

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

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**Abstract**— Aircraft enthusiasts who desire to build and fly their own 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 (POH), 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 documentation 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 experimental amateur built (E-AB) aircraft 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.

## INTRODUCTION

### *I. Experimental Aircraft Association (EAA)*

The EAA was founded in 1953 with a group of aircraft enthusiasts interested in building their own airplanes. The EAA demonstrated their desire to promote aviation safety by creating the Flight Advisors program in July of 1994. “The Flight Advisors program 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. [1]” 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 the project team 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.

### *II. 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. Since its

inception, there has been an average increase of 756 certified experimental aircraft per year, as well as an increase of .26% annually compared to the general aviation (GA) fleet [3].

### *III. Flight Data Recording and Analysis System*

Flight data analysis systems are critical to the successful completion of phase I flight-testing. Pilots require in-flight aircraft measurements to properly determine their aircraft parameters for entry into their POH. Proper aircraft parameterization is critical to the flight safety of amateur-built aircraft operation.

The Federal Aviation Agency, currently known as the Federal Aviation Administration (FAA), first recognized the importance of flight data analysis systems in their 1947 technical standard order (TSO) – TSO C4c – regulating minimum standards for civil aircraft bank and pitch instruments [4]. This TSO was last updated in 1958, and still serves as the current regulatory standard for mechanically operated gyroscopic flight instruments; however, newer attitude heading reference systems (AHRS) technology makes use of solid state or microelectromechanical system inertial measurement units (MEMS IMU’s) to take readings using digital or analog accelerometers and gyroscopes, before processing that information with an on-board micro-processor, and sending it to a digital display located in the aircraft cockpit instrument panel. The FAA regulates minimum digital AHRS requirements in TSO-C201 [5], and advisory circular (AC) supplement AC 20-181 [6]. These documents were published in 2012 and 2014 respectively.

## 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.

The FAA developed AC 90-89A to be used as a reference guide for amateur builders when developing their phase I flight-testing program [7]. 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.

### I. 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 video recording 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 controlling and parameterizing the aircraft.

### II. 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 [8]. Many loss of control in flight accidents could be prevented if these amateur pilots were able to properly parameterize their aircraft. 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 percentage of fatal accidents caused by loss of control in flight.

## PROBLEM AND NEED STATEMENTS

### I. 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).

### II. Problem Statement

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

### III. NTSB Recommendation

“...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. [8]”

### IV. 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.

## CONCEPT OF OPERATIONS

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.

### I. Flight Plan

This system will need a set of flight plans specifically tailored to the individual needs of each amateur builder. The flight plans will be designed to take a pilot through the first 40 hours of flight in their 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 flight plans, though individually customizable, will be generated in a manner that adheres to the requirements set forth by FAA AC 90-89A [7].

### II. Device

The second piece of the 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 ergonomic 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 generally smaller in size. This device

should 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.

### *III. 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 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 POH.

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 [9]. 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, around 1.3 times stall velocity.

The POH would fulfill FAA requirements IAW AC 20-27G, including the development of aircraft emergency procedures [9]. This feature offers the added benefits of proper aircraft parameterization, and creating a standardized format for submittal to the FAA. These handbooks would be guaranteed to meet FAA requirements without the need to seek guidance or consultation from local FAA offices.

## **DESIGN ALTERNATIVES**

### *I. Currently Available Monitoring Alternatives*

There are currently several monitoring devices available to E-AB aircraft pilots that can be force fit to meet their specific needs of aircraft parameterization.

The Garmin Virb 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 Garmin is affordable, at \$270, but does require the pilot to do manual calculations post flight.

The Dynon is an AHRS that installs into an aircraft instrument panel, and ties into to aircraft subsystems for additional 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 Dynon has a high cost of \$2,600, which does not include the cost of installation.

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 SBG costs \$4,000 before purchasing a computer that runs the software needed to record the data.

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 for \$900.

### *II. 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 storage 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 is an analog device without 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 Arduino prototyping cost is \$120.

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. The Raspberry Pi prototyping cost is \$175.

