Critical Design Review

Collision Encounter Reduction for Unmanned Aerial Systems (CERUNAS)

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Overview

- Project Purpose and Objectives
- Design Solution
- Critical Project Elements
- Design Requirements
- Project Risks
- Verification and Validation
- Project Planning
Project Purpose and Objectives
Background and Project Objective

PROBLEM

- Increase in unmanned aircraft systems (UAS) from recreational flyers, researchers, industry
- No UAS has been certified to satisfy See and Avoid requirements in VFR conditions
- Future aircraft (manned and UAS) need a collision avoidance system

SOLUTION

- Design a collision avoidance system (CAS) for sUAS (< 2 lbs)
  - sUAS
    - Detects beacon from manned aircraft
    - Interrupts the sUAS autopilot to evade the manned aircraft flight path
  - Manned Aircraft
    - Propeller-driven (100 m/s)
    - Flying straight and level
    - Flying in uncontrolled airspace over remote terrain
The goal of this project is to design a collision avoidance system (CAS) for small Unmanned Aerial Systems (sUAS) (< 2 lbs) which can detect a beacon mounted on a single, simulated, low-speed (100 m/s) propeller-driven aircraft flying straight and level and can interrupt the sUAS autopilot in order to evade the aircraft’s set flight path, all in uncontrolled airspace over remote terrain.
Summary of Success Level 1
- Verify Sensing Functionality and characterize Manned Aircraft Encounter Cone (MAEC) via Ground Test.

Summary of Success Level 2
- Verify and Characterize Avoidance Functionality only via Flight Test.

Summary of Success Level 3
- Verify full CERUNAS functionality and reduction of collision probability by factor of 1000 via flight test.
Visualization of Manned A/C Encounter Cone (MAEC)

- Pre-CERUNAS Manned A/C Encounter Cone (MAEC) defined by nominal velocities of manned A/C and sUAS (See Project Description)
  - Extends out 2 km in front of manned aircraft
  - Initial area at x = 0 is ellipse formed by average GAA wingspan and height
  - y slope: \( \tan \theta = 0.1 \rightarrow \theta = 5.7106^\circ \)
  - z slope: \( \tan \theta = 0.03 \rightarrow \theta = 1.7184^\circ \)

<table>
<thead>
<tr>
<th>Aircraft/Regime</th>
<th>V (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manned aircraft</td>
<td>100</td>
</tr>
<tr>
<td>sUAS horizontal</td>
<td>10</td>
</tr>
<tr>
<td>sUAS climb/descent</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manned A/C Dimensions</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingspan</td>
<td>12</td>
</tr>
<tr>
<td>Height</td>
<td>3</td>
</tr>
</tbody>
</table>
Definition of Reduction Factor

Minimum distance ($d$) to avoid collision volume

**Factor of Reduction** = \( \frac{Volume_{minimum}}{Volume_{MAEC}} \) needs to be 1000 (customer requirement)

- Minimum distance to avoid collision ($d$) needs to be calculated for a given latency time to initiate FTM
- Latency time to initiate FTM is unknown but is less than 10 seconds (according to customer)

Requirements Satisfied
CAS-PRJ-001– Factor of 1000 Reduction
Design Solution
Concept of Operations

Simulated Manned Aircraft (100 m/s ± 10%)

1. Manned A/C component transmits signal

2. sUAS senses incoming manned aircraft

3. sUAS determines if it will be in MAEC

4. IF: sUAS is in MAEC then initiate avoidance maneuver ELSE: continue on flight path

5. sUAS evades incoming manned aircraft

6. sUAS resumes autopilot flight path

7. sUAS records telemetry data of encounter onboard memory storage

Legend:
- Aircraft Flight Path
- Manned Aircraft Encounter Cone (MAEC)
- Telemetry Data Path

~ 2 km
(~20 seconds to avoid encounter)
(x, y, z)_{\text{mannedAC}}

- Cross-sectional area of cone changes in area with range (y-direction)
- sUAS determines if its coordinates \((x, y, z)_{\text{SUAS}}\) are within MAEC ellipse coordinates \((x, y, z)_{\text{MAEC}}\)
  \[
  \left(\frac{x_{\text{SUAS}}}{a_{\text{MAEC}}}\right)^2 + \left(\frac{z_{\text{SUAS}} - z_{\text{mannedAC}}}{b_{\text{MAEC}}}\right)^2 < 1
  \]
  \(a = \) semimajor axis of MAEC, \(b = \) semiminor axis of MAEC

Logic at range \(r\):
- If: sUAS is within cross-sectional area of MAEC → initiate avoidance maneuver
- Else: sUAS is not in MAEC → continue on autopilot flight path

\(\sim 2 \text{ km} \) (~20 seconds to avoid encounter)
Avoidance Concept of Operations

1. Manned Aircraft GPS and Altitude Locations Transmitted

2. sUAS GPS and Altitude Locations Measured and Manned Aircraft Telemetry Received

3. Microcontroller on sUAS calculates flight paths of manned aircraft and sUAS and determines if sUAS is in MAEC

4. Microcontroller stops outputting the 3.3 V signal and interrupts the autopilot initiating Flight Termination Mode

4. Microcontroller continues to output 3.3V signal and sUAS maintains flight path

Return to step 2
Flight Termination Mode

Collision Avoidance System initiates FTM

FTM is fully engaged

Logic High

Output from 3.3V Digital I/O Line

Logic Low

Time latency for sUAS to initiate FTM

sUAS begins FTM maneuvers

sUAS descends at ~10 m/s in tight right banked turn
Critical Project Elements
## Critical Project Elements

