Boston University
Electrical & Computer Engineering

EC463 Senior Design Project

User's Manual

Aerobatics Black Box

Submitted to

Dr. Kenneth D. Sebesta
859-648-0272
kenn@cypiltd.com

by

Team 11
Aerobatic Black Box Team

Team Members

Qi Luo	tomqiluo@bu.edu
Yanbo Zhu	zhuyanbo@bu.edu
Eli Carroll	elivc@bu.edu
Maxwell Bakalos	maxbak@bu.edu

Submitted: 4/18/2023

Aerobatics Black Box

Table of Contents

Executive Summary

Aerobatic pilots have trouble visualizing their routines from a viewer's perspective and figuring out which actions they perform result in a successful flight. Our team's solution is an in-flight recording system. After a flight, the pilot can watch the recording back to learn what inputs caused which outputs and improve their abilities.

This project was proposed by our client, Dr. Kenneth Sebesta, who flies an aerobatic plane himself! In order to record the flight, we need to know the plane's position and orientation, as well as the pilot's inputs and the plane's response. We created a cyber-physical system that uses a GPS, IMU (accelerometer & gyroscope), and a camera along with a microcontroller to record the flight. The camera uses an image processing system to read the dashboard dial information and the pilot's maneuvers. After the processing is done, a flight visualization application displays a 3D animation alongside the data values.

1 Introduction

Aerobatics is a type of stunt flying where pilots fly aircraft in unconventional maneuvers, such as loops, rotations, etc. usually done in a specific routine for competition or entertainment. As a pilot, it is difficult to visualize how your movements in the air will be seen from the audience's perspective on the ground. A perfect mid-air loop may look too elliptical on the ground and will fail to impress. Pilots do not know which exact steering angles, speed, and other inputs cause the best flights. Adjusting controls could yield better results, but they have no way of remembering exactly what they did when a flight turned out well. There is no high-tech equipment in the small aerobatic planes that could tell them what they did. The most complex device is often a digital clock!

Our client is an aerobatics pilot who wants to create a flight recording system that can play back the flight as a 3D animation. He is also a professor at BU who has experience with robotics. This animation would show the position of the plane, its orientation, as well as the pilot's inputs and other information as needed. This flight recreation would give the pilot a better understanding of how their aerobatic routine appears to a grounded observer and allow them to improve it.

Existing software will be used to display the flight path animation, so our team is primarily tasked with collecting the data and processing it into a neat format for the software. A BU Senior Design team from last school year started this project, and we are building off their results. However, their entire physical setup has been lost, so we have to rebuild it from scratch. Luckily, their code was mostly saved on GitHub, so we were able to access that for reference, though we will likely rewrite most of it to fit our new equipment.

In order to record all of this data there will be multiple sensors installed on the plane including a GPS to record the location (latitude, longitude, altitude), an accelerometer for acceleration, a gyroscope for orientation (pitch, roll, yaw), and cameras to record dashboard meter values (engine RPM, airspeed, etc), as well as pilot steering and pedal motions. Thus there are two main sections of recording for the project: reading from the sensors we implement (GPS, accelerometer, gyroscope) and reading from the plane's information (cameras). Legally, our system cannot permanently modify the plane, so everything has to be easily detachable and non-invasive. So cameras must be used instead of directly physically accessing the dashboard.