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 the most logical choice for use as a device prototyping alternative within the smartphone market. The cost of purchasing an iPhone 6 is \$650.

## **DESIGN OF EXPERIMENT**

This project seeks to develop recommendations for a device

that would help EA-B aircraft pilots determine flight characteristics for their aircraft. A simulation was developed that outputs recommendation for device requirements given sensitivity and accuracy of each sensor. Actual flight data will be used to develop a POH from a QuickSilver GT500, derived from a video using the Garmin Virb Elite Camera. This will record the aircraft's instrument panel while also outputting GPS coordinates to use in the post flight analysis. This data will be manually entered post flight spreadsheet that uses this raw data to output flight characteristics. These flight characteristics will be compiled and put into a POH.

**PILOT'S OPERATING HANDBOOK**

The POH for an aircraft is a concise reference book that provides specific information about their aircraft to the pilot. Along with basic facts about the aircraft, the POH will include aircraft limitations and graphs to let the pilot know how the aircraft preforms under varying conditions.

A prototype POH will be created for this project by obtaining readings from a Quicksilver GT500 with a R912UL powerplant and comparing the results obtained to the official POH for this aircraft to verify the results.

To create the prototype POH the pilot must fly a series of flight tests with a camera mounted at the instrument panel of the aircraft and perform the maneuvers specified in the flight test. Post flight the gauges of the instrument panel can be monitored via the video and the relevant information can be recorded into a spreadsheet application for further analysis.

This prototype will include graphs and charts to evaluate an aircrafts cruise performance, rate of climb, stall speed, and lift and drag coefficients. Rate of climb will be recorded by instructing the pilot to fly at full engine power to a series of different altitudes at varying flap positions from this data graphs of the feet per minute (FPM) the aircraft can climb at various altitudes can be created.

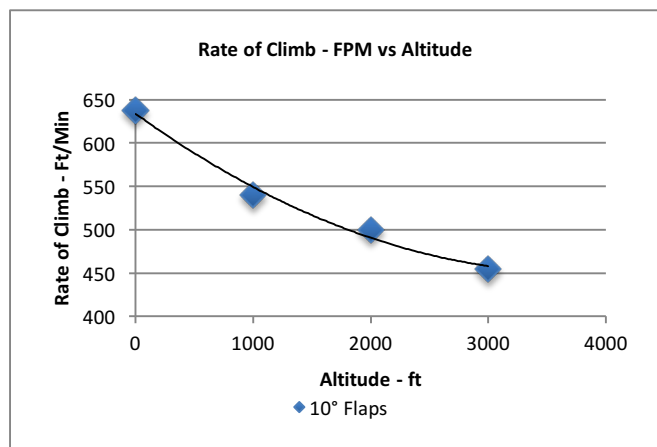


FIGURE 1  
QUICKSILVER GT500 RATE OF CLIMB

Cruise performance will be determined by having the pilot fly at a constant altitude with a constant powerplant RPM to compare and graph airspeed at different RPM and different altitudes.

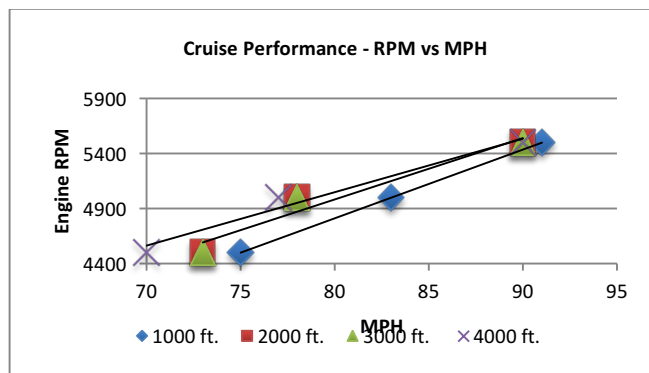


FIGURE 2  
QUICKSILVER GT500 CRUISE PERFORMANCE

The preliminary flight plans also include tests to determine stall speeds and varying flap positions and bank angles. The flight plans specify that the pilot be at a safe altitude to perform these tests where they must recover from a potential stall.