<table>
<thead>
<tr>
<th>Project Element Identifier</th>
<th>Critical Project Element Description</th>
<th>Rationale for Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The CAS must determine that the sUAS is in the encounter cone of a manned A/C based on reception of a signal provided by the manned A/C</td>
<td>Indication of potential manned A/C-sUAS collisions</td>
</tr>
<tr>
<td>2</td>
<td>The manned A/C mountable CAS transmission device must be able to indicate either or both: The location and heading of the A/C, Encounter cone boundaries for a sUAS</td>
<td>Indication of potential manned A/C-sUAS collisions</td>
</tr>
<tr>
<td>3</td>
<td>The CAS must complete any sUAS maneuvers required to move the sUAS outside of the manned aircraft encounter cone</td>
<td>Avoidance of manned A/C-sUAS collisions</td>
</tr>
<tr>
<td>4</td>
<td>The sUAS elements of the CAS must have a mass of less than 100g</td>
<td>Weight key to effective integration of CAS with existing sUAS components</td>
</tr>
<tr>
<td>5</td>
<td>Telemetry data for the sUAS must be collected and downlinked for any collision avoidance maneuvers</td>
<td>Need to understand CAS effectiveness in real-world flight and to validate mission success</td>
</tr>
<tr>
<td>6</td>
<td>The CAS transmitter and receiver units must each be mass producible for less than $100</td>
<td>- Cost-effective compared to cost of sUAS - Cost-effective for private pilot implementation</td>
</tr>
</tbody>
</table>
Design Requirements

Manned A/C Component Hardware
sUAS Component Hardware
Software Development
Manned A/C Component Hardware
Manned A/C Component Layout

1. PVC Housing
2. Acrylic Lid
3. GSM 900 MHz 2dB Antenna
4. Transmitter XBee Pro 900 HP
5. Receiver Xbee Pro 900 HP
6. Venus 638 FLPx GPS Receiver
7. LD1117 Voltage Regulator
8. MB5611 Barometric Pressure Sensor
9. PIC 18F47J13 Microcontroller
10. VTGPSIA-3 GPS Internal Active Antenna
11. Venom 50C 5000 mAh LiPO Battery
12. 3” Threaded Suction Cup (x3)

Requirements Satisfied
CAS-SYS-004 – CAS Interference with Manned A/C

All Components are to Scale
### Manned A/C Power/Mass Budget Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
<th>Nominal Current (mA)</th>
<th>Nominal Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus GPS Receiver</td>
<td>8</td>
<td>68</td>
<td>3.3</td>
</tr>
<tr>
<td>Embedded SMA GPS Antenna</td>
<td>18</td>
<td>12</td>
<td>3.3</td>
</tr>
<tr>
<td>Xbee Pro 900 HP w/SMA</td>
<td>8</td>
<td>215</td>
<td>3.3</td>
</tr>
<tr>
<td>GSM 900 MHz 2dBi Antenna</td>
<td>13</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>PIC18F47J13 Micro Controller</td>
<td>1</td>
<td>0.06</td>
<td>3.3</td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>1</td>
<td>0.01</td>
<td>3.3</td>
</tr>
<tr>
<td>Venom 1S 5000 mAh Lipo Battery</td>
<td>156</td>
<td>N/A</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>205</strong></td>
<td><strong>295.07</strong></td>
<td></td>
</tr>
</tbody>
</table>

Venom 5000 mAh battery provides greater than 8 hour flight time
Manned A/C Component Layout

- 5000 mAh LiPo Battery
- Voltage Regulator
- 3.7 V Unregulated Power
- 3.3 V Regulated Power
- 115200 bps Serial Communication
- 20 MHz Clock SPI Communication
- Pressure Altitude Sensor
- Venus GPS
- PIC18F47J13 Microprocessor
  - XBee Pro 900 HP Broadcast
  - 115200 bps Serial Communication
  - 20 MHz Clock SPI Communication
- XBee Pro 900 HP Listen
Manned A/C Power Management

Venom 50C 1S 5000mAh Lithium Battery

- Will supply 8 hours of battery life
- Easily regulated to 3.3V from 3.7V
- Modular and Rechargeable
- 156 g

LD1117V33 Voltage Regulator

- Up to 800 mA current at 3.3V
- Up to 15V input
- 2g

Requirements Satisfied
CAS-FUN-007 – Power Management
CAS-FUN-008 – Battery Charge Interval

All Components are to Scale
Manned A/C Transmitter System

Xbee Pro 900 HP Transceiver

- 915 MHz Frequency
- 2 km Operation Range
- 215 mA Transmit/29 mA Receive Current

GSM 900 MHz 2dBi Antenna

- 2 dBi Transmit Power
- 900 MHz Frequency Range

Requirements Satisfied
CAS-SYS-001 – MAEC Range
CAS-SYS-008 – Power Consumption
CAS-FUN-009 – Transmitter Frequency

All Components are to Scale
Communication Link Budget

\[ \text{Margin} = P_t + G_t - \text{FSPL} + G_r - \text{Sensitivity} \]

- \( P_t \) = Power Transmitted
- \( G_t \) = Transmitter Gain
- FSPL = Free Space Path Loss
- \( G_r \) = Receiver Gain

- Overall Transmitter Gain: 24 dBm
- Receiver Gain (Antenna): 2.1 dB
- Operating Frequency: 915 MHz
- Required Operating Range: 2 km
- \( \text{Margin} = 31.03 \text{ dB} \)

XBee Pro 900HP is rated for <10% packet error rate at -101 dBm @ 200 Kbps

Margin is difference between received power and receiver sensitivity
Communication Link Budget

- Manned A/C Tx: 24 dBm
- sUAS Rx: -69.7 dB
- Path loss: -97.7 dB
- EIRP: 2 km
- Tx power: 2 dB
- Rx power: 31.03 dB
- Margin: -69.7 dB
- Rx sensitivity: -101 dBm
Manned A/C Microcontroller Selection

**PIC18F47J13**

- Extra low power consumption
- 128 KB Program Memory
- 3.8 K RAM
- 2 UART & 2 A/EUSART Pins
- 2 SPI & 2 MSSP/I2C Pins
- 10 CCP Modules
- 13 ch, 12 bit ADC

Requirements Satisfied
CAS-SYS-008 – Power Consumption
CAS-SYS-010 – Data Processing

All Components are to Scale
Manned A/C GPS System

Venus GPS Receiver
- Up to 20 Hz update rate
- 2.5 m Accuracy
- SPI/UART Interfacing

Embedded SMA GPS Antenna
- 26 dB Receiver Gain
- 12 mA current
- VSWR < 2.0

Requirements Satisfied
CAS-SYS-003 – Sensing Accuracy

All Components are to Scale
Manned A/C Pressure Sensor

MS5611-01BA03 – Pressure Sensor

- 24 bit ADC for highly linear pressure and temperature measurements
- SPI/I2C Communication Pins
- 1 μA current draw