2 System Overview & Installation

2.1 Overview Block Diagram

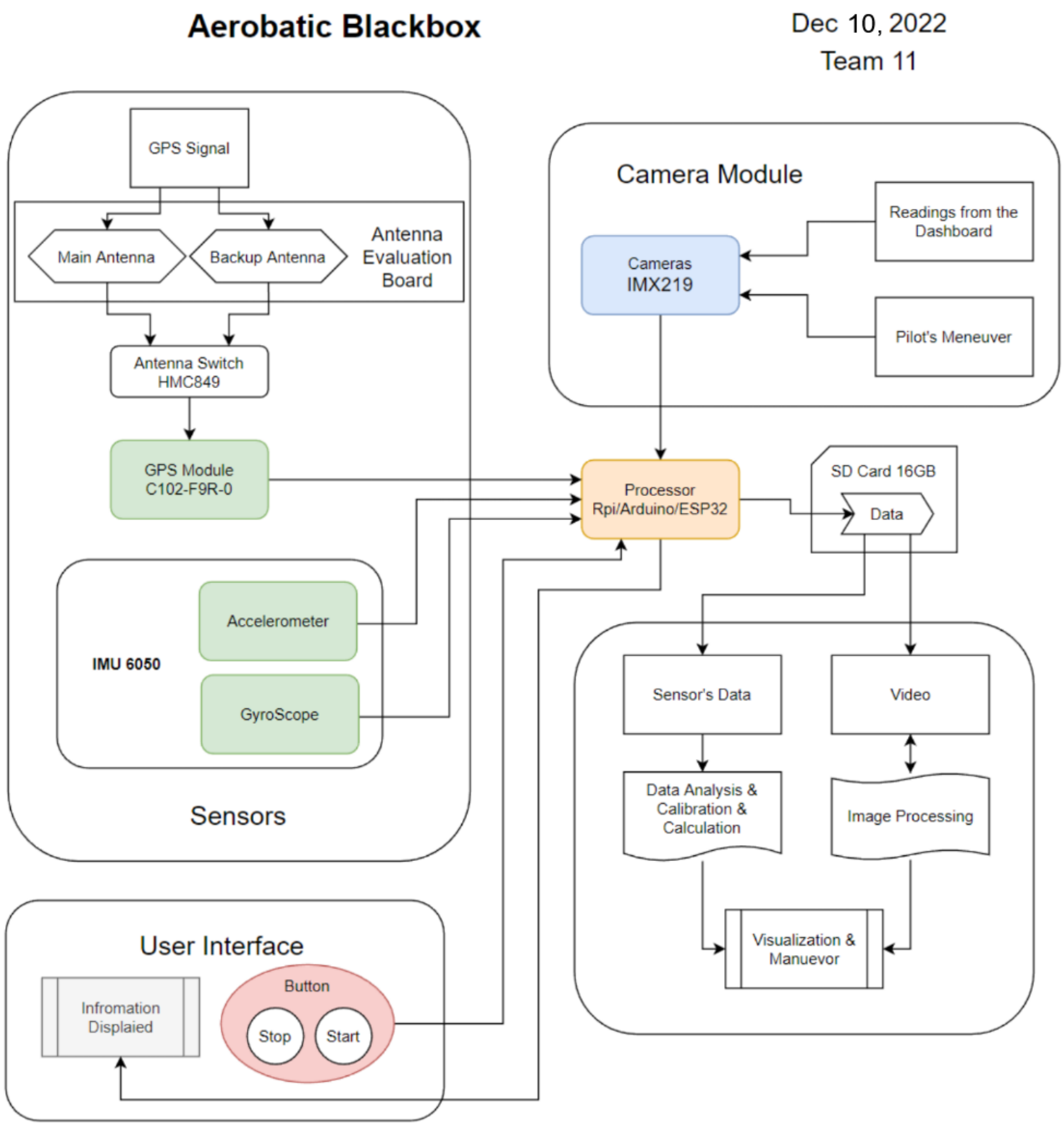

Figure # - System Block Diagram: The device consists of 2 physical parts:(1) the main sensor box, housing the GPS, IMU, user interface, and microprocessor, and (2) the camera module, which holds the camera(s). The main box has an SD card that holds all the collected data. Once the collection is complete, the SD card is put into a separate computer and processed into an animation.

2.2 User Interface

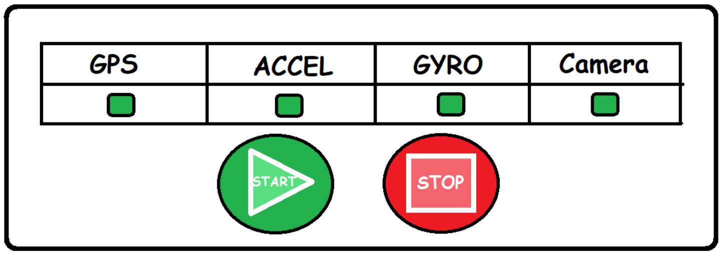

Figure # - Data Display Box: On the main box (includes the GPS, IMU, and processor) there are 4 LED lights that indicate whether or not the specified sensor is active. There is also a start button and a stop button to control the recording process.

