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Design of a Low-Cost Flight Parameterization System for use by General Aviation

Chad Bonadonna, Donald Brody, and Alejandro Lopez
Department of Systems Engineering and Operations Research
George Mason University
Fairfax, Virginia

Corresponding author's Email: cbonadon@gmu.edu

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Abstract: Experimental Amateur-Build (EA-B) aircraft are 350% more likely to be involved in an accident during the first 40 hours of flight than all other aircraft in the General Aviation (GA) fleet. Pilots must manually collect measurements that are used to develop a pilot's operating handbook, to include emergency procedures. Currently, no system exists to automate the process of recording specific in-flight aircraft measurements, parameterizing the aircraft, and creating the necessary manuals and documents required by the FAA. This project proposes a low-cost flight data recording and analysis system that uses a combination of hardware and software for E-AB pilots to use during the first 40 hours of their testing process that will help reduce error and inconsistencies. Final simulation data will be used to influence the ultimate device requirements for both the microcontroller platform, and inertial and positional sensors.

Keywords: Experimental Amateur-Built Aircraft, Stochastic Modeling, Flight Data Analysis

1. Introduction

The Experimental Aircraft Association (EAA) is a group of aircraft enthusiasts interested in building their own airplanes. The EAA created the Flight Advisors program which, "is designed to increase sport aviation safety by developing a corps of volunteers who have demonstrated expertise in specific areas of flying and making them available to EAA members who may be preparing to fly an unfamiliar aircraft. ("Experimental Aircraft Association," n.d.)" One emphasis of this program is to assist pilots preparing for flight in a newly built or restored aircraft. Chapter 571 of the EAA, located in Annapolis Maryland, has tasked us with creating a low-cost general aviation flight data recording and analysis system. The purpose of the system will be to assist in determining aircraft flight characteristics. This system will promote one of the EAA's fundamental goals, increasing aviation safety.

1.1 Experimental Aircraft

The Federal Aviation Administration (FAA) may issue special airworthiness certificates for aircraft that do not have a type certificate, or aircraft that do not conform to their type certificate, and are safe for operation. These aircraft fall under the FAA's experimental aircraft category, if they can be certified for any of the following purposes in accordance with (IAW) FAA Title 14 paragraph 21.191 ("14 CFR," 2004a):

1.2 Flight Data Recording and Analysis System

Flight data analysis systems are critical to the successful completion of phase I flight-testing, the first 40 hours of flight that EA-B pilots must complete to obtain their aircraft's airworthiness certificate. Pilots require in-flight aircraft measurements to properly determine their aircraft parameters for entry into their pilot's operating handbook. Proper aircraft parameterization is critical to the flight safety of amateur-built aircraft operation.

2. Decision Making Factors

The EAA created the Flight Advisor's Program to assist amateur builders in developing a set of flight plans for phase I flight-testing. This approach by the EAA has the benefit of creating a custom procedure that is tailored to fit the specific needs of the pilot and the aircraft, but falls short in the area of efficiency.

The FAA developed Advisory Circular (AC) 90-89A to be used as a reference guide for amateur builders when developing their phase I flight-testing program ("AC 90-89A," 1995). AC 90-89A additionally sets forth the maneuvers required by the FAA to be completed during phase I flight-testing to demonstrate that the aircraft can safely operate within its flight envelope; however, this AC is general in nature and does not conform to the needs of the individual pilots or aircraft, nor does it take into consideration locational constraints or operational restrictions of the aircraft.

This lack of standardization results in inconsistent flight plans for individual amateur builders during their phase I flight-testing. Inconsistency within the development of flight plans ultimately leads to a significant potential source for error in determining aircraft parameters before the pilot has even left the ground.