Requirements Satisfied
CAS-SYS-003 – Sensing Accuracy

All Components are to Scale
sUAS Component Hardware
Requirements Satisfied
CAS-FUN-015 - Added mass to sUAS shall be distributed about center of mass to maintain original mass distribution.
### sUAS Electronic Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
<th>Nominal Current (mA)</th>
<th>Nominal Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xbee Pro 900 HP w/ Wired Antenna</td>
<td>8</td>
<td>29</td>
<td>3.3</td>
</tr>
<tr>
<td>PIC18F47J13 Micro Controller</td>
<td>1</td>
<td>0.06</td>
<td>3.3</td>
</tr>
<tr>
<td>Turnigy 1S 300mAh Lipo Battery</td>
<td>8</td>
<td>N/A</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>17</strong></td>
<td><strong>29.06</strong></td>
<td></td>
</tr>
</tbody>
</table>

Turnigy 300 mAh battery provides greater than 30 minute flight time
sUAS Component Layout

1. Receiver XBee Pro 900 HP
2. LD1117 Voltage Regulator
3. 8-Lead SOIC 64 Mbit Dual I/O Flash
4. PIC18F47J13 Microcontroller
5. Turnigy nano-tech 300mAh LiPO

Requirements Satisfied
CAS-SYS-007 - The sUAS elements of the CAS shall have a mass of less than 100g.

All Components are to Scale
sUAS Component Layout

- 300 mAh LiPo Battery
- Voltage Regulator
- Flash Memory
- PIC18F47J13 Microprocessor
- XBee Pro 900 HP Broadcast

Connectors:
- 3.7 V Unregulated Power
- 3.3 V Regulated Power
- 115200 bps Serial Communication
- Serial Communication
- 20 MHz SPI Communication
- Descent Mode Toggle
- Datahawk Telemetry
sUAS Power Management

Turnigy Nano 35C 1S 300mAh Lithium Polymer Battery

- Will supply 5 hours of battery life
- Easily regulated to 3.3V from 3.7V
- Modular and Rechargeable
  - 8 g

LD1117V33 Voltage Regulator

- Up to 800 mA current at 3.3V
- Up to 15V input
- 2g

Requirements Satisfied
CAS-FUN-007 – Power Management
CAS-FUN-020 – Battery Charge Interval

All Components are to Scale
sUAS Transmitter System

Xbee Pro 900 HP Transceiver

- 915 MHz Frequency
- 2 km Operation Range
- 215 mA Transmit/29 mA Receive Current

Requirements Satisfied
CAS-SYS-001 – MAEC Range
CAS-SYS-008 – Power Consumption
CAS-FUN-009 – Transmitter Frequency

All Components are to Scale
sUAS Microcontroller Selection

PIC18F47J13

- Extra low power consumption
- 128 KB Program Memory
- 3.8 K RAM
- 2 UART & 2 A/EUSART Pins
- 2 SPI & 2 MSSP/I2C Pins
- 10 CCP Modules
- 13 ch, 12 bit ADC

Requirements Satisfied
CAS-SYS-008 – Power Consumption
CAS-SYS-010 – Data Processing
sUAS Telemetry Storage

SST25VF064C Serial Flash

- 8MB Capacity
- SPI Compatible
- 12 mA current draw
- 4 KB Sectors, 32 KB Overlay Blocks

Requirements Satisfied
CAS-SYS-010 – Data Storage

All Components are to Scale
Software Development
System Simulation

- sUAS
- sUAS in MAEC
- Manned A/C
  - Initial sUAS distance 3000 m
  - FTM Latency 3 s
Simulations indicated that factor of 1000 reduction in collision volume was achievable for all latencies and one orientation of the sUAS.

Determined that reduction factor is highly dependent on initial sUAS position, flight path, FTM latency time.

Full Monte Carlo analysis to be performed to vary more parameters than the current simulations.
Manned A/C Software Algorithm

- Loop running at 10 Hz

```
Initialize sensors, LEDs

Check Battery
  - Nominal
  - Low
    - Set Low Battery LED
    - Set TX LED Red
    - Set TX LED Green

Check packet validity
  - Valid

Read from pressure sensor
  - Read from GPS logger
    - Compute altitude
      - Convert lat, lon, alt, to ENU
        - Packetize Data
          - Send data to Xbee transmitter

Read from backup Xbee

```

- Design Requirements
  - Critical Project Elements
  - Design Solution

- Project Risks
- Verification and Validation
- Project Planning

- Project Purpose and Objectives
Manned A/C TX Packet Structure

- Packet consists of start sequence, payload data, checksum, and end sequence
- Packet length is 30 bytes

<table>
<thead>
<tr>
<th>0x0A 0xA1</th>
<th>Status</th>
<th>Mode</th>
<th>UTC Time</th>
<th>Position</th>
<th>Course</th>
<th>CS</th>
<th>0x0D 0xA0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Start</td>
<td></td>
<td></td>
<td></td>
<td>Start</td>
<td>Payload Data</td>
<td>CS</td>
<td></td>
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</tbody>
</table>

- Packet consists of start sequence, payload data, checksum, and end sequence
- Packet length is 30 bytes
sUAS Software Algorithm

- Loop running at 10 Hz

1. Initialize
2. Read sUAs GPS data from UART
3. Read from Xbee
4. Have valid data?
   - No
   - Yes: Compute relative position vector
5. Set CAS pin high
   - No
   - Yes: In MAEC
     - Set CAS pin low
6. Buffer 20 data points
   - No
   - Yes: Recent detection
     - No
     - Yes: Write data to flash
Project Risks
Risk Assessment: Manned A/C

Critical Fault: Manned aircraft does not transmit GPS/Pressure packets

- **Power**
  - Manned aircraft battery is ruptured
  - During operations, battery discharges or user forgets to charge the battery

- **GPS/Pressure Altitude**
  - Loss of GPS lock
  - Unpressurized aircraft cockpit will not give reliable pressure/altitude data

