16.6</td>
</tr>
<tr>
<td>200 @ 1 m AGL</td>
<td>51</td>
<td>55</td>
<td>7.27</td>
</tr>
</tbody>
</table>

**Collected Data vs. Received Data**

- Link budget exceeds system requirements
- 100% accuracy of data received vs. data stored on SP
SYSTEMS ENGINEERING APPROACH
SYSTEMS ENGINEERING OVERVIEW

Project Context  Design Solution  V&V  Systems and Management

Concept of Operations  System Requirements  High-Level Design  Detailed Design  Subsystem Verification  Component Fabrication  System Verification  System Validation

Fall 2015  Spring 2016
Key Lessons
- Understanding of how CONOPS and design are interconnected
- Heritage project scope – simulate vs. build

CONOPS Development
- Two major possibilities for deployment carried through design
- Two major CONOPS changes due to design influence

Finalized INFERNO CONOPS

Concept of Operations

Project Context Design Solution V&V Systems and Management
Key Lessons
- Requirements negotiation with customer
- Use qualitative metrics to ensure testability
- Balance between specificity and constraining design
- Don’t impose unnecessary requirements

INFERNO Requirements Metrics

<table>
<thead>
<tr>
<th>Number of:</th>
<th>Initial Draft</th>
<th>Final Draft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Requirements</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>Derived Requirements</td>
<td>63</td>
<td>27</td>
</tr>
<tr>
<td>Total Requirements Rewrites</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Requirements Definition
- Customer negotiation on endurance requirements
- Four rewrites required to achieve acceptable requirements

SYSTEMS APPROACH: REQUIREMENTS
Key Lessons
• Design through context of both requirements and CONOPS
• Examine realistic design solution spaces
• Consider influence of all resources (time, financial, personnel) on design
Key Lessons

- Software is most time consuming and difficult element
- Material testing required for unfamiliar mediums (ABS print grains)
- Plan for multiple iterations - 3D printed elements and SP structure

Component Fabrication

- Risk Mitigation: early material testing for 3D printed ABS print grain effects
- Several iterations of manufactured components (baseplates, SP foam housing, 3D printed mounts)
- Many hours writing / debugging software
Key Lessons

- Keep ICDs current to minimize difficulties with subsystem integration
- Ensure compatibility of major system interfaces (ex. deployment SP-CD 3D printed component)

Subsystem Verification

- Issues Identified: video transmission encoding, temperature sensor accuracy, SP software debugging
- Risk Mitigation: Used ICDs to track changing interfaces to ease airframe integration
Key Lessons
• Address system level risk not mitigated at subsystem level
• Resource allocation is essential for successful verification

System Verification
• Issues Addressed: video transmission encoding, SP software debugging
• Issues Identified: RF interference with video transmission
• Risk Mitigation: stocked spare components to limit impact of CD crash
SYSTEMS APPROACH: SYSTEM VALIDATION

Key Lessons
• Successful proof of concept of INFERNO scope
• Test critical functionalities during system verification

Preparing CD in System Validation Testing

System Validation
• Issues Identified: flight controller limitations on autonomous landing hold during deployment
• Risk Mitigation: Secured COA months before System Validation
• Successful completion of all other mission elements
Final Systems Engineering Lessons
- Customer involvement is key – negotiation, understanding of ultimate goal
- Invest time in developing clear, testable requirements
- Interface control is critical to mission success
- Maintain traceability throughout design and testing
- “Start with your eye on the finish line”

Anticipated Risk Description | Prevented | Realized
---|---|---
Crashing Child Drone | ✔ | ✔
Software Development Delay | ✔ | ✔
Camera Mount Structural Failure | ✔ | ✔
Improper SP Orientation | ✔ | ✔
Failure to Obtain COA | ✔ | ✔
Airframe Integration Difficulties |  | ✔

- Realized risks had greatest likelihood, most difficult to directly prevent
- Minimize realized risk impact via schedule margin, extra component procurement, personnel allocation
PROJECT MANAGEMENT
MANAGEMENT APPROACH

• Maintain the long term view
  • Schedule Impact, logistics, workload…
• Anticipate issues, preemptively address
  • Spare parts, scheduling conflicts…
• Employ team in accordance with their capabilities
  • Diverse talents on the team
• Let the team focus of their work
  • Interface with JPL, the PAB, and others…
• Focus the team as necessary
  • Identify tasks critical to the project
• Support individuals as needed
MANAGEMENT LESSONS LEARNED