2.1 Recording Devices

Currently, no device exists to automate the process of recording specific in-flight aircraft measurements for amateur builders. The FAA recommends that amateur builders use a tape or video recorder to record measurements or tasks while in flight ("AC 20-27G," 2009). Pilots often use either a GoPro position-mounted to record panel measurements, or simply attach a pad of paper to their thigh and manually record instrument readings with a pen while in flight. Manually compiling data from either a video recording or pen and paper is imperfect at best, and introduces the potential for additional sources of error when manually parameterizing the aircraft.

2.2 Loss of Control in Flight

Loss of control in flight accidents are a major concern for amateur builders, and will be a major topic of discussion throughout the remainder of this report. Loss of control in flight accidents are a usually a result of insufficient takeoff speed, early rotation, too steep of a climb on takeoff, inadequate airspeed management during approach or landing, and are generally the result of aerodynamic stalls ("NTSB/SS-12/01," 2012). We believe many loss of control in flight accidents could be prevented if these amateur pilots were able to properly parameterize their aircraft; however, our opinion is insufficient evidence to act on. If our assumption is correct, there should be evidence of a higher E-AB accident rate during phase I flight-testing than all other non E-AB aircraft in the GA fleet. Additionally, there should be evidence of an overall higher rate of fatal E-AB accidents than all other non E-AB aircraft due to the high number of fatal accidents caused by loss of control in flight.

3. Problem and Need Statements

3.1 Gap Analysis

As expected, the E-AB accident rate, during their first 40 hours of flight, is significantly higher than all other combined aircraft in the GA fleet. From 2001-2010, E-AB aircraft were 350% more likely to be involved in an accident than their non-E-AB counterparts ("NTSB/SS-12/01," 2012). Additionally, properly parameterizing their aircraft during the first 40 hours of flight will likely reduce the overall risk of being involved in an accident over the entire life of the aircraft.

As of 2010, E-AB aircraft are 123% more likely to be involved in an accident, and 238% more likely to be involved in a fatal accident than all other aircraft in the GA fleet. Loss of control in flight accidents have been a major ongoing problem due to the correlation between the significantly higher fatal accident rate among E-AB aircraft, and the overwhelmingly high percentage of fatal E-AB accidents that are a result of loss of control in flight during the same timespan, 2001-2010 ("NTSB/SS-12/01," 2012).

3.2 Problem Statement

There exists a lack of proper tools for amateur aircraft builders to properly parameterize their aircraft during phase I flight-testing. Improper parameterization results in a high potential for fatal loss of control in flight accidents.

3.3 NTSB Recommendation

The NTSB has recognized the same problem, and determined that the use of "…recording devices can significantly enhance the efficient accomplishment of flight test objectives, as well as 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. ("NTSB/SS-12/01," 2012)"

3.4 Need Statement

There exists a need for a low-cost general aviation flight data recording and analysis system designed specifically for the purpose of parameterizing amateur-built aircraft.

4. Concept of Operation

Amateur builders are in need of a low-cost alternative to the currently available monitoring systems. The system should be designed for general aviation use to maximize the potential market share, despite being purpose built for amateur aircraft builders. The system should be capable of flight data recording to automate the process of aircraft measurement collection, and reduce the potential for error. The system should also be an analysis system capable of automating the parameterization process, thus further reducing the potential for error in parameterization.

4.1 Flight Plan

The first piece of this system will need to be a set of flight plans specifically tailored to the individual needs of each amateur builder. These flight plans will be designed to take a pilot through the first 40 hours of flight in their new aircraft. Pilots will be able to input parameters that their flight plans must adhere to. These parameters will include locational constraints, operational restrictions, preliminary aircraft parameters, and pilot ability level. The flight plans will automatically update following each flight based on maneuvers completed and aircraft parameters that have been determined. The proposed flight plan generation subsystem will be generated to the requirements set forth by FAA AC 90-89A ("AC 90-89A," 1995).