- **Transmission**
  - Alteration of XBee transmitter antenna pattern by aircraft cockpit
  - Can't mount the antenna to achieve desired transmission pattern
  - Interference of XBee transmitter with existing aircraft instrumentation
Risk Assessment: sUAS

Critical Fault: CAS interferes with Data Hawk science instrumentation
- Altering center of mass

Critical Fault: sUAS does not receive manned aircraft GPS/Pressure packets
- GPS/Pressure Altitude
  - Loss of GPS link (tapping off of UART line fails)
  - Interference of CAS receiver with existing Data Hawk receiver
- Microcontroller
  - sUAS microcontroller will not be able to calculate MAEC due to large number of calculations
  - Flash memory can only read/write a certain number of times

Added mass of CAS battery limits science collection

Project Purpose and Objectives
Design Solution
Critical Project Elements
Design Requirements
Project Risks
Verification and Validation
Project Planning
Risk Assessment: Full System

<table>
<thead>
<tr>
<th>likelihood</th>
<th>Negligible - 1</th>
<th>Marginal - 2</th>
<th>Severe - 3</th>
<th>Critical - 4</th>
<th>Catastrophic - 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent - 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probable - 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occasional - 3</td>
<td></td>
<td>Added mass of CAS battery on Data Hawk</td>
<td></td>
<td>Loss of GPS lock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flash memory can only be read/write a certain number of times</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test facilities could prove insufficient or inappropriate to allow for designed testing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alteration of XBee transmitter antenna pattern by aircraft cockpit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improbable - 2</td>
<td></td>
<td>Altering center of mass (CG) of Data Hawk</td>
<td>Unpressurized aircraft cockpit will not give reliable pressure/altitude data</td>
<td>Can’t mount the antenna where it needs to be to get desired transmission pattern</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weather conditions could negatively impact testability</td>
<td>COA is not approved</td>
<td>Loss of GPS link (tapping off of UART line fails)</td>
<td>sUAS microcontroller will not be able to calculate MAEC due to large number of calculations</td>
</tr>
<tr>
<td>Remote - 1</td>
<td></td>
<td></td>
<td></td>
<td>During operations, battery discharges or user forgets to charge the battery</td>
<td>Manned aircraft battery is ruptured</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interference of XBee transmitter with existing aircraft instrumentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interference of CAS receiver with existing Data Hawk receiver</td>
<td></td>
</tr>
</tbody>
</table>
Verification and Validation
Test: Level of Success 1

Test 1a Goals:
- Verify Xbees can transmit/receive required data
- Verify manned A/C component can transmit from within mock cockpit
- Characterize antenna pattern shape

Test 1b Goals:
- Validate MAEC model
- Characterize MAEC dimensions at 2km
- Characterize CERUNAS sensing accuracy

Equipment:
- sUAS, Manned A/C componentry
- Mock cockpit
- Stakes
- Rope
- Testing stands

Test Location:
- CU Boulder Business Field
- SE Corner, NCAR
- Green Mountain Mem. Park

Legend:
- BL MAEC
- Broadcast Pattern
- Manual Movement of Receiver

Receiver is Moved in increments to differing lateral and axial positions

Stationary Transmitter mounted in a cockpit or a cockpit mock up simulates manned A/C and broadcasts in a set direction

MAEC Definition is Mathematical, not Broadcast Based

2km or Scaled Equivalent
Test: Level of Success 2

Test Location:
- Arvada Airfield
- Table Mountain
- Pawnee National Grassland

Test 2 Goals:
- Verify the sUAS can perform emergency descent spiral necessary to remove itself from the MAEC
- Verify the sUAS can terminate avoidance maneuver once outside MAEC
- Verify sUAS can reinitiate autopilot
- Characterize avoidance latency time

Equipment/ Personnel:
- sUAS, Manned A/C componentry
- Certificate of Authorization (Arvada)
- Two-way radios
- Pilot in Command (PIC)
- Supplemental Pilot
- System Operator
- Observer

Legend:
- Nominal Flight Conditions
- Avoidance Flight Conditions
- Telemetry Downlink
- Contrived Avoidance Signal

Each Test Begins With Nominal Flight

Flight Termination Mode is Manually Triggered

After dropping worst case distance, sUAS resumes Nominal Flight

40m (Worst Case)
Test: Level of Success 3

Test 3 Goals:
- Verify same goals from Test 1a and Test 2
- Successful integration of sensing and avoidance subsystems
- Characterize full CERUNAS performance
- Generate Data for validation of factor of 1000 model

Equipment/ Personnel:
- sUAS, Manned A/C componentry
- Certificate of Authorization (Table Mountain)
- Two-way radios
- Pilot in Command (PIC)
- Supplemental Pilot
- System Operator
- Observer

Beacon Mounted on
Ground Broadcasts
contrived GPS
Coordinates

Avoidance initiated by
CERUNAS, nominal flight
resumes after cone exit

Stationary Beacon
Simulates Manned A/C

MAEC Definitions are
Mathematical, not
Broadcast Based

MAEC Calculated
Based on Test

Nominal Flight
Conditions

Avoidance Flight
Conditions

Telemetry
Downlink

Broadcast
Pattern

700m (Based on CoA Ceiling)

Test Location:
Arvada Airfield, Table Mountain, Pawnee National Grassland

Legend
- Beacon Apparatus
- BL MAEC

Project Purpose and Objectives
Design Solution
Critical Project Elements
Design Requirements
Project Risks
Verification and Validation
Project Planning
Project Planning
Organizational Chart (OC)
Work Breakdown Structure (WBS)
Work Plan (WP)
Cost Plan (1 of 2)

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Needed Cost</th>
<th>Minimum Ordering Cost</th>
<th>Maximum Ordering Cost</th>
<th>Quantity to Order</th>
<th>Quantity Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team Management</td>
<td>$20.00</td>
<td>$20.00</td>
<td>$40.00</td>
<td></td>
<td></td>
</tr>
<tr>
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Project Total Cost: $1,456.09
Expected Cost Margin: $2,087.82

