Design of a Low-Cost General Aviation Flight Data Recording and Analysis System

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Faculty Advisor: Dr. George Donohue

Sponsor: Experimental Aircraft Association

Chapter 571

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Context and Gap
Experimental Aircraft

**Experimental Amateur Built (E-AB) Aircraft**

Constructed by an amateur builder, from an amateur builder’s original design, purchased plans, or pre-fabricated kit. The amateur builder must assemble over one-half of the aircraft. [2]

**Kit-Built Experimental Light Sport Aircraft (ELSA)**

Constructed by an amateur builder, from a kit manufactured by a licensed Light Sport Aircraft manufacturer. The amateur builder must assemble over one-half of the aircraft. [3]

70% of experimental aircraft are classified as E-AB (2012)  
17% of experimental aircraft are classified as ELSA (2012)

Cumulative Accidents by Airframe Hours

E-AB aircraft are 350% more likely to be involved in an accident than all other GA aircraft during their first 40 hours of flight.

Data Compiled: 2001-2010

224 > Accidents
350% > Accident Rate

567 > Accidents
59% > Accident Rate


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**Accident Rate Gap**

*E-AB aircraft are 123% more likely to be involved in an accident than all other General Aviation (GA) aircraft*

![Graph showing the accident rate gap between E-AB and non-E-AB aircraft.](image)

*E-AB aircraft are 238% more likely to be involved in a fatal accident than all other GA aircraft*

![Graph showing the fatal accident rate gap between E-AB and non-E-AB aircraft.](image)

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Current Phase I Testing Process

**Pre-Flight:** Pilot determines flight-plan necessary to parameterize aircraft

Pilot must manually record in-flight data from cockpit gauges

**Post-Flight:** After landing, pilot manually parameterizes aircraft

\[
L = C_l \frac{rv^2}{2} S \\
D = C_d \frac{rv^2}{2} S \\
C_l = \frac{2w}{rv^2 S} \\
C_d = \frac{C_l^2}{\pi Ar e}
\]

Pilot must compile manual data for submission to the FAA

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Loss of control in flight:

“...insufficient takeoff speed, early rotation, or too steep a climb on takeoff led to aerodynamic stalls and loss of control. Inadequate airspeed...also led to aerodynamic stall and loss of control...[2]”

Project Scope

In-Scope

FAA Governed E-AB and ELSA Experimental Aircraft:
- 11.2 ± 0.1% of all GA aircraft (2012)
- 23,474 total aircraft (2012)

E-AB Loss of Control in Flight Accidents:
- 44% of all fatal E-AB accidents (2001-2010)

Out-of-Scope

FAA Governed non Amateur Built Experimental Aircraft and non Experimental Light Sport Aircraft:
- 1.5 ± 0.1% of all GA aircraft (2012)
- 3,240 total aircraft (2012)

E-AB Powerplant Accidents:
- 15% of all fatal E-AB accidents (2001-2010)

Problem and Need
Closing the Gap

Lack of Aircraft Parameterization → Loss of Control in Flight → Problem

E-AB Aircraft vs. GA Fleet
350% > Phase I Accidents
238% > Fatalities

“[D]ata obtained from...recording devices can significantly enhance...the monitoring of parameters important to the continuing airworthiness of the E-AB aircraft, provided that they are demonstrated to be precise and reliable, record at sufficiently high sampling rates, and are easily downloaded by the aircraft owner. [2]” (2012)

NTSB: National Transportation Safety Board

Lack of Aircraft Parameterization + Loss of Control in Flight → Problem

E-AB Aircraft vs. GA Fleet
350% > Phase I Accidents
238% > Fatalities

Need for a Low-Cost Flight Data Recording and Analysis System

Proposed Phase I Testing Procedure

**Pre-Flight:** Pilot puts device in plane and executes pre-determined flight plan

- **Device**
- **Flight Plan**

Pilot activates device prior to entering maneuvers while in flight.

**Post-Flight:** After landing, pilot connects device to computer for post-flight analysis

- **Device**
- **Computer**
- **Graph**

Raw data is run through analysis software and outputs flight characteristics.