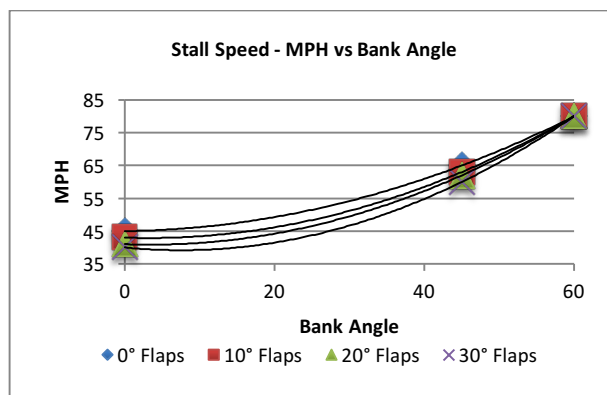


FIGURE 3  
QUICKSILVER GT500 STALL SPEEDS

An analytical approach was taken to determine the lift coefficient (C<sub>L</sub>) and parasitic drag coefficient (C<sub>D0</sub>) of an aircraft [10].

$$C_L = \frac{2mg}{\rho v^2 A}, \text{ in steady state} \tag{1}$$

$$C_{D0} = \frac{\sin(\gamma_{bg})(mg)}{\rho v_{bg}^2 A} \tag{2}$$

- m*: mass
- g*: gravitational constant
- mg*: weight (aircraft + cargo + fuel)
- ρ* =  $\frac{\text{air pressure}}{(\text{gas constant})(\text{temperature})}$  : air density
- gas constant*: 287.05 for dry air
- v*: velocity
- v<sub>bg</sub>*: best glide velocity
- A*: wing surface area

$Y_{bg}$ : best glide angle

The assumptions must be made to generalize the conditions the aircraft will be in. While the aircraft is in steady state the lift of the aircraft is exactly equal to the weight of the aircraft, cargo, and fuel. Then air density must be calculated, which varies depending on the weather in the location the pilot is flying in, however the International Standards on Atmosphere (ISA) have a standard for dry air that can be used for generalizing this condition for varying altitudes. The air pressure was graphed versus velocity and had a trend line fit so that air pressure could be found easily for varying altitudes. The graph for the velocity vs. lift coefficient plot is below. It can be noted that the max lift for this aircraft is approximately 1.3, which occurs at stall velocity and is similar to a Clark Y airfoil.

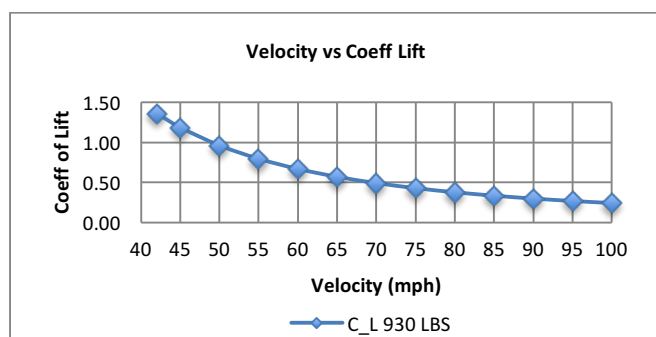


FIGURE 4  
QUICKSILVER GT500 LIFT COEFFICIENT

John T. Lowry looked to also solve the problem of high accident rates in the light aircraft category by developing what he calls “The Bootstrap Approach.” The Bootstrap Approach (TBA) is a method that lets any pilot calculate his or her airplane's performance numbers. These numbers include performance for any gross weight at any density altitude. Lowry's method uses simple flight tests where the pilot would record some important data that can then be plugged into an Excel spreadsheet to determine aircraft characteristics that an aircraft manufacturer would not normally provide [10]. TBA allows the pilot to easily calculate the parasitic drag coefficient of an aircraft as well as thrust to drag ratio, and sink rate.