- Factor of Safety (FOS) for cost margin: 2.5
- Majority of costs centered on test components, system development
- Minimum Raw budget margin is ~$2700.00 (~$500.00 with FOS)
- Largest single cost: Data Hawk Platform
  - Customer may provide all or part of assembly
  - Project still cost feasible if full platform needs to be purchased
Largest margins: Test, HW components
- Test component cost could be reduced if necessary by simplifying mockups
- HW, test components are majority of the budget
- Miscellaneous costs are dominated by manufacturing
  - Could be removed for proof of concept investigation if cost prohibitive
- No special access required for ground testing. **No Feasibility Concerns.**
- CoA required for flight testing
  - 3 CoAs Submitted (Arvada Airfield, Table Mountain, Pawnee National Grassland)
  - CoAs are all <400ft. Approval likely in ~60 days.
  - No CoA locations required special access.
    - Weather is only limiting factor, Flight tests allowed two weekend periods to help mitigate weather. **Mild Feasibility Concerns.**
    - Weather and CoA limitations have been identified as risks. Have mitigation, contingency plans.
- Requirements not verified during flight or ground tests are D, O, or A verification method.
  - Verification in ITLL facilities or via post-processing efforts. **No Feasibility Concerns.**
Questions?
### Project Requirements

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<thead>
<tr>
<th>Requirement Number</th>
<th>Requirement Text</th>
<th>Requirement Driver</th>
<th>Requirement Verification Method</th>
<th>Child Requirements</th>
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<tbody>
<tr>
<td>CAS-PRJ-001</td>
<td>The CAS shall determine that the sUAS is in the encounter cone of a manned A/C based on reception of a signal provided a manned A/C in order to reduce the volume of the MAEC by a factor of 1000.</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-SYS-001, CAS-SYS-002</td>
</tr>
<tr>
<td>CAS-PRJ-002</td>
<td>The manned A/C mountable element of the CAS shall not interface with existing manned A/C components while maintaining the capability to indicate either the location and heading of the A/C or encounter cone boundaries.</td>
<td>Customer Requirement</td>
<td>Analysis</td>
<td>CAS-SYS-003, CAS-SYS-004</td>
</tr>
<tr>
<td>CAS-PRJ-003</td>
<td>The CAS shall complete any sUAS maneuvers required to move the sUAS outside of the MAEC while placing primary focus on avoidance and secondary focus on preservation of the sUAS.</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-SYS-005, CAS-SYS-006</td>
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<tr>
<td>CAS-PRJ-004</td>
<td>The sUAS elements of the CAS shall have minimal impact on existing sUAS componentry.</td>
<td>Customer Requirement</td>
<td>Observation</td>
<td>CAS-SYS-007, CAS-SYS-008, CAS-SYS-009</td>
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<tr>
<td>CAS-PRJ-005</td>
<td>Telemetry data for the sUAS shall be collected and downlinked or saved for later download for any collision avoidance maneuvers</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-SYS-010, CAS-SYS-011</td>
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<tr>
<td>CAS-PRJ-006</td>
<td>Testing shall be carried out to allow for characterization and validation of CERNUNAS system behaviors and to provide discrete data for post-processing analysis of system functionality.</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-SYS-012, CAS-SYS-013, CAS-SYS-014</td>
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<tr>
<td>CAS-PRJ-007</td>
<td>Computer models shall be developed to allow for characterization, prediction, and initial validation of sUAS behavior after CERNUNAS implementation.</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-SYS-015, CAS-SYS-016, CAS-SYS-017, CAS-SYS-018</td>
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<tr>
<td>CAS-PRJ-008</td>
<td>Element of the CERNUNAS system designed for both the manned A/C and sUAS platforms shall be mass reproducible for less than $100.</td>
<td>Customer Requirement</td>
<td>Analysis</td>
<td>CAS-SYS-019</td>
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### System Requirements (1 of 2)