4.2 Device

The second piece of the proposed system will be a flight-recording device capable of taking all necessary in-flight measurements required for proper aircraft parameterization. Special consideration will be given to specific human factors needs of the amateur builders. One such consideration will be device placement. Currently aircraft instruments must either be panel mounted, or level mounted with the aircraft. These stipulations create complications for amateur-built aircraft, which are often smaller in size. The device will be capable of taking accurate readings from any mounted position in the aircraft.

Pilots will take the device into flight while completing each individual flight plan. The device will collect the data needed for aircraft parameterization in a format that is easily transferable to post-flight simulation software for analysis.

4.3 Software

The software sub-system will be the heart of the analysis system. This system will receive and analyze data from the device sub-system. The purpose of the data analysis is multi-faceted, but has the primary purpose of parameterizing the aircraft. The proposed software will additionally store data from all flights, generate and update flight plans for each flight, generate and maintain a set pilot's training records, and generate and maintain a pilot's operating handbook.

The pilot's training records will not only satisfy the FAA's requirement for a pilot's logbook IAW AC 20-27G, but address additional safety considerations ("AC 20-27G," 2009). The training record will document general flight data for each flight, while additionally notifying the amateur builder of any errors that pose a heightened risk for loss of control in flight accidents. For example, if a pilot were to take off at 1.1 times stall velocity, this could be considered insufficient takeoff speed and potentially lead to a loss of control in flight accident. The software would be able to detect this error, and recommend a safer takeoff velocity for the pilot's subsequent flights, somewhere around 1.3 times stall velocity.

The pilot's operating handbook would fulfill FAA requirements IAW AC 20-27G, including the development of aircraft emergency procedures ("AC 20-27G," 2009). These handbooks will be designed to meet FAA requirements without the need to seek guidance or consultation from local FAA offices.

5. Design Alternatives

5.1 Currently Available Monitoring Alternatives

There are currently several monitoring devices available to E-AB aircraft pilots that can be force fitted to meet their specific needs of aircraft parameterization. A representative sample of these devices includes the Garmin VIRB Elite, Dynon EFIS-D100, SBG Ellipse-N, and Appareo Stratus 2.

The Garmin is a camera that can be position mounted to record aircraft panel instruments while in flight, which allows for manual post-flight analysis. The camera also has extra sensors that could be used to aid in post flight analysis including; Accelerometer, Barometer and a GPS.

The Dynon is an AHRS that fits directly into the aircraft instrument panel, and ties into to aircraft subsystems for additional monitoring capabilities. This instrument has an on-board microprocessor, which makes it capable of performing in-flight analysis of aircraft measurements. This instrument is not, however, capable of recording data for post-flight analysis.

The SBG is a MEMS driven device that is capable of connecting to a separate computer for in-flight aircraft measurement analysis. There is no on-board processing, data recording, or post-flight analysis ability.

The Appareo is an AHRS device that connects via Wi-Fi to an iPhone or iPad for in-flight aircraft measurement analysis. The Appareo does have on-board processing, data recording, and post-flight analysis ability.

5.2 Low-Cost Monitoring Alternatives

Several low-cost monitoring alternatives have been determined to act as the base of the subsystem. These alternatives were chosen as a representative sample of technologies capable of handling the data collection and storing required to meet the needs of the pre-defined system.

The Arduino microcontroller is a popular option for many different applications including robotics. One important note is that the Arduino is a microcontroller, which means it is an analog device with no on-board processing ability. Both configurations considered during alternative analysis are equipped with a 3-axis accelerometer and gyroscope, barometer, thermometer, and data logger. One configuration is additionally equipped with a GPS unit.

The Raspberry Pi microprocessor is a popular option for many different applications including use as the base of a simple home built computer. The Raspberry Pi differs from the Arduino mainly due to the fact that it is a digital device capable of on-board processing. Both configurations considered during alternative analysis are equipped with a 3-axis accelerometer and gyroscope, barometer, thermometer, data logger, and a 5.5” touch-screen. One configuration is additionally equipped with a GPS unit. The touch-screen was originally added to this alternative to fully use the ability of its on-board processing unit.

