AN INNOVATIVE LOW MAINTENANCE DATA ACQUISITION SOLUTION FOR LOAD FACTOR CAPTURE

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ABSTRACT

This paper describes an innovative approach to implementing and packaging a versatile data acquisition system for capturing load factor time-histories in United States Air Force (USAF) TG-16A gliders. The solution was developed by the Center for Aircraft Structural Life Extension (CAStLE) using commercial off-the-shelf (COTS) data acquisition equipment from the Curtiss-Wright Controls Avionics & Electronics division (CWC-AE).

The system measures and records load factor data for both aerobatic and basic mission types with two primary goals: to determine if the aircraft can fly the missions interchangeably, and to compare with the certificated load spectrum to assess usage severity. The system has been designed to be installed or removed from the aircraft within minutes to maximize flexibility by requiring no tools, aircraft modifications, or mechanical fasteners. To date, four production units have been built, installed, and are successfully recording data.

Keywords:
OLM, FDR, ODR, Solid State Memory, Aircraft Structural Integrity, Structural and Spectral Analysis

INTRODUCTION

Since its beginning in 1995, CAStLE has grown into the United States Air Force Academy's (USAFA) largest research center. Its experienced team of highly skilled scientists and engineers fulfills the unique role of simultaneously serving the Department of Engineering Mechanics by engaging cadets to solve real-world research problems while delivering the highest quality products and services to all branches of the military and to the greater structural sustainment community. [1]

The USAFA Soaring Program trains cadets in basic soaring, aerobatics, and cross-country flying. Between 2002 and 2011, these missions were primarily flown in several variants of the TG-10 glider. The service life of the TG-10C variant used for aerobatics was unexpectedly halved when the usage was determined to be more severe than originally expected. Ultimately an economic decision was made to replace the entire TG-10 fleet. [2] During the procurement phase, separate contracts were awarded for aircraft dedicated to each of the three primary mission types. The DG Flugzeugbau DG-1000S was selected for the basic (14 aircraft) and aerobatic (5 aircraft) mission types and given the USAF designation TG-16A (Figure 1).

Figure 1: USAF TG-16A glider, tail number 3AT (courtesy USAF).

With the transition to a new fleet came an emphasis on structural integrity motivated by two questions:

- Since the same aircraft were selected for both missions, can they be flown interchangeably?
- What is the severity of the soaring missions and what is the impact on service life?

Interchanging aircraft simplifies scheduling and maintenance for the operations and maintenance communities, yet may have broader service life implications that cannot be fully understood without better knowledge of mission severity.

The second question stems from unexpectedly running out of service life on the TG-10C fleet as well as a desire to apply economically appropriate elements of the USAF aircraft structural integrity program described in MIL-STD-1530C to the glider fleet. The DG-1000S composite airframe has a maximum service life of 12,000 hours. [3] The spectrum used for the certification basis includes a wide sampling of various soaring flight regimes [4], but the USAFA soaring mission severities have never been quantitatively characterized. With over 30,000 sorties flown per year in a student pilot training environment [5], there exists an unknown risk of structural failure possibly leading to loss of assets or life.

PROGRAM OVERVIEW

At the beginning of the program in May 2012, the available data suggested that load factors from acceleration measurements would sufficiently characterize mission severity for comparison with the certificated spectrum. Global Positioning System (GPS) data would be used to provide aircraft location, take-off and landing times, mission durations, and other informational parameters. Sufficient budget was available to instrument 4 aircraft and build a spare recorder; 2 dedicated to flying the basic soaring mission and 2 dedicated to the aerobatic mission.

The operational tempo of the soaring program dramatically increases during the summer months when more of the cadets' time can be devoted to flying. Thus, the schedule goal was to have a prototype ready as soon as 4-6 weeks.

The goal of the design was to provide acceleration and GPS measurement capability within a package sufficiently light and portable to qualify as pilot carry-on equipment to minimize impact to the aircraft and its availability. However, the system still had to remain secured during JAR22 crash loads and create no detrimental electromagnetic interference (EMI) with communication and navigation equipment.

In order to meet schedule and budget pressures, the system design relied on significant use of COTS hardware and the unique combination of facilities, equipment, and expertise located at the USAFA. DASs developed for aircraft sustainability analysis are typically tailored based on program requirements, often leading to inflexible "black box" systems with bespoke hardware. Generally the qualification of the hardware, and occasionally the software, is expensive and maintenance costs are high which often result in a poor return on investment. The time required to debug and qualify the system can make the system obsolete even before entering service. Subsequent reuse of the system would be difficult and expensive if it were incapable of being adapted or upgraded. [6]

COTS solutions designed to be modular and upgradable over a long lifetime can avoid many of the disadvantages inherent with bespoke systems. Some of the benefits of COTS include: [7]

- The initial cost can easily be a factor lower
- New technologies and upgrades can be integrated at low risk
- A wide range of avionics interfaces are available and future standards can be added
- Systems are flexible, expandable and programmable
- Overall cost of ownership is lower
- Spares are a standard product and production equipment lead times are shorter
- Systems are already qualified to environmental standards such as MIL-STD-810/461
- High quality software is already available and thoroughly tested

In particular, COTS equipment can take advantage of new acquisition, processing and data storage technologies that emerge as a result of requirements in other aerospace instrumentation fields.

SYSTEM OVERVIEW

The oxygen bottle holder (O_2 tube) located next to the rear pilot seat was chosen as the best candidate for locating the data recorder because it is infrequently used and provides a large volume of space, approximately 5.5 inches in diameter by 24 inches deep. Its location is shown circled in red in Figure 2.

CAStLE chose a 6 slot KAM-500 from CWC-AE as the DAS. Previous success using this system to characterize TG-10B tail landing gear loads and determine the safe operational service life of the Coast Guards fleet of HC-130H left them with both a reusable DAS and confidence in its reliability. This enabled them to quickly develop a prototype with existing hardware.

Figure 2: TG-16A O_2 tube.

The KAM-500 is compatible with typical 28VDC aircraft