**Post-Simulation:** Pilot uses simulation data to generate training record and handbook

- **Simulation Data**
- **Pilot’s Training Record**
- **Pilot’s Operating Handbook**
- **Federal Aviation Administration**
Prototype

**Pre-Flight:** Pilot puts device in plane and executes pre-determined flight plan

- Flight Plan
- Device
- Pilot activates device prior to entering maneuvers while in flight

**Post-Flight:** After landing, pilot connects device to computer for post-flight analysis

- Device
- Raw data is run through analysis software and outputs flight characteristics

**Post-Simulation:** Pilot uses simulation data to generate training record and handbook

- Pilot's Operating Handbook
- Pilot's Training Record
- Raw data from simulation

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Pilot’s Operating Handbook
Rate of Climb for Quicksilver GT500

Mitigating loss of control in flight risk

“To steep a climb on takeoff [2]”

Obtaining the data

Climb 1,000 ft at 100% engine power with 0° and 10° flaps

Measurements required

3-axis velocity derived from 3-axis position

Sink Rate for GT500

Mitigating loss of control in flight risk
“Inadequate airspeed [2]”

Obtaining the data
Descend 1,000 ft at set velocities

Measurements required
3-axis velocity derived from 3-axis position

Stall Speed for GT500

<table>
<thead>
<tr>
<th>Mitigating loss of control in flight risk</th>
<th>“Inadequate airspeed [2]”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obtaining the data</td>
<td>Enter bank turn with flaps set, and reduce velocity until stall</td>
</tr>
<tr>
<td>Measurements required</td>
<td>3-axis velocity derived from 3-axis position</td>
</tr>
<tr>
<td></td>
<td>Bank angle of aircraft, and force applied to pilot</td>
</tr>
</tbody>
</table>

### Stall Speed

<table>
<thead>
<tr>
<th>INDICATED AIRSPEED (MPH)</th>
<th>BANK ANGLE (DEGREES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0° Flaps</td>
</tr>
<tr>
<td>42</td>
<td>10° Flaps</td>
</tr>
<tr>
<td>44</td>
<td>20° Flaps</td>
</tr>
<tr>
<td>46</td>
<td>30° Flaps</td>
</tr>
<tr>
<td>48</td>
<td>40° Flaps</td>
</tr>
<tr>
<td>50</td>
<td>50° Flaps</td>
</tr>
<tr>
<td>52</td>
<td>60° Flaps</td>
</tr>
</tbody>
</table>

Device
Flight Monitoring Device Value Hierarchy

- **Monitoring**
  - **Suitability** (0.250)
    - **Sensitivity** (0.500)
      - Accelerometer (0.087)
      - Gyroscopic (0.087)
      - Barometric (0.435)
      - Global Positioning (0.304)
      - Variability (0.087)
  - **Range** (0.500)
    - Accelerometer (0.250)
    - Gyroscopic (0.250)
    - Barometric (0.500)
  - **Usability** (0.500)
    - Data Analysis (0.333)
    - Device Interaction (0.250)
    - Device Placement (0.417)
  - **Portability** (0.250)
    - Battery Life (0.400)
    - Data Storage (0.500)
    - Weight (0.100)
Low-Cost Monitoring Device Alternatives

Arduino Microcontroller
Capable of reading and writing real-time IMU sensor data for post-flight analysis

Configured with:
- Arduino Mega
- Adafruit 10 DOF IMU board
- GPS Data logger

Hardware Cost - $105

iPhone 6 Smartphone App
Makes use of the iPhone 6’s integrated IMU’s, GPS, and barometer for both in-flight and post-flight analysis

Stock configuration
Hardware Cost - $650

Raspberry Pi Microprocessor
On-board processing enables in-flight reading, writing, and calculation of data for post-flight analysis

Configured with:
- Raspberry Pi
- Adafruit 10 DOF IMU board
- 5” Touch-screen display
- Adafruit GPS

Hardware Cost - $175

IMU: Inertial Measurement Unit
Ranking of Monitoring Alternatives

- Arduino w/ GPS
- Arduino
- Raspberry Pi w/ GPS
- iPhone 6
- Raspberry Pi

Utility vs. Cost graph showing:
- Arduino w/ GPS
- Arduino
- Raspberry Pi w/ GPS
- iPhone 6
- Raspberry Pi
Simulation and Requirements
## Design of Experiment (Simulation)