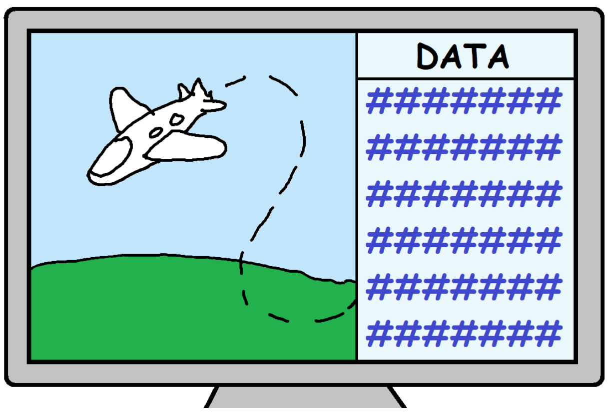

Figure # - Final Flight View in Xplane: The animation of the flight will play along with an updating overlay of some of the data values.

2.3 Physical Description

The black box consists of two components: the main sensor box and the camera module. The main sensor box contains the microprocessor, IMU, GPS, SD card, and user interface. The camera module includes the camera to view the dashboard dials.

2.4 Installation, Setup, & Support

Airplane Installation Steps:

1. Use the strap to secure the main box to the inside of the aircraft.
2. Strap the camera to a location where it can easily see the dashboard.
3. Plug in the device via USB (from a battery or cigarette lighter).

Visualization Installation Steps:

1. Download the Aerobatic Black Box software.
2. Download the X-plane 12 software.

3 Operation of the Project

3.1 Operating Mode 1: Normal Operation

<u>Airplane Operation Steps:</u>

1. Make sure the airplane is in the desired start location.
2. Press the *start button* (start recording).
3. Record the flight.
4. Press the *stop button* (stop recording).

LEDs on the *data display box* will show which sensors are picking up information.

To start a new recording the user simply presses the *start button* again.

<u>Visualization Operation Steps:</u>

1. Remove the SD card from the device.
2. Open the *Aerobatic Black Box* software.
3. Insert the SD card into your computer.
4. Click *Analyze & Format Data* (processes data).
5. Open the .fdr file in Xplane.

3.2 Operating Mode 2: Abnormal Operations

If one or more sensors fail, the recording will continue with the remaining sensors. The LEDs on the *data display box* for the failed sensors will stop glowing.

If adequate power is not provided to the device it will fail to run and no data will be recorded. In this case, the user should reconnect to power and the device will restart its operation.

If data is missing from the flight record, the X Plane visualization will be missing those features, but the rest of the flight information should still be displayed.

3.3 Safety Issues

If the pilot is engaging in complex maneuvers and the user has failed to securely strap in the device, it could cause injury. Before each flight, make sure everything is secured and none of the straps have any tears.

4 Technical Background

The product requires the combination of a variety of parts, including both software and hardware.

System Functions

1) Data Collection and Visualization:

- Collect flight data which includes the position and orientation of the plane.
- Model the plane with 6 degrees of freedom.
- Input this data into X-plane which puts them into a built-in 3D visualizer.

2) Pilot's Maneuver and Its relation to the Plane's Behavior:

- Collect the maneuver and the readings from the instruments using image processing.
- Display it alongside the visualization.

Technical Details

1) Sensors:

a) GPS Module: We are using a GPS module to record the accurate position of the plane. We will use two antennas for the GPS and select the antenna with the strongest signal to feed to GPS. Thus, we ensure that the GPS module is always connected to the satellites even though the plane is upside down.

b) IMU: We are using the accelerometer and gyroscope in the IMU to record the accurate acceleration in 3 axes as well as pitch, roll, and yaw. We will use the acceleration to calculate the position and compare it to the result of GPS. Also, we will use the acceleration to calculate the pitch, yaw, and roll. Thus, we can calibrate both the position and orientation.

c) Cameras: We are using 8MP Raspberry Pi cameras to record everything in the cockpit. The Camera will both record the maneuver of the pilot and the instruments in the cockpit. A stabilization system will prevent them from experiencing unnecessary shaking. We will use image processing to collect the data we need from these videos.

2) Dataflow:

The three sensors are now controlled by three main processors because of the constraints in computational capabilities and power. The GPS module and IMU draw a lot of power. Besides this, the Arduino Due is the only processor that has enough power and memory to use and it can read and write to an SD card with the extended SD card module.

As all the data is stored in the SD card with one file named **text.txt**, we will plug it into our laptop. By using the file conversion program, we will be able to input the position (GPS) and orientation (IMU) data to X-plane 12 and visualize it. Then, we will input the video into our image processing function.