The results of the preliminary testing have led to the recommendation of using a combination of a video camera such as the Garmin Virb to record an aircraft instrument panel and implementing parts of TBA to develop a POH that will allow pilots to “fly by the numbers.” This model has been tested with three aircraft (Quicksilver GT500, Cessna C152, Rans S-7C) to compare how different aircraft affect the output. Initial results of this model have produced the following graphs for thrust to drag ratio and rate of sink.

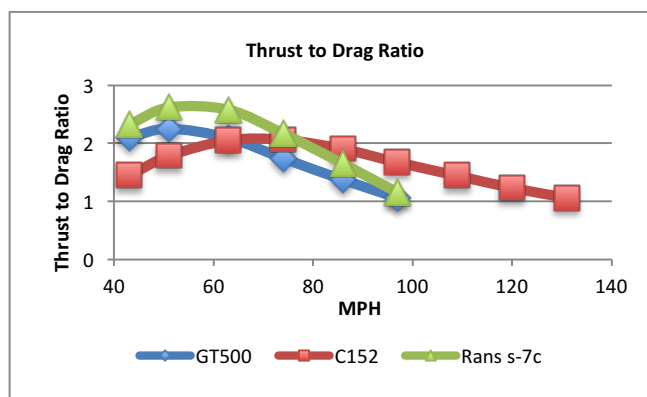


FIGURE 5  
COMPARISON OF THRUST/DRAG VS AIRSPEED

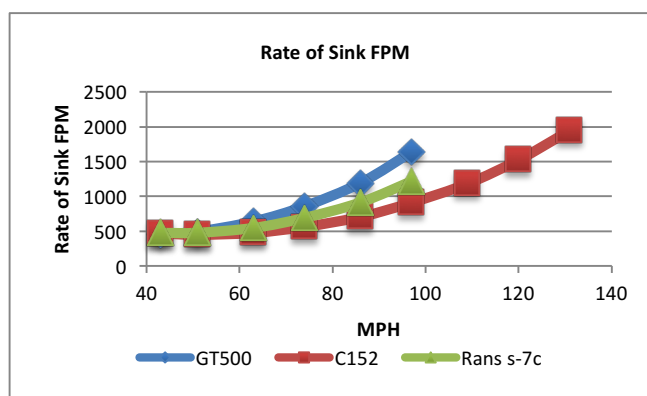


FIGURE 6  
COMPARISON OF RATE OF SINK VS AIRSPEED

### UTILITY VS. 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 the decision maker, analysis was made of the utility versus cost of the 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 Uno microcontroller configured with GPS. This alternative had the highest utility at approximately .95, and the second lowest cost at \$120. 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. Unfortunately the initial prototype did not have sufficient random access memory (RAM) to process the necessary real-time sensor data, however, the failed prototype did give the necessary data needed to help form requirements and ultimately lead to a recommendation.

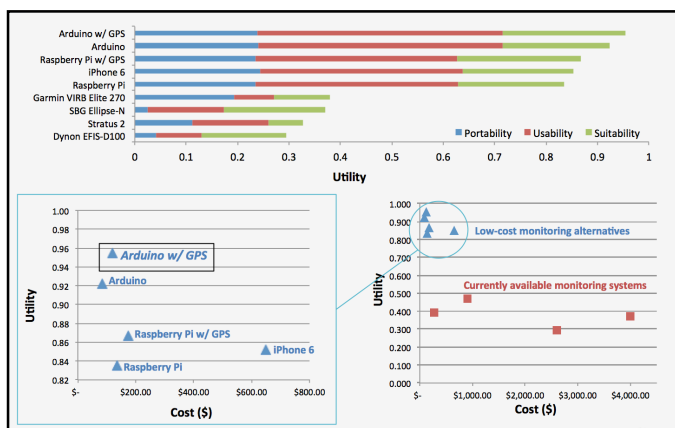


FIGURE 7  
UTILITY VS. COST ANALYSIS

Fortunately Arduino makes another microcontroller, the Mega, which has four times the RAM of the Uno, and costs only fifteen dollars more. This additional memory meets the memory requirements established during simulation [11]. With the new price point, substituting the Arduino Mega for the Uno still maintains the utility established during the decision analysis phase, and is still the second lowest priced alternative.