<table>
<thead>
<tr>
<th>Suitability</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Axis Accelerometer</td>
<td>---</td>
</tr>
<tr>
<td>3-Axis Gyroscope</td>
<td>---</td>
</tr>
<tr>
<td>GPS (for latitude and longitude)</td>
<td>---</td>
</tr>
<tr>
<td>Barometer</td>
<td>---</td>
</tr>
<tr>
<td>Data Recorder</td>
<td>---</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintainability</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Reliability</td>
<td>---</td>
</tr>
<tr>
<td>Device Availability</td>
<td>---</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Portability</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Life</td>
<td>---</td>
</tr>
<tr>
<td>Data Storage</td>
<td>---</td>
</tr>
<tr>
<td>Static Random Access Memory (SRAM)</td>
<td>---</td>
</tr>
<tr>
<td>Weight</td>
<td>---</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interface</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>File Format</td>
<td>---</td>
</tr>
</tbody>
</table>
Design of Simulation

Inputs

Device Parameters:
- GPS (x,y) Accuracy
- GPS(z) Accuracy
- Accelerometer Sensitivity
- Gyroscopic Sensitivity
- Barometer Sensitivity

RNG Seed:
- GPS
- Accelerometer
- Gyroscope
- Barometer

Configuration:
- Iterations
- Sample Rate
- Flight Plan

Navigation and Sensor Model

Raw Data Computation

Analyze Raw Data and Reduce Noise

Outputs

Device Error:
- Position
- Linear Acceleration
- Rotational Acceleration

Graphs:
- Uncorrected Position, Acceleration, Gyro
- Corrected Position, Acceleration, Gyro
- Actual Position, Acceleration, Gyro

Statistical Data:
- Histograms of Error
- Confidence Intervals

Files:
- Original XML
- Condensed XML
Analyze Raw Data and Reduce Noise

Line Smoothing Algorithm:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>2.2</th>
<th>2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (m)</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>Array Index</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{Time (s)}: & \\
0.6 & \quad 0.8 & \quad 1.0 & \quad 1.2 & \quad 1.4 & \quad 1.6 & \quad 1.8 & \quad 2.0 & \quad 2.2 & \quad 2.4 \\
\text{Position (m)}: & \\
3 & \quad 5 & \quad 8 & \quad 9 & \quad 10 & \quad 12 & \quad 14 & \quad 15 & \quad 18 & \quad 21 \\
\text{Array Index}: & \\
0 & \quad 1 & \quad 2 & \quad 3 & \quad 4 & \quad 5 & \quad 6 & \quad 7 & \quad 8 & \quad 9 \\
\end{align*}
\]

\[
\begin{align*}
(3+5+8+9+10) / 5 &= 7 \\
(12+14+15+18+21) / 5 &= 16 \\
1.0 & \quad 2.0 \\
7 & \quad 16 \\
0 & \quad 1 \\
\end{align*}
\]

Linear Velocity

\[
\begin{align*}
\mu &= 11.9 \\
\sigma &= 3,266.9 \\
\sigma^2 &= 10,672,395.7 \\
\end{align*}
\]

Linear Velocity

\[
\begin{align*}
\mu &= 1.1 \\
\sigma &= 256.9 \\
\sigma^2 &= 65,979.3 \\
\end{align*}
\]
Sensitivity Analysis

**Accelerometer Sensitivity** (% of actual acceleration)

- **Raw**: $y = 6.7672x + 0.0144$
- **Smoothed**: $y = 2.9x + 0.0268$

**Error (m/s²)**

- **Accumulated Raw Error**: $y = 108.18x + 0.2857$
- **Accumulated Smoothed Error**: $y = 245.3x + 0.1642$

**Gyroscopic Sensitivity** (% of actual rotational velocity)

- **Raw**: $y = 245.3x + 0.1642$
- **Smoothed**: $y = 108.18x + 0.2857$

**Error (degrees/second)**

- **Accumulated Raw Error**: $y = 108.18x + 0.2857$
- **Accumulated Smoothed Error**: $y = 245.3x + 0.1642$
# Device Subsystem Requirements