3) Image Processing

Reading the dashboard dials will enable us to record information such as the engine RPM, carb temp, amps, airspeed, altitude, vertical speed, acceleration, etc. directly from the plane's systems. On a separate computer, the video files from each camera will be read into a program that will process each frame and output a numerical result for each dial it focuses on. The data gained from the image processing module will correspond to each data point for the other sensors.

4) Casing

The case is made of black plastic with a ventilation hole design, or thin aluminum alloy plates, to ensure the heat dissipation ability. Multiple openings will exist for USB ports, so cables can be connected with the chip and sensors without opening the box. There will be a shock-damping layer between the outer case and the electrical components to prevent any electrical or wiring damage caused by cockpit vibration. Sensors and chips shall be mounted on the case using screws to ensure stability.

For cameras, a case with some stabilization function to encounter the vibrations from the cockpit and engine will help. It will steady the battery pack as well.

5) Power supply

The major power supply of the black box shall come from the 12V DC cigarette lighter in the cockpit. An adaptor will be used to connect the chip to the power supply. For sensors that are not mounted inside the box, such as cameras, multiple 6V batteries can be used.

GUI (Graphical User Interface)

The interface of our integrated onboard display contains a start button and a stop button. It also displays flight information including the status of all the sensors, their readings, and an indicator showing if everything is working correctly. If some errors occur, the display should also show the errors.

Visualization on our Laptop

After collecting the data of the flight, the algorithm combines the data of the main body of the black box and the readings from the camera to one single .fdr file, which represents the "flight data recorder" file. The file has a specific rule of the sequence of each data, shown as follows. The visualization of the recorded flight is formed based on the "Load a flight" menu on X-plane. It allows the user to upload the .fdr file and to export an animation of the flight.

```
COMM,time,Longitude,Latitude,Altitude,HDG,Pitch,Roll,BaroA,AltMSL,VSpd,TAS,IAS,GndSpd,Stall Warning,flap,flap,OAT,wind,wi
DATA,0,-86.395050,44.533020,8498.7,161.6,-0.1,0.2,30,5755.5,-12.9,148,131.9,137.4,0,0,0,15.2,357,12,19.2,19.3,27.9,0.4,44
DATA,1,-86.394829,44.532410,8497.7,161.9,-0.1,0.5,30,5754.1,-4.3,148,131.9,137.5,0,0,0,15.2,357,13,19.2,19.3,27.9,0.1,44.
DATA,2,-86.394608,44.531803,8497.7,161.8,0,0.4,30,5752.8,-24.8,148,132.1,137.5,0,0,0,15.2,357,13,19.2,19.3,27.9,0.2,44.4,
DATA,3,-86.394371,44.531189,8498.7,161.9,0,0.2,30,5752.9,4.2,148,132.1,137.6,0,0,0,15.2,357,13,19.2,19.3,27.9,0.4,44.4,18
DATA,4,-86.394150,44.530560,8499.7,161.9,0,0.4,30,5752.7,25.8,148,132.2,137.6,0,0,0,15.2,357,13,19.2,19.3,27.9,0.1,44.4,1
DATA,5,-86.393921,44.529949,8498.7,161.9,0,0.2,30,5752.1,18.4,148,132.1,137.7,0,0,0,15.2,357,13,19.2,19.3,27.9,0.3,44.6,1
DATA,6,-86.393715,44.529377,8497.7,161.9,0.1,0.1,30,5751.9,-4.4,148,132,137.7,0,0,0,15.2,357,13,19.2,19.3,27.9,0.5,44.4,1
DATA,7,-86.393478,44.528751,8497.7,161.9,0.3,0,30,5752.5,-22.7,148,132,137.7,0,0,0,15.5,357,13,19.2,19.4,27.9,0.2,44.5,18
DATA,8,-86.393250,44.528141,8496.7,161.9,0.4,0.1,30,5753.2,-35.3,148,131.8,137.7,0,0,0,15.5,357,13,19.2,19.4,27.9,0.5,44.
DATA,9,-86.393036,44.527535,8496.7,161.9,0.5,0.1,30,5753.2,-26.8,147,131.5,137.6,0,0,0,15.5,357,13,19.2,19.4,27.9,0.3,44.
DATA,10,-86.392799,44.526924,8495.7,161.8,0.6,0.1,30,5753.3,-27.6,147,131.3,137.5,0,0,0,15.5,357,13,19.2,19.4,27.9,0.4,44
DATA,11,-86.392571,44.526291,8496.7,161.7,0.7,0.3,30,5753.2,-15.8,147,131.1,137.4,0,0,0,15.5,357,13,19.2,19.4,27.9,0.2,44
DATA,12,-86.392365,44.525726,8495.7,161.6,0.7,0.4,30,5752.8,-4.6,147,130.9,137.3,0,0,0,15.5,357,13,19.2,19.4,27.9,0.4,44.
```