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<tr>
<td>CAS-SYS-001</td>
<td>The initial volume of the MAEC for the manned A/C shall extend 2km in front of the manned A/C at an angle defined by the expected velocities for both the sUAS and manned A/C.</td>
<td>Customer Requirement</td>
<td>Ground testing shall allow for verification of presence of standalone CAS components within encounter cone and characterization of cone geometry with no more than 20% error.</td>
<td>CAS-PRJ-001</td>
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<tr>
<td>CAS-SYS-002</td>
<td>The post-CERNUNAS volume of the MAEC shall be determined by the expected velocities of the sUAS and manned A/C along with the time necessary for the sUAS to leave the MAEC at a typical velocity.</td>
<td>Team Analysis</td>
<td>The MAEC shall be modeled before and after implementation of CERNUNAS to allow for characterization of MAEC dimensions and ensure the volume has decreased by a factor of 1000.</td>
<td>CAS-PRJ-001</td>
</tr>
<tr>
<td>CAS-SYS-003</td>
<td>The sUAS mountable element of CERNUNAS shall be able to sense edge of MAEC with an error of no greater than 3m.</td>
<td>Team Analysis</td>
<td>Telemetry shall be used to record the approach and presence in the stationary MAEC of the sUAS and CERNUNAS technology; analysis shall determine the error of the MAEC detection.</td>
<td>CAS-PRJ-002</td>
</tr>
<tr>
<td>CAS-SYS-004</td>
<td>The manned A/C mountable element of the CAS shall not impact the functionality of any manned A/C HW or communications systems and shall have the ability to comply with applicable FAA regulations.</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-PRJ-002</td>
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<tr>
<td>CAS-SYS-005</td>
<td>All avoidance maneuvers implemented by the CAS shall comply with applicable FAA guidelines for sUAS operation.</td>
<td>Government Requirement</td>
<td>Analysis</td>
<td>CAS-PRJ-003</td>
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<tr>
<td>CAS-SYS-006</td>
<td>All avoidance maneuvers implemented by the CAS shall aim for recoverability of sUAS flight after mitigation of the collision situation.</td>
<td>Customer Requirement</td>
<td>Avoidance maneuvers instantiated by CERNUNAS shall be modeled to verify evasive maneuvers are appropriate for desired avoidance flight path, and that return of control to autopilot will ensure recoverability of original heading</td>
<td>CAS-PRJ-003</td>
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<tr>
<td>CAS-SYS-007</td>
<td>The sUAS elements of the CAS shall have a mass of less than 100g.</td>
<td>Customer Requirement</td>
<td>Test</td>
<td>CAS-PRJ-004</td>
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<tr>
<td>CAS-SYS-008</td>
<td>The sUAS elements of the CAS shall draw no more than 0.3 W from pre-existing UAV power.</td>
<td>Customer Requirement</td>
<td>Test by multimeter</td>
<td>CAS-PRJ-004</td>
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<tr>
<td>CAS-SYS-009</td>
<td>sUAS development shall promote ease of implementation.</td>
<td>Customer Requirement</td>
<td>Observation</td>
<td>CAS-PRIJ-004</td>
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<tr>
<td>CAS-SYS-010</td>
<td>Telemetry data for any collision avoidance maneuvers shall be saved on implemented sUAS internal data storage.</td>
<td>Customer Requirement</td>
<td>Analysis</td>
<td>CAS-PRIJ-005</td>
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<tr>
<td>CAS-SYS-011</td>
<td>Telemetry data for any collision avoidance maneuvers shall be uniquely recorded for a period beginning one (1) maneuver duration before the maneuver start time and extending one (1) maneuver duration beyond the maneuver end time.</td>
<td>Team Analysis</td>
<td>Analysis</td>
<td>CAS-PRIJ-005</td>
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<tr>
<td>CAS-SYS-012</td>
<td>All CERNUNAS test procedures shall be fully documented to ensure they are repeatable for a minimum of three (3) iterations</td>
<td>Project Requirement</td>
<td>Observation</td>
<td>CAS-PRIJ-006</td>
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<td>CAS-SYS-013</td>
<td>CERNUNAS flight testing shall be fully telemetered to allow for post-processing characterization and verification of MAEC reduction by functional system.</td>
<td>Project Requirement</td>
<td>Observation</td>
<td>CAS-PRIJ-006</td>
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<tr>
<td>CAS-SYS-014</td>
<td>All testing of the CERNUNAS system shall comply with FAA regulations applicable to the operation of sUASs for research purposes.</td>
<td>Government Requirement</td>
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<td>CAS-PRIJ-007</td>
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<tr>
<td>CAS-SYS-015</td>
<td>The manned A/C mountable element of the CAS shall not impact manned A/C flight dynamics or characteristics.</td>
<td>Team Analysis</td>
<td>A/C dynamics-based simulations shall be used to characterize impact of the CERNUNAS package on sUAS flight characteristics.</td>
<td>CAS-PRIJ-007</td>
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<td>CAS-SYS-016</td>
<td>The methodology and assumptions made for all CAS computer models shall be fully documented.</td>
<td>Project Requirement</td>
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<td>CAS-PRIJ-007</td>
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<td>CAS-SYS-017</td>
<td>Sensitivity analysis shall be carried out in conjunction with all CAS computer models.</td>
<td>Project Requirement</td>
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<td>CAS-PRIJ-007</td>
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<td>CAS-SYS-018</td>
<td>The CAS elements for both the manned A/C and sUAS platforms shall be demonstratably reproducible for $100 +/- 10% based on manufacturer input.</td>
<td>Customer Requirement</td>
<td>Analysis</td>
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<td>CAS-FUN-001</td>
<td>Initial MAEC shall have a semi-minor half-angle of 1.71° and a semi-major half angle of 5.71°, as defined by expected manned A/C and sUAS velocities in a typical flight regime.</td>
<td>Team analysis</td>
<td>Computer model showing MAEC geometry with respect to sUAS nominal velocity.</td>
<td>CAS-SYS-001</td>
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<tr>
<td>CAS-FUN-002</td>
<td>MAEC volume shall enclose the manned A/C such that the cross-section of the cone will grow from an ellipse enclosing the manned A/C dimensions to one that adds 60m to the minor axis and 120m to the major.</td>
<td>Team analysis</td>
<td>Computer model displaying MAEC with respect to manned A/C size and velocity vector.</td>
<td>CAS-SYS-001</td>
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<td>CAS-FUN-003</td>
<td>CERUNAS-installed sUAS shall engage emergency descent mode upon detection of MAEC for full avoidance.</td>
<td>Team analysis</td>
<td>Computer model showing MAEC geometry with respect to sUAS emergency descent mode velocity.</td>
<td>CAS-SYS-002</td>
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<td>CAS-FUN-004</td>
<td>Manned A/C mountable element of CAS shall comply with Title 14 Code of Federal Regulations (14 CFR) §21.21, §21.19, and §21.113 such that no re-certification of aircraft type is required by installation of element.</td>
<td>Project requirement</td>
<td>Analysis</td>
<td>CAS-SYS-004</td>
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<td>CAS-FUN-005</td>
<td>Manned A/C mountable element of CAS shall comply with 14 CFR §91.21 so as not to impinge upon the operation of the existing navigation or communication systems</td>
<td>Project requirement</td>
<td>Analysis of manned A/C system functionality in presence of CAS component.</td>
<td>CAS-SYS-004</td>
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<td>CAS-FUN-006</td>
<td>Manned A/C mountable element of CAS shall be powered by a designated power supply external to all A/C systems.</td>
<td>Team analysis</td>
<td>Observation</td>
<td>CAS-SYS-004</td>
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<td>CAS-FUN-007</td>
<td>Manned A/C mountable element power supply shall operate as a single cell, with at least 5000 mAh and 3V.</td>
<td>Team analysis</td>
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<td>CAS-FUN-008</td>
<td>Manned A/C mountable element power supply shall be chargeable, with ~8 hr between charges.</td>
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<td>CAS-FUN-009</td>
<td>Manned A/C radio communication system shall operate in 900MHz frequency range.</td>
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<td>CAS-FUN-010</td>
<td>sUAS post-MAEC recovery shall return control of sUAS flight operations to autopilot immediately after leaving MAEC.</td>
<td>Team analysis</td>
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<td>CAS-SYS-006</td>
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<td>CAS-FUN-011</td>
<td>sUAS autopilot shall be allowed full control of sUAS flight operations for remainder of mission following avoidance.</td>
<td>Team analysis</td>
<td>Test</td>
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<tr>
<td>CAS-FUN-012</td>
<td>Upon leaving MAEC, CERUNAS shall return control of sUAS to the installed autopilot.</td>
<td>Customer requirement</td>
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<td>CAS-FUN-013</td>
<td>Recovery of sUAS shall return vehicle to original, pre-encounter flight regime.</td>
<td>Team analysis</td>
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<tr>
<td>CAS-FUN-014</td>
<td>A tolerance of 10% shall be applied to sUAS recovery flight regime with respect to pre-encounter sUAS velocity and maneuver (i.e. steady level flight, spiral, etc.)</td>
<td>Team analysis</td>
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<td>CAS-SYS-006</td>
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<td>CAS-FUN-015</td>
<td>Added mass to sUAS shall be distributed about center of mass to maintain original mass distribution.</td>
<td>Customer requirement</td>
<td>Test</td>
<td>CAS-SYS-007</td>
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<tr>
<td>CAS-FUN-016</td>
<td>sUAS hardware mass shall be distributed so as to not alter sUAS stability derivatives or other flight characteristics.</td>
<td>Customer requirement</td>
<td>Test</td>
<td>CAS-SYS-007</td>
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<td>CAS-FUN-017</td>
<td>The battery powering CERUNAS shall represent no more than 60% of the total CERUNAS mass budget.</td>
<td>Team analysis</td>
<td>Observation</td>
<td>CAS-SYS-007</td>
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<tr>
<td>CAS-FUN-018</td>
<td>Added mass of CERUNAS to sUAS shall reduce sUAS flight time limitations based on power supply by no more than 10%.</td>
<td>Team analysis</td>
<td>Test</td>
<td>CAS-SYS-007</td>
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<tr>
<td>CAS-FUN-019</td>
<td>Power supply for sUAS mountable component of CAS shall be rechargeable.</td>
<td>Team analysis</td>
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<td>CAS-FUN-020</td>
<td>Power supply for sUAS mountable component of CAS shall hold a charge for a minimum of 30 minutes.</td>
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<td>CAS-FUN-021</td>
<td>Manned A/C mountable component of CAS shall be installable by a person with required training for A/C operation.</td>
<td>Customer requirement</td>
<td>Analysis</td>
<td>CAS-SYS-009</td>
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<tr>
<td>CAS-FUN-022</td>
<td>sUAS mountable component of CAS shall be installable by a person with ability to assemble base sUAS system.</td>
<td>Team analysis</td>
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<td>CAS-SYS-009</td>
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<tr>
<td>CAS-FUN-023</td>
<td>Technical installation of manned aircraft component should require &lt;5 minutes for full functionality.</td>
<td>Team analysis</td>
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<td>CAS-SYS-009</td>
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<tr>
<td>CAS-FUN-024</td>
<td>Telemetry data for collision avoidance maneuvers shall be stored in sUAS onboard memory to be analyzed upon landing.</td>
<td>Team analysis</td>
<td>Observation</td>
<td>CAS-SYS-010</td>
</tr>
<tr>
<td>CAS-FUN-025</td>
<td>Telemetry system for CERUNAS avoidance maneuvers shall be included in full sUAS component mass budget for test vehicle.</td>
<td>Customer requirement</td>
<td>Observation</td>
<td>CAS-SYS-010</td>
</tr>
<tr>
<td>CAS-FUN-026</td>
<td>Telemetry shall be stored in a format which allows for direct download to a standard laptop or desktop computer.</td>
<td>Customer requirement</td>
<td>Observation</td>
<td>CAS-SYS-010</td>
</tr>
<tr>
<td>CAS-FUN-027</td>
<td>Ground testing of the CAS shall provide approximate characterize the antenna gain pattern emitted from the manned A/C cockpit.</td>
<td>Team analysis</td>
<td>Spectrum analyzer used for attenuation readings, providing a gain pattern plot and indication of 2km range.</td>
<td>CAS-SYS-012</td>
</tr>
<tr>
<td>CAS-FUN-028</td>
<td>Avoidance testing of CAS shall determine time period after entering MAEC that sUAS avoidance maneuver is initiated, as well as the time to descend to a given height.</td>
<td>Team analysis</td>
<td>Pressure altitude readings with respect to time taken in conjunction with telemetry indication of presence in MAEC.</td>
<td>CAS-SYS-012</td>
</tr>
<tr>
<td>CAS-FUN-029</td>
<td>Full system testing of CAS shall demonstrate ability of full CAS to successfully sense and avoid MAEC.</td>
<td>Team analysis</td>
<td>Telemeter data for when sUAS first senses presence in MAEC: how long sUAS is in cone, and how fast sUAS descends.</td>
<td>CAS-SYS-12</td>
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# Functional Requirements (4 of 5)