<table>
<thead>
<tr>
<th><strong>Suitability</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Axis Accelerometer</td>
<td>Minimum range $20 \text{ m/s}^2$ with max. 0.16% sensitivity</td>
</tr>
<tr>
<td>3-Axis Gyroscope</td>
<td>Minimum range $360^\circ$ with max. 0.08% sensitivity</td>
</tr>
<tr>
<td>GPS (for latitude and longitude)</td>
<td>Maximum 6 meters sensitivity</td>
</tr>
<tr>
<td>Barometer</td>
<td>Minimum $0.25 \text{ m}$ operable range $-30^\circ$ to $50^\circ \text{C}$ [2]</td>
</tr>
<tr>
<td>Data Recorder</td>
<td>Minimum 5 readings per second [3]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Maintainability</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Reliability</td>
<td>Minimum 96% with 5-year lifespan</td>
</tr>
<tr>
<td>Device Availability</td>
<td>Minimum 50,000 hours (MTBF)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Portability</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Life</td>
<td>Minimum 140 mAh (2 hours of battery life)</td>
</tr>
<tr>
<td>Data Storage</td>
<td>Minimum 76 MB (2 hours of raw data capacity)</td>
</tr>
<tr>
<td>Static Random Access Memory (SRAM)</td>
<td>Minimum 8 kB</td>
</tr>
<tr>
<td>Weight</td>
<td>Maximum 1 lb.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Interface</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>File Format</td>
<td>Extensible Markup Language (XML)</td>
</tr>
</tbody>
</table>

---


Cost-Modeling and Results
## Cost Model

### Prototyping and Production

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order Prototype Components</td>
<td>$1,500</td>
</tr>
<tr>
<td>Assemble Prototype Components</td>
<td>$1,000</td>
</tr>
<tr>
<td>Bench Test Prototype</td>
<td>$9,500</td>
</tr>
<tr>
<td>Flight Testing</td>
<td>$5,000</td>
</tr>
<tr>
<td>Production Kit Assembly</td>
<td>$270,000</td>
</tr>
<tr>
<td>Marketing</td>
<td>$100,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$387,000</td>
</tr>
</tbody>
</table>

**TOTAL COST:**

### Software Modules

<table>
<thead>
<tr>
<th>Software Modules</th>
<th>Platform</th>
<th>SLOC</th>
<th>Cost / Line</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-Time Device</td>
<td>C++</td>
<td>250</td>
<td>$92</td>
<td>$23,000</td>
</tr>
<tr>
<td>Flight Plan Generator</td>
<td>Java</td>
<td>3000</td>
<td>$92</td>
<td>$276,000</td>
</tr>
<tr>
<td>Raw Data Analyzer</td>
<td>Java</td>
<td>3000</td>
<td>$92</td>
<td>$276,000</td>
</tr>
<tr>
<td>POH Generator</td>
<td>Java</td>
<td>5000</td>
<td>$92</td>
<td>$460,000</td>
</tr>
<tr>
<td>Training Records</td>
<td>Java</td>
<td>2000</td>
<td>$92</td>
<td>$184,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>$1,219,000</td>
</tr>
</tbody>
</table>

*SLOC: source lines of code*
Design of a Low-Cost General Aviation Flight Data Recording and Analysis System

Units Until Return on Investment (ROI)

- Break-Even: 800 Units Sold
- Break-Even: 1,067 Units Sold
- Break-Even: 1,600 Units Sold
- Break-Even: 3,200 Units Sold

Profit ($) vs. Units Sold

- Units Sold:
  - 0
  - 500
  - 1,000
  - 1,500
  - 2,000
  - 2,500
  - 3,000

- Profit ($):
  - $0,000
  - $1,000,000
  - $2,000,000
  - $3,000,000
  - $4,000,000

- Costs: $500, $1,000, $1,500, $2,000

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Design of a Low-Cost General Aviation Flight Data Recording and Analysis System
# Currently Available Monitoring Systems