• Communication can always be better
  • Early Difficulties: Keeping the team apprised
  • Later Successes: Standardized methods
• Detailed yet flexible schedule
  • Early Difficulties: Switching from following class milestones to setting our own schedule.
  • Later Successes: Detailed schedule which can be easily referenced and updated.
• Transitioning from “Steering” the team to “Pushing”
  • Easy when the team is highly motivated
  • Keeping people accountable as motivation waned
  • Schedule is an important reference
BUDGET

INFERNO BUDGET

- CDR Projection $2799
- Final Budget $3877.4

- CHILD DRONE: $1,692
- IMAGING SYSTEM: $292
- SENSOR PACKAGE: $290
- GSMRS: $325
- TESTING: $0
- SHIPPING: $0
- LOGISTICS: $20
- MARGIN: $1,122.60

6/9/2016
## RELATIVE INDUSTRY COST

<table>
<thead>
<tr>
<th>Item</th>
<th>Hours</th>
<th>Rate</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Hours</td>
<td>3871.3</td>
<td>$31.25 per hour</td>
<td>$120,978.13</td>
</tr>
<tr>
<td>Project Supplies</td>
<td></td>
<td>$5000</td>
<td>$5000.00</td>
</tr>
<tr>
<td>RIFLE Range</td>
<td>30</td>
<td>$200 per hour</td>
<td>$6000.00</td>
</tr>
<tr>
<td>Table Mountain Access</td>
<td></td>
<td>$5000 per year</td>
<td>$5000.00</td>
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<tr>
<td>Pilot/Spotter</td>
<td>40</td>
<td>$40 per hour</td>
<td>$1600.00</td>
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<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td><strong>$138,578.13</strong></td>
</tr>
<tr>
<td>Overhead</td>
<td></td>
<td>200%</td>
<td><strong>$277,156.25</strong></td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$415,734.38</strong></td>
</tr>
</tbody>
</table>

### Project Context
- **Design Solution**
- **V&V**
- **Systems and Management**

5/9/2016
QUESTIONS
BACKUP SLIDES
• Levels of Success
• Requirements
• Thermal Sensor Analysis
• SP Internal Temperature Analysis
• Human Factors Testing
• Mass and Power Model Updates
• Tensile Strength Testing
• CD Airspeed
• CD EMI
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
<table>
<thead>
<tr>
<th>Requirement (FR)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 1.0</td>
<td>The system shall collect 1 Hz ambient temperature data at ground level for 60 minutes at the LOI.</td>
</tr>
<tr>
<td>DR 1.1</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>DR 1.1.1</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>DR 1.1.2</td>
<td>The sensor package shall be capable of operating continuously for a minimum of 60 minutes.</td>
</tr>
<tr>
<td>DR 1.1.2.1</td>
<td>The sensor package shall contain a power system capable of sustaining operations for 60 minutes.</td>
</tr>
<tr>
<td>DR 1.1.2.2</td>
<td>The sensor package shall have a minimum storage capacity of 10.8 kilobytes.</td>
</tr>
<tr>
<td>DR 1.1.3</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>DR 1.2</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>DR 1.2.1</td>
<td>The system shall contain a drone with a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td>DR 1.2.2</td>
<td>The system shall contain a drone with a minimum airspeed of 10 meters per second.</td>
</tr>
<tr>
<td>DR 1.3</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>DR 1.3.1</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>DR 1.3.2</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>
<tr>
<td><strong>FR 2.0</strong></td>
<td>The system shall collect 1080P aerial video at 30 fps for 15 minutes.</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------------------------------</td>
</tr>
<tr>
<td><strong>DR 2.1</strong></td>
<td>The drone shall carry an imaging system capable of capturing 1080P video at 30 fps for 15 minutes.</td>
</tr>
<tr>
<td><strong>DR 2.1.1</strong></td>
<td>The imaging system shall have a minimum FOV of 90°.</td>
</tr>
<tr>
<td><strong>DR 2.1.2</strong></td>
<td>The imaging system shall have a maximum mass of 200 g.</td>
</tr>
<tr>
<td><strong>DR 2.1.2</strong></td>
<td>The imaging system shall have a minimum storage capacity of 1.35 GB.</td>
</tr>
<tr>
<td><strong>DR 2.2</strong></td>
<td>The drone shall have a minimum flight endurance of 15 minutes.</td>
</tr>
<tr>
<td><strong>FR 3.0</strong></td>
<td>The system shall collect 8MP aerial pictures.</td>
</tr>
<tr>
<td><strong>FR 3.1</strong></td>
<td>The drone shall carry an imaging system capable of capturing 8MP pictures.</td>
</tr>
<tr>
<td><strong>DR 3.1.1</strong></td>
<td>The imaging system shall have a minimum storage capacity of 1.35 GB.</td>
</tr>
<tr>
<td><strong>FR 4.0</strong></td>
<td>The system shall wirelessly receive commands at a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td><strong>DR 4.1</strong></td>
<td>The drone shall possess a communication system capable of receiving commands at a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td><strong>FR 5.0</strong></td>
<td>The system shall wirelessly transmit data at a minimum horizontal range of 200 meters.</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>DR 5.1</strong></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><strong>DR 5.2</strong></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><strong>DR 5.2.1</strong></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><strong>DR 5.3</strong></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><strong>DR 5.3.1</strong></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>
<tr>
<td><strong>FR 6.0</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>DR 6.1</strong></td>
<td>The system shall have a maximum footprint of 0.730 m long by 0.730 m wide.</td>
</tr>
<tr>
<td><strong>DR 6.2</strong></td>
<td>The drone shall land in the designated landing area with 80% confidence.</td>
</tr>
</tbody>
</table>
Primary Test: Hold at 47.8°C