Many smart phones on the market today have accelerometers and gyroscopes capable of taking the necessary inertial readings for aircraft parameterization; however, only a few come equipped with the barometer necessary to take altitude measurements. Of the phones equipped with all of the necessary technology, the iPhone 6 has by far the largest market share. This makes the iPhone 6 is the most logical choice for use as a device prototyping alternative within the smartphone market.

5.3 Utility/Cost Analysis

Following the development of a value hierarchy that reflects the specific needs of amateur aircraft builders, and the elicitation of swing weights from one of our decision makers, analysis was made of the utility verses cost of our prototyping alternatives against the currently available monitoring systems. It was immediately apparent that the low-cost monitoring alternatives had significantly higher utility and far lower cost than the currently available monitoring systems.

Following this analysis, the decision was made to begin prototyping with the Arduino microcontroller configured with GPS. This alternative had the highest utility at approximately .95, and the second lowest cost at $105. This device significantly exceeds the FAA flight instrument requirements, meets the device subsystem portability design goals, and comes in well under the prototyping cost design goal.

6. Design of Experiment

For this project we seek to develop recommendations for a device that would help EA-B aircraft pilots determine flight characteristics for their aircraft. We developed a simulation that outputs recommendation for device requirements given sensitivity and accuracy of each sensor. To develop a pilots operating handbook we will use actual flight data, from a QuickSilver GT500, derived from a video using the Garmin VIRB Elite Camera. This will record the aircraft’s instrument panel while also giving us GPS coordinates to air in the post flight analysis. Post flight we will manually enter this data into a simulation or spreadsheet that will use this raw data to output flight characteristics. These derived flight characteristics will be compiled and put into a pilots operating handbook.

7. Simulation

This project uses simulation, to include stochastic modeling, to establish a quantifiable set of device requirements moving forward. The purpose of the simulation is to model device sensor readings and their associated error. Device and sensor requirements are based on an acceptable error threshold of 2.5% across all components.

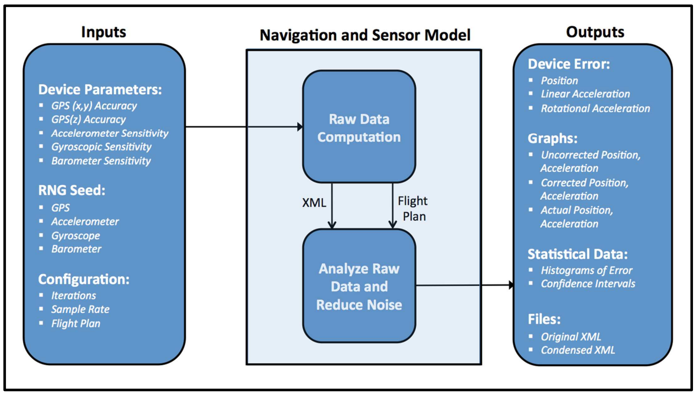

Figure 1. Simulation Architecture

Inputs are separated into device parameters, random number generator (RNG) seeds, and. The device parameters are the accuracy and sensitivity specifications of the modeled sensor configuration for the device. One important note is that the model takes into account that GPS accuracy must be broken down into its x and y components, and its z component. The reason for this is that GPS has a greater level of accuracy in its horizontal components (usually around 6 meters), than it does in its vertical component (usually around 15 meters). For that reason, the model is built to determine position error using GPS for all three axes, as well as comparing the z component of the GPS with altitude determined by barometric pressure and temperature. This distinction is used to determine whether a barometer and thermometer will be required for the final device requirements.