<table>
<thead>
<tr>
<th>System</th>
<th>AHRS Connection</th>
<th>Flight Data Recording</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dynon EFIS-D100</strong></td>
<td>AHRS fits directly into instrument panel for in-flight analysis</td>
<td>Data recording not available</td>
<td><img src="image" alt="Dynon EFIS-D100" /></td>
</tr>
<tr>
<td><strong>SBG Ellipse-N</strong></td>
<td>MEMS driven device connects to computer for in-flight analysis</td>
<td>Data recording not available</td>
<td><img src="image" alt="SBG Ellipse-N" /></td>
</tr>
<tr>
<td><strong>Appareo Stratus 2</strong></td>
<td>AHRS connects to iPad or iPhone via Wi-Fi for in-flight analysis</td>
<td></td>
<td><img src="image" alt="Appareo Stratus 2" /></td>
</tr>
<tr>
<td><strong>Garmin VIRB Elite</strong></td>
<td>Records aircraft instruments for manual post-flight analysis</td>
<td></td>
<td><img src="image" alt="Garmin VIRB Elite" /></td>
</tr>
</tbody>
</table>

**Notes:**
- **AHRS:** Attitude Heading and Reference System
- **MEMS:** Microelectromechanical System
- **Data recording not available:**
  - Dynon EFIS-D100
  - SBG Ellipse-N

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*Design of a Low-Cost General Aviation Flight Data Recording and Analysis System*
Ranking of SYSTEM Alternatives

- Arduino Based System
- Stratus 2
- Garmin VIRB Elite 270
- SBG Ellipse-N
- Dynon EFIS-D100

Utility

- Portability
- Usability
- Suitability

Retail Price ($)

- $0.00
- $500.00
- $1,000.00
- $1,500.00
- $2,000.00
- $2,500.00
- $3,000.00
- $3,500.00
- $4,000.00
- $4,500.00
Ranking of SYSTEM Alternatives

- Arduino Based System
- Stratus 2
- Garmin VIRB Elite 270
- SBG Ellipse-N
- Dynon EFIS-D100

Utility vs. Retail Price ($)
**easyPOH**

**Pre-Flight:** Pilot mounts *Garmin* in plane and executes flight plan generated by *easyPOH*

1. Flight Plan
2. Pilot activates device prior to entering maneuvers while in flight

**Post-Flight:** Pilot manually enters data from *Garmin* recording into *easyPOH*

1. Raw data is run through analysis software and outputs flight characteristics

**Post-Simulation:** Pilot uses *easyPOH* to manually compile training record and handbook
## Conclusion and Recommendation

### Utility vs. Cost Analysis

<table>
<thead>
<tr>
<th>System</th>
<th>Portability</th>
<th>Usability</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Based System</td>
<td>0.3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Garmin w/ easyPOH</td>
<td>0.2</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Stratus 2</td>
<td>0.1</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Garmin VIRB Elite 270</td>
<td>0.2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>SBG Ellipse-N</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Dynon EFIS-D100</td>
<td>0.1</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Cost Analysis

<table>
<thead>
<tr>
<th>System</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garmin w/ easyPOH</td>
<td>500.00</td>
</tr>
<tr>
<td>Stratus 2</td>
<td>1,000.00</td>
</tr>
<tr>
<td>Garmin VIRB Elite 270</td>
<td>1,500.00</td>
</tr>
<tr>
<td>SBG Ellipse-N</td>
<td>2,000.00</td>
</tr>
<tr>
<td>Dynon EFIS-D100</td>
<td>2,500.00</td>
</tr>
</tbody>
</table>

### Recommendation

The Arduino Based System is recommended due to its high utility and cost-effectiveness.
Phase I testing simplified.
Spend your first 40 hours of flight flying.
Let us take care of the rest.

**Flight Plan Generator**
Use easyPOH's flight plan generator as a guide to safely and efficiently parameterize your aircraft. Just tell it what your local constraints are, then kick back and relax.

[Download] [More Info]

**POH Generator**
Use easyPOH's pilot's operating handbook graph generator to safely automate the process of determining aircraft parameters such as sink rate, stall speed, and coefficient of lift.

[Download] [More Info]


Backup Slides
Experimental Aircraft Association

Founded in 1953
180,000 members worldwide

Established EAA Flight Advisor Program:

- “Designed to increase sport aviation safety... [for] EAA members who may be preparing to fly unfamiliar aircraft [1]”

The EAA serves the community by:

- “Encouraging affordable flying in a local environment.”