5 Relevant Engineering Standards

1. SAE AS8034: This standard covers the design and installation of electrical wiring and connectors for aerospace applications. This standard helps us ensure that our wiring and connectors are designed and installed correctly.

2. SAE ARP4754: This standard covers the development processes for aircraft and systems. It provides guidance on the development process.

3. SAE AS50881: This standard covers the design and installation of electrical wiring interconnect systems for aerospace applications. It provides guidance on how to design and install the wiring to ensure safety and reliability.

4. ASTM F3172: This standard covers the design and testing of unmanned aircraft systems (UAS). Our development involves a UAS for recording the aerobatic routine.

5. ISO 9001: This standard covers quality management systems.

6. ISO 14001: This standard covers environmental management systems.

7. ASME Y14.5: This standard covers geometric dimensioning and tolerancing (GD&T). It aids our GPS development.

8. ANSI/ISA-5.1: This standard covers instrumentation symbols and identification. It aids our image processing system in analyzing the dials on the plane.

6 Cost Breakdown

1. GPS module and antenna: $368
2. MPU: $10
3. Processor: $20
4. Camera: $204
5. GPIO connector: $15
6. Microcontroller: $70
7. SD Card reader module: $6.99
8. X-Plane 12: $59.99

7 Appendices

7.1 Appendix A - Specifications

- GPS
    - C102-F9R
    - Decimeter accuracy in both position and altitude
    - https://content.u-blox.com/sites/default/files/C102-F9R_UserGuide_%28UBX-20029244%29.pdf
- IMU
    - MPU 6050
    - Degree-precision for orientation of aircraft
    - https://invensense.tdk.com/wp-content/uploads/2015/02/MPU-6000-Datasheet1.pdf
- Camera
    - Fixed-focus, stabilized, 8 MP UVC Camera
    - https://docs.arducam.com/Raspberry-Pi-Camera/Native-camera/source/IMX219DS.PDF
- Microcontroller
    - Arduino Due
    - https://docs.arduino.cc/hardware/due

7.2 Appendix B - Team Information

Maxwell Bakalos: *maxbak@bu.edu, 978-793-3580*

Max is a senior student majoring in electrical engineering at Boston University. His interests include digital image processing, signal processing, computer vision, machine learning, electric vehicles, robotics, computer architecture, electromagnetics, analog circuits, renewable energy, etc. After graduation, Max plans to work and may attend graduate school later on.

Qi Luo: *tomqiluo@bu.edu, 617-763-9599*

Qi is a dedicated senior student majoring in computer engineering at Boston University. His interests span across multiple disciplines, including embedded systems, robotics, real-time computing, and control systems. Qi's ambition is to pursue graduate studies at Carnegie Mellon University, furthering his knowledge and expertise in these fields. His ultimate dream is to make a significant impact on the industry by working as an innovative engineer, pushing the boundaries of performance and technology.

Eli Carroll: *elivc@bu.edu, 413-834-7503*

Eli is a senior studying electrical engineering at Boston University. His primary interests lie in VLSI design and embedded systems. After graduation, Eli plans to pursue a career in hardware design, and perhaps work towards a graduate degree in the future.

Yanbo Zhu: *zhuyanbo@bu.edu, 571-443-9927*

Yanbo is a senior student majoring Electrical engineering at Boston University. His interests span across multiple disciplines, including control systems, analog circuits, mechanical engineering, and modification of cars. He is also a regular participant in track days where he can unleash his driving skills and push his car to the limits. With a clear vision for his future, Yanbo plans to pursue his graduate studies in electrical engineering at the University of Southern California (USC). After completing his graduate program, he aspires to work in the field of control systems, where he can apply his knowledge and expertise to develop cutting-edge technologies that make our lives better and easier.