The raw readings recorded from the sensors are not continuous and contain random error. The modeled sensors record a discrete number of measurements per second determined by the user and are placed in an .xml file. Using a proprietary noise reduction algorithm the error created by these sensors can be greatly reduced. This algorithm accepts any number of readings per second, then averages the readings over a one second range and compresses that data down to one reading per second. Several methods of line smoothing were analyzed prior to finalizing the design decision. The method shown in Figure 2 produces the lowest error of the four methods analyzed.

Outputs are broken down into the three categories of statistical data associated with device error, graphs, and files. The statistical data associated with device error will be discussed in greater detail in the following results section.

8. Results

The initial decision analysis of this project determined that an Arduino Uno microcontroller would be the best prototyping platform for the device subsystem. Following weeks of disappointment with this platform, it was determined that the Arduino Uno had insufficient memory to meet the needs of a prototyping device. Additionally, the device output was prone to error. These setbacks inspired the design of a simulation to model what the Arduino was supposed to accomplish as a prototyping device. Fortunately the Arduino was not a complete loss, as sufficient data was obtained from the device sensors to determine a realistic error distribution for use in the simulation model.

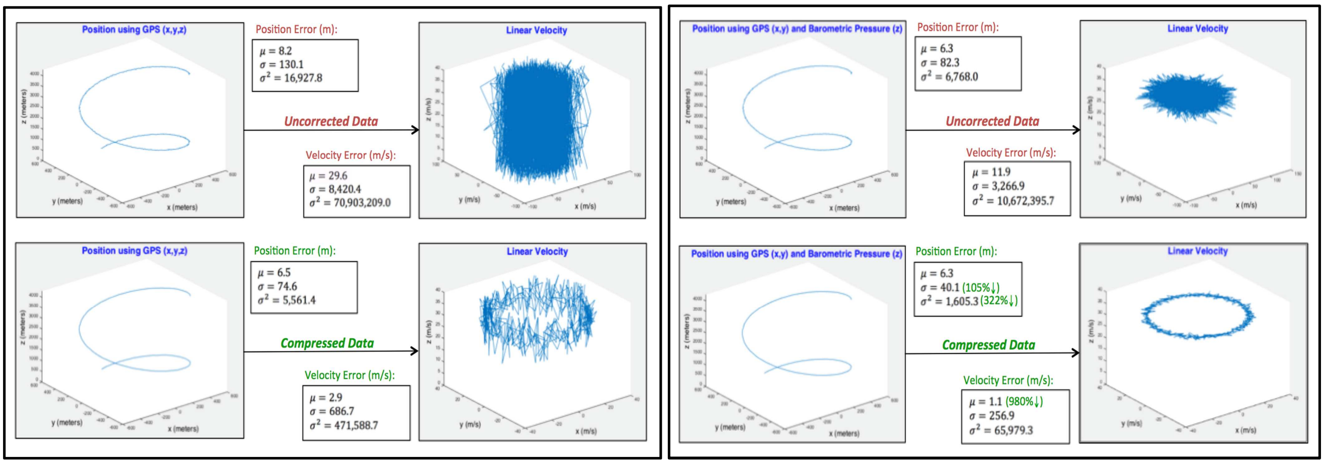

Figure 2. Comparison of GPS z vs Barometric Pressure z Error Correction

GPS position error is standardized across all low-cost commercial sensors due to their reliance on an outside system of satellites used to determine global position. For this reason, the x and y component accuracy of aircraft position are locked at 6 meters, and the z component accuracy is locked at 15 meters. One common way to improve positional accuracy is to measure aircraft altitude by measuring barometric pressure and temperature. This method is capable of calculating altitude with an accuracy of .25 meters.

Uncorrected position determined from GPS sensors for x, y, and z components were found to have a mean magnitudinal error of $\mu = 8.2$ meters, a standard deviation of $\sigma = 130.1$, and a variance of $\sigma^2 = 16{,}927.8$. Smoothing and compressing this data reduces these error outputs to $\mu = 6.5$ meters, $\sigma = 74.6$, and $\sigma^2 = 5{,}561.4$. The main benefit here is the significant reduction of standard deviation and variance, which leads to compounding error reduction in velocity determination. The resulting mean magnitudinal velocity error determined from raw positional data comes to $\mu = 29.6$ m/s, which can be reduced to a mean magnitudinal velocity error of $\mu = 2.9$ m/s when using the condensed positional measurements.