E-AB and ELSA Certification Process

1. **Build Aircraft**
2. **Register the aircraft with the FAA**
3. **Identify and mark the aircraft**
4. **Apply for Airworthiness Certificate**
   - **Phase I Testing:** Flight test the aircraft
   - **Phase II Testing:** Operate and maintain the aircraft
   - **First 40 hours of flight**
     - Develop pilot’s operating handbook
   - **Continued airworthiness**
     - Annual condition inspection

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E-AB Accidents by Phase of Flight (2011)

Loss of control in flight:
“...insufficient takeoff speed, early rotation, or too steep a climb on takeoff led to aerodynamic stalls and loss of control. Inadequate airspeed...also led to aerodynamic stall and loss of control...[2]”

- Takeoff: 9% of fatalities
- Initial Climb: 24% of fatalities
- En Route: 22% of fatalities
- Maneuvering: 22% of fatalities
- Approach: 15% of fatalities
- Other Fatal: 8% of fatalities


Department of Systems Engineering and Operations Research – Senior Design - 2015
Design of a Low-Cost General Aviation Flight Data Recording and Analysis System
E-AB Accidents by Category

Loss of control in flight:
“...insufficient takeoff speed, early rotation, or too steep a climb on takeoff led to aerodynamic stalls and loss of control. Inadequate airspeed...also led to aerodynamic stall and loss of control...[2]”

Data compiled from 2001 - 2010

Annual Increase of E-AB Aircraft

**E-AB aircraft are increasing at a rate of 671 aircraft per year**

**E-AB aircraft are increasing at a rate of .25% annually vs. the General Aviation (GA) Fleet**

Mitigating loss of control in flight risk

“Inadequate airspeed [2]”

Obtaining the data

Maintain level flight at a fixed rpm and altitude

Measurements required

3-axis velocity derived from 3-axis position

Cruise Performance for GT500

Lift Coefficient

\[ C_L = \frac{2mg}{\rho v^2 A}, \text{in steady state} \]  \hspace{1cm} (1)

\[ C_{D0} = \frac{\sin(\gamma_{bg})(mg)}{\rho v_{bg}^2 A} \]  \hspace{1cm} (2)

- \( m \): mass
- \( g \): gravitational constant
- \( mg \): weight (aircraft + cargo + fuel)
- \( \rho \): air pressure
- \( \rho = \frac{(\text{gas constant})(\text{temperature})}{\text{air density}} \): air density
- \( \gamma_{bg} \): best glide angle
- \( A \): wing surface area

\[ \text{Velocity (mph)} \]

\[ \text{Coefficient of Lift} \]
Wind speed: 20 mph

V = 70 mph

V = 90 mph

V = 110 mph

5/12/2015
Raw Data Computation

Each sensor executes independently and concurrently.

Arc Length Formula:
\[L = \int_0^{10} \sqrt{f'(t)^2 + g'(t)^2 + h'(t)^2} \, dt\]

\[= \int_0^{10} 0.0891 \, dt = 0.891\]

\[\frac{0.891 m}{10 s} = 0.0891 \frac{m}{s}\]

adjust for \(\frac{45 m}{s} \rightarrow \frac{45}{0.0891} \approx 505\)
Analyze Raw Data and Reduce Noise

Controller

Model

Raw Data Computation

XML Reader Utility

Simulate Controller

Noise Reduction Algorithm

XML Reader Utility

XML

raw data

Flight Plan

Analyze Raw Data and Reduce Noise

Line Smoothing Algorithm:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Position (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>3</td>
</tr>
<tr>
<td>0.8</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>8</td>
</tr>
<tr>
<td>1.2</td>
<td>9</td>
</tr>
<tr>
<td>1.4</td>
<td>10</td>
</tr>
<tr>
<td>1.6</td>
<td>12</td>
</tr>
<tr>
<td>1.8</td>
<td>14</td>
</tr>
<tr>
<td>2.0</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>21</td>
</tr>
</tbody>
</table>

Array Index:

0 1 2 3 4 5 6 7 8 9

(3+5+8+9+10) / 5 = 7
(12+14+15+18+21) / 5 = 16

Position (m):

<table>
<thead>
<tr>
<th>Raw Data</th>
<th>Compressed Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>XML Reader Utility</td>
<td>Simulation Controller</td>
</tr>
<tr>
<td>XML</td>
<td>raw data</td>
</tr>
<tr>
<td>data request</td>
<td>compressed data</td>
</tr>
<tr>
<td>raw data</td>
<td>raw data</td>
</tr>
<tr>
<td>XML Reader Utility</td>
<td>compressed data</td>
</tr>
</tbody>
</table>

Department of Systems Engineering and Operations Research – Senior Design - 2015
Design of a Low-Cost General Aviation Flight Data Recording and Analysis System
Output Analysis

Uncorrected Data

Position Error (m):
\[ \mu = 8.2 \]
\[ \sigma = 130.1 \]
\[ \sigma^2 = 16,927.8 \]

Velocity Error (m/s):
\[ \mu = 29.6 \]
\[ \sigma = 8,420.4 \]
\[ \sigma^2 = 70,903,209.0 \]

Compressed Data

Position Error (m):
\[ \mu = 6.5 \]
\[ \sigma = 74.6 \]
\[ \sigma^2 = 5,561.4 \]

Velocity Error (m/s):
\[ \mu = 2.9 \]
\[ \sigma = 686.7 \]
\[ \sigma^2 = 471,588.7 \]
Output Analysis

**Uncorrected Data**

Position Error (m):

- \( \mu = 6.3 \)
- \( \sigma = 82.3 \)
- \( \sigma^2 = 6,768.0 \)

Velocity Error (m/s):

- \( \mu = 11.9 \)
- \( \sigma = 3,266.9 \)
- \( \sigma^2 = 10,672,395.7 \)

**Compressed Data**

Position Error (m):

- \( \mu = 6.3 \)
- \( \sigma = 40.1 \) \((105\% \downarrow)\)
- \( \sigma^2 = 1,605.3 \) \((322\% \downarrow)\)

Velocity Error (m/s):

- \( \mu = 1.1 \) \((980\% \downarrow)\)
- \( \sigma = 256.9 \)
- \( \sigma^2 = 65,979.3 \)
Portability Goal Values

**Battery Life**
- Mid Value: 120 min
- Range of Variation: 0 to 1400 min

**Data Storage Capacity**
- Mid Value: 2 GB
- Range of Variation: 0 to 64 GB

**Weight**
- Mid Value: 655 grams
- Range of Variation: 47 to 1360 grams
Suitability Goal Values: Measurement Range

**Accelerometer Range**
- Mid Value: \( \pm 2 \text{ g} \)
- Range of Variation: \( \pm 0 \text{ to } \pm 16 \text{ g} \)

**Barometer Range**
- Mid Value: 3000 m
- Range of Variation: 0 to 9144 m

**Gyroscopic Range**
- Mid Value: 360 degrees/sec
- Range of Variation: 0 to 2000 degrees/sec
Suitability Goal Values: Measurement Sensitivity

**Accelerometer Sensitivity**
- **Mid Value:** 0.1% error
- **Range of Variation:** 0 to 0.35% error

**Barometer Sensitivity**
- **Mid Value:** 15 m error
- **Range of Variation:** 0 to 30 m error

**GPS Accuracy**
- **Mid Value:** 6 m error
- **Range of Variation:** 0 to 8 m error

**Variable Sensitivity**
- **Mid Value:** 2 additional settings
- **Range of Variation:** 0 to 3 additional settings

**Gyroscopic Sensitivity**
- Appareo Stratus 2: .500
- Arduino: .766
- Arduino w/ GPS: .766
- Dynon EFIS-D100: .500
- Garmin Virb: .500
- Raspberry Pi: .766
- Raspberry Pi w/ GPS: .766
- SBG Ellipse-N: .715
- iPhone 6: .766
# Discrete Value Function Descriptions

<table>
<thead>
<tr>
<th>Data Analysis</th>
<th>0</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Manual:</td>
<td>calculations must be done manually from device recording</td>
</tr>
<tr>
<td></td>
<td>2 External Software:</td>
<td>calculations completed by external software</td>
</tr>
<tr>
<td></td>
<td>3 On-Board Processor:</td>
<td>calculations performed on device processor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device Interaction</th>
<th>0</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Screen:</td>
<td>touch-screen display</td>
</tr>
<tr>
<td></td>
<td>2 Button:</td>
<td>device mounted push-button</td>
</tr>
<tr>
<td></td>
<td>3 Extended Button:</td>
<td>push-button attached to extended cord</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device Placement</th>
<th>0</th>
<th>Panel-Mounted: device must be mounted in dash</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Position Mounted:</td>
<td>device must be mounted in a specified position</td>
</tr>
<tr>
<td></td>
<td>2 Level Mounted:</td>
<td>device must be mounted level with the aircraft</td>
</tr>
<tr>
<td></td>
<td>3 Free Mounted:</td>
<td>device may be mounted in any position within aircraft</td>
</tr>
</tbody>
</table>
## Usability Goal Values

### Data Analysis

<table>
<thead>
<tr>
<th>On-Board Processing</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Software</td>
<td>0.857</td>
</tr>
<tr>
<td>Manual</td>
<td>0.286</td>
</tr>
<tr>
<td>None</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Device Placement

<table>
<thead>
<tr>
<th>Free Mounted</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level Mounted</td>
<td>0.714</td>
</tr>
<tr>
<td>Position Mounted</td>
<td>0.143</td>
</tr>
<tr>
<td>Panel Mounted</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Device Interaction

<table>
<thead>
<tr>
<th>Extendable Push Button</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Extendable Push Button</td>
<td>0.714</td>
</tr>
<tr>
<td>Touch Screen Display</td>
<td>0.143</td>
</tr>
<tr>
<td>None</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Project Cost Analysis

![Graph showing cost analysis with Planned Value (PV), Actual Cost (AC), and Earned Value (EV) over time.](image-url)
Performance Index

Time (weeks)

Cost Performance Index (CPI)
Schedule Performance Index (SPI)

Performance Index

0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

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Design of a Low-Cost General Aviation Flight Data Recording and Analysis System

Project Management 1.1
- Project Plan 1.1.1
- Project Schedule 1.1.2
- Budget 1.1.3
- EVM 1.1.4

CONOPS 1.2
- Context Analysis 1.2.1
- Problem Statement 1.2.2

Requirements 1.3
- Fundamental Requirements 1.3.1
- Means Requirements 1.3.2

Data Analysis 1.4
- Gap Analysis 1.4.1
- Risk Analysis 1.4.2

Simulation 1.5
- Aircraft Model 1.5.1
- Develop 1.5.1.1
- Test 1.5.1.2
- Gather Results 1.5.1.3

Design Alternatives 1.6
- Sensitivity Analysis 1.6.1
- Trade-off Analysis 1.6.2
- Cost/Utility 1.6.3

Research/Development 1.7
- Software 1.7.1
- Hardware 1.7.2
- Background 1.7.3

Deliverables 1.8
- Briefings 1.8.1
- Faculty 1.8.2
- Conferences 1.8.3
- Final 1.8.4

Work Breakdown Structure

Flight Recording System 1.0

Fundamental Requirements 1.3.1

Need Statement 1.2.4
# Budget

<table>
<thead>
<tr>
<th></th>
<th>Rates and Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Hours</td>
<td>2,000</td>
</tr>
<tr>
<td>Equipment Cost</td>
<td>$500.00</td>
</tr>
<tr>
<td>Direct Labor</td>
<td>$20.00/hr</td>
</tr>
<tr>
<td>Overhead</td>
<td>$20.00/hr</td>
</tr>
<tr>
<td>G&amp;A</td>
<td>$4.00/hr + $100.00</td>
</tr>
<tr>
<td>Fringe</td>
<td>$2.00/hr</td>
</tr>
<tr>
<td>Fee</td>
<td>$2.00/hr</td>
</tr>
<tr>
<td>Fully Burdened</td>
<td>$48.00/hr + $600.00</td>
</tr>
<tr>
<td>Planned Cost</td>
<td>$96,600.00</td>
</tr>
</tbody>
</table>