One important side note is that strap down methods such as the Stratus 2 alternative and the Arduino platform developed for this project have their shortcomings. True airspeed of the aircraft cannot be obtained while in flight without additional equipment to determine wind speeds around the aircraft. The GPS velocity can only obtain speed over the ground. This will cause some calculation error that cannot be corrected without the wind speed data. Many of the calculations require knowing the indicated airspeed of the aircraft, so it is critical to know the wind speed to help reduce error in the POH calculations. The low cost option that can gather data from the instrument panel is a video recording option such as the Garmin Virb; however, it is possible to estimate the average wind speed of the flight with the strap down devices by incorporating a box pattern at the beginning and end of each flight. The device and subsequent analysis software will be able to estimate wind speed by analyzing fluctuations in velocity while the pilot maintains a constant throttle position throughout the box pattern.

### CONCLUSION AND RECOMMENDATIONS

For the purposes of prototyping it is recommended that the Garmin video monitoring and Lowry Bootstrap method as a proof of concept; however, moving forward it would be best to build a complete system that automates the process of phase I testing using a microcontroller like the Arduino Mega as a base for the device subsystem. Automating this process will eliminate the need for pilots to manually compile their flight plans, data, and analysis in an effort to increase aviation safety.

The following table lists the device requirements derived from simulation for this system moving forward [11].

TABLE 1  
FLIGHT ANALYSIS DEVICE REQUIREMENTS

Suitability	
3-Axis Accelerometer	Range 20 m/s <sup>2</sup> with 0.16% sensitivity
3-Axis Gyroscope	Range 360° with 0.08% sensitivity
Barometer	.25 m operable range -30° to 50°C
Data Recorder	5 readings per second
Maintainability	
Device Reliability	96% with 5-year lifespan
Device Availability	50,000 hours (MTBF)
Portability	
Battery Life	140 mAh (2 hours of battery life)
Data Storage	76 MB (2 hours of raw data capacity)
SRAM	8kB
Weight	<1 lb.
Interface	
File Format	Extensible Markup Language (XML)

### REFERENCES

- [1] "Experimental Aircraft Association," *ea.org*. [Online]. Available: [www.eaa.org](http://www.eaa.org). [Accessed: 04-Nov-2014].
- [2] "(14 CFR) Title 14: Aeronautics and Space, Part 21 - Certification Procedures for Products and Parts, Subpart H - Airworthiness Certificates." Federal Aviation Administration, 01-Sep-2004.
- [3] "2013 General Aviation Statistical Databook & 2014 Industry Outlook." General Aviation Manufacturers Association, Jan-2014.
- [4] "TSO-C4C: Bank and Pitch Instruments." Federal Aviation Agency, 01-Apr-1959.
- [5] "TSO-C201: Attitude and Heading Reference Systems (AHRS)." Federal Aviation Administration, 26-Jul-2012.
- [6] "AC 20-181: Airworthiness Approval of Attitude Heading Reference System (AHRS) Equipment." Federal Aviation Administration, 07-Apr-2014.
- [7] "AC 90-89A: Amateur-Built Aircraft and Ultralight Flight Testing Handbook." Federal Aviation Administration, 24-May-1995.
- [8] "NTSB/SS-12/01: The Safety of Experimental Amateur-Built Aircraft." National Transportation Safety Board, 22-May-2012.
- [9] "AC 20-27G: Certification and Operation of Amateur-Built Aircraft." Federal Aviation Administration, 30-Sep-2009.
- [10] John Lowry, *Performance of Light Aircraft*. AIAA (American Institute of Aeronautics & Ast, 1999.
- [11] Chad P. Bonadonna, "Design of a Low-Cost Flight Parameterization System for use by General Aviation," presented at the General Donald R. Keith Memorial Capstone Conference, West Point, NY, 2015.

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