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<tbody>
<tr>
<td>CAS-FUN-031</td>
<td>CAS telemetry system shall support sufficient memory to save data for all avoidances maneuvers plus one average maneuver duration time.</td>
<td>Team analysis</td>
<td>Analysis</td>
<td>CAS-SYS-013</td>
</tr>
<tr>
<td>CAS-FUN-032</td>
<td>Characterization of MAEC reduction shall quantify CERUNAS operation as related to pre-CERUNAS MAEC.</td>
<td>Team analysis</td>
<td>Test</td>
<td>CAS-SYS-013</td>
</tr>
<tr>
<td>CAS-FUN-033</td>
<td>Certificates of authorization (COAs) shall be composed and submitted to the FAA for Table Mountain (Golden, CO) to accommodate possibility of testing with moored balloons.</td>
<td>Project requirement</td>
<td>Observation</td>
<td>CAS-SYS-014</td>
</tr>
<tr>
<td>CAS-FUN-034</td>
<td>Certificate of authorization (COA) shall be composed and submitted to FAA for Arvada Aero Modelers to accommodate possibility of testing with the Research and Engineering Center for Unmanned Vehicles's (RECUV's) Pilatus platform.</td>
<td>Project requirement</td>
<td>Observation</td>
<td>CAS-SYS-014</td>
</tr>
<tr>
<td>CAS-FUN-035</td>
<td>Manned A/C component of CAS shall be mounted via industrial suction cups to A/C windshield.</td>
<td>Team analysis</td>
<td>Observation</td>
<td>CAS-SYS-015</td>
</tr>
<tr>
<td>CAS-FUN-036</td>
<td>Manned A/C component of CAS shall be functional without impingement on pilot field of vision.</td>
<td>Team analysis</td>
<td>Test</td>
<td>CAS-SYS-015</td>
</tr>
<tr>
<td>CAS-FUN-037</td>
<td>Simplifying assumptions for CAS computer models shall be demonstrably appropriate for physical system operation.</td>
<td>Team analysis</td>
<td>Analysis</td>
<td>CAS-SYS-016</td>
</tr>
<tr>
<td>CAS-FUN-038</td>
<td>Assumptions made for CAS computer models shall be shown to have negligible effect on the modelling performance.</td>
<td>Team analysis</td>
<td>Analysis</td>
<td>CAS-SYS-016</td>
</tr>
</tbody>
</table>
### Functional Requirements (5 of 5)