Uncorrected position determined from GPS sensors for the x and y positional components, and barometric pressure to determine altitude, were found to have a mean magnitudinal error of $\mu = 6.3$ meters, a standard deviation of $\sigma = 82.3$, and a variance of $\sigma^2 = 6768.0$. Smoothing and compressing this data reduces these error outputs to $\mu = 6.3$ meters, $\sigma = 40.1$, and $\sigma^2 = 1605.3$. The resulting mean magnitudinal velocity error determined from raw positional data comes to $\mu = 11.9$ m/s, which can be reduced to a mean magnitudinal velocity error of $\mu = 1.1$ m/s when using the condensed positional measurements. In this case, there is no improvement mean positional error; however, the use of line smoothing still halves the standard deviation, which in turn leads to a vast improvement in the determination of velocity.

Because our error threshold is set to 2.5%, and our measurements are taken at a simulated velocity of 45 m/s, our acceptable error threshold is 1.125 m/s. Based on this criteria it is determined that the use of a barometer and thermometer to determine altitude is required in the final proposed device subsystem, and is to be used in conjunction with the previously defined noise reduction algorithm.

The simulation will output an error for each sensor for every time the simulation is run. To find the sensitivity requirement of the gyroscope and accelerometer we ran the simulation for different values sensitivity input values to graph the error against the sensitivity of the sensor. Before being able to derive requirements we had to determine the threshold for both the sensors. At a rotational velocity of 360°/s, the established 2.5% threshold requires the gyroscopic error to be within 9°/s. At a linear acceleration of 20 m/s^2, the established 2.5% threshold requires the accelerometer error to be within 0.50 m/s^2. For both the gyroscope (1) and the accelerometer (2) the relationship between the error and sensitivity were perfectly linear given by the following equations, where “T” is the required threshold for the sensor and “s” is the sensitivity.

$$T = 108.18s + 0.2857 \quad (1)$$
$$T = 2.9s + 0.0268 \quad (2)$$

After replacing 9°/s in for T in equation (1) we find the required sensitivity for the gyroscope to be 0.08%. Similarly, replacing 0.50 m/s^2 in for T in equation (2) we find the required sensitivity for the accelerometer to be 0.16%. Moving forward we will use the requirements, in table 1, derived from the simulation to build and test a prototype for a flight data recording analysis system used to help E-AB pilots determine flight characteristics during phase 1 testing.

Table 1. Flight Data Recorder Sensor Requirements

Sensor	Sensitivity
GPS (x,y)	6 meters
Barometer/Thermometer	0.25 meters
Gyroscope	0.08 %
Accelerometer	0.16 %

10. Conclusions and Recommendation

The recommendation moving forward is to continue to prototype with the Arduino Mega microcontroller to be used for in-flight testing and post flight analysis. Developing this system on the Arduino platform will allow for the device to be manufactured at a low cost. Furthermore, it is recommended to start developing software that will interface with the output from the Arduino device for further data analysis on a desktop computer. This software will analyze the in-flight data as well as develop a pilot’s training record and a pilots operating handbook for submittal to the FAA to obtain the aircraft’s airworthiness certificate. The system will make the current phase 1 testing process obsolete by automating the process of determining in flight aircraft characteristics without the need for manual input by the pilot while flying. The ultimate goal of this system is to streamline the process of phase 1 flight-testing for experimental aircraft as well as increase sport aviation safety by giving pilots the information they need to fly safely. The information that the completed system will allow experimental aircraft pilot’s to understand the limitation of their aircraft thus, reducing loss of control in flight accidents.

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