<table>
<thead>
<tr>
<th></th>
<th>Mean (°C)</th>
<th>Confidence Interval (°C)</th>
<th>System Error (°C)</th>
<th>Bin Error (°C)</th>
<th>Mean Error (°C)</th>
<th>Max Error (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient</td>
<td>47.85</td>
<td>±0.072</td>
<td>±1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SP Sensor</td>
<td>46.11</td>
<td>-</td>
<td>-</td>
<td>0.67</td>
<td>1.74</td>
<td>3.48</td>
</tr>
</tbody>
</table>

- Unable to verify the thermal sensor error is < 2.78°C
- Range of thermal sensor verified during ramp from 10-47.8°C
- Visible bias in the SP thermal sensor reading.
  - Calibrate SP software to account for the bias
## SP INTERNAL TEMPERATURE ANALYSIS

### Table: Mean Temperature Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mean (°C)</th>
<th>Confidence Interval (°C)</th>
<th>System Error (°C)</th>
<th>Bias Offset (°C)</th>
<th>Bias Error (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient</td>
<td>47.85</td>
<td>±0.072</td>
<td>±1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Internal</td>
<td>47.94</td>
<td>±0.006</td>
<td>±2</td>
<td>+0.43</td>
<td>±0.11</td>
</tr>
</tbody>
</table>

### Table: Temperature Difference

<table>
<thead>
<tr>
<th></th>
<th>Mean Temperature Difference (°C)</th>
<th>Temperature Difference Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeled</td>
<td>2.70</td>
<td>0.90-3.40</td>
</tr>
<tr>
<td>Experimental</td>
<td>0.52</td>
<td>0-3.71</td>
</tr>
</tbody>
</table>

### Observations

- Inconclusive results due to large system errors.
- Model over predicts actual internal temperature.
- Error Sources:
  - Free convection modeled using vertical plate
  - Ignores internal convection
  - Decreases conduction area
  - Assumes all power is dissipated as heat
• 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

**Pilot Interaction**

- **Is the drone controllable?**
  - No
  - Improvement Mandatory

- **Is controllability obtainable without intolerable strain?**
  - No
  - Deficiencies Require Improvement

- **Is controllability satisfactory without improvements?**
  - No
  - Deficiencies Warrant Improvement

- **Deficiencies Warrant Improvement**
  - Excellent, highly desirable
    - Pilot strain is not a factor
  - Good, negligible deficiencies
    - Minimal pilot strain is required
  - Minor but tolerable deficiencies
    - Desired performance requires moderate pilot strain
  - Moderately unpleasant deficiencies
    - Adequate performance requires considerable pilot strain
  - Major deficiencies
    - Maintaining control requires considerable pilot strain
    - Maintaining control requires maximum pilot strain
    - Control will be lost
### MASS/POWER BUDGET:
**UPDATE SINCE CDR**

#### Component Summary
<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><strong>-145</strong></td>
</tr>
<tr>
<td>Margin vs. Max Thrust</td>
<td><strong>2653</strong></td>
<td><strong>-145</strong></td>
</tr>
</tbody>
</table>

#### Component Changes
- **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)

#### Charge Used Summary
<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><strong>6.0</strong></td>
<td><strong>1,255</strong></td>
<td><strong>-335</strong></td>
</tr>
</tbody>
</table>

**Summary**
- Mass increase primarily due to structure changes and cabling
- 29% margin vs. MTOW
- 15.7% margin vs. endurance
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>
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</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>
CHILD DRONE EMI TESTING

Internal Compass vs. Current

Internal vs. External Compass

Mag Field (µT)

Time (s)
Internal Compass Axes

- MagX
- MagY
- MagZ

Mag Field (μT)

Time (s)