<table>
<thead>
<tr>
<th>Requirement Number</th>
<th>Requirement Text</th>
<th>Requirement Driver</th>
<th>Requirement Verification Method</th>
<th>Parent Requirements</th>
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</thead>
<tbody>
<tr>
<td>CAS-FUN-039</td>
<td>Computational sensitivity analysis shall be used to verify feasibility of CAS computer models.</td>
<td>Team analysis</td>
<td>Simulation varies sUAS orientation, position, and speed relative to manned aircraft, recording number of collisions compared to avoidance.</td>
<td>CAS-SYS-017</td>
</tr>
<tr>
<td>CAS-FUN-040</td>
<td>Sensitivity analysis of CAS models shall be used to quantify MAEC reduction factor of 1000.</td>
<td>Team analysis</td>
<td>Analysis</td>
<td>CAS-SYS-017</td>
</tr>
<tr>
<td>CAS-FUN-041</td>
<td>Unit count to lower per unit price by mass production shall be driven by conservative manufacturer price.</td>
<td>Team analysis</td>
<td>Observation</td>
<td>CAS-SYS-018</td>
</tr>
</tbody>
</table>
Hardware Component Dimensions (1 of 2)
Hardware Component Dimensions (2 of 2)
## Full CERUNAS Cost Plan

| Item Description                          | Part Number | MA/C Component | sUAS Component | Needed Cost | Minimum Ordering Cost | Maximum Ordering Cost | Quantity to Order | Quantity Needed |
|------------------------------------------|-------------|----------------|----------------|-------------|----------------------|-----------------------|-------------------|----------------|----------------|
| Team Management                          |             | n              | n              | $20.00      | $20.00               | $40.00               | 400               | 400            |
| Development Tools                        |             | n              | n              | $20.00      | $20.00               | $50.00               | 2                 | 2              |
| Soldering Iron                           |             | n              | n              | $8.00       | $8.00                | $30.00               | 1                 | 1              |
| Electronic Components                    |             |                |                |             |                      |                      |                   |                |
| Venus GPS Receiver                       | GPS-11058   | y              | n              | $39.96      | $39.96               | $49.95               | 1                 | 1              |
| Antenna GPS Embedded SMA                 | GPS-00177   | y              | n              | $9.56       | $9.56                | $11.99               | 1                 | 1              |
| Xbee Pro 900 HP w/ Wired Antenna         | 602-1301-ND | y              | y              | $39.00      | $39.00               | $39.99               | 1                 | 1              |
| Xbee Pro 900 HP w/ Wired SMA             | 602-1346-ND | y              | n              | $41.75      | $41.75               | $41.75               | 1                 | 1              |
| GSM 900 MHz 2 dBi Antenna                | WRL-09143   | y              | n              | $6.36       | $6.36                | $7.95                | 1                 | 1              |
| PIC18F47J13 Micro Controller             | PIC18F47J13-PT-ND | y | n | $2.76 | $2.76 | $4.56 | 1 | 1 |
| 3.3 V Voltage Regulator                  | COM-00526   | y              | n              | $3.90       | $3.90                | $3.90                | 1                 | 2              |
| Pressure Sensor                          | M55611-01BA03 | y | n | $17.95 | $17.95 | $17.95 | 1 | 1 |
| Venom 50C 15 5000 mAh Lipo Batt.         | 15036       | y              | n              | $41.99      | $83.98               | $83.98               | 2                 | 1              |
| Turnigy Nano 35C 15 300 mAh Lipo Batt.   | 92100000001 | n              | y              | $1.99       | $7.96                | $7.96                | 4                 | 1              |
| HW Components                            |             |                |                |             |                      |                      |                   |                |
| Data Hawk Airframe                       |             | n              | n              | $20.00      | $20.00               | $50.00               | 1                 | 1              |
| Data Hawk Platform Components            |             | n              | n              | $500.00     | $500.00             | $600.00              | 1                 | 1              |
| Chemical Resistant PVC                   | 8747X108    | y              | n              | $23.10      | $23.10               | $23.10               | 1                 | 1              |
| Acrylic Tep Sheet                        | 8560K275    | y              | n              | $5.07       | $5.07               | $5.07                | 1                 | 1              |
| 3" Suction Cups                          | 5353A45     | y              | n              | $29.94      | $39.92               | $39.92               | 4                 | 3              |
| Test Components                          |             |                |                |             |                      |                      |                   |                |
| Manned A/C Mockup                        |             | n              | n              | $200.00     | $200.00              | $300.00              | 1                 | 1              |
| Two Way Radios                           |             | n              | n              | $120.00     | $120.00             | $200.00              | 4                 | 4              |
| Trundle Wheel                            |             | n              | n              | $60.00      | $60.00               | $150.00              | 2                 | 2              |
| Range Marking Equipment                  |             | n              | n              | $100.00     | $100.00             | $150.00              | 1                 | 1              |
| Miscellaneous Costs                      |             |                |                |             |                      |                      |                   |                |
| PCB Manufacturing                        |             | n              | n              | $150.00     | $150.00             | $350.00              | 1                 | 1              |
| Manned A/C Components                    |             |                |                |             | $261.34              | $313.31              |                   |                |
| Unmanned A/C Components                  |             |                |                |             | $43.75               | $49.72               |                   |                |
| Project Total Cost                       |             |                |                |             | $1,456.09            | $1,514.03            |                   |                |
| Expected Cost Margin                     |             |                |                |             | $2,087.82            | $1,971.94            |                   |                |

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Simulation Plots: (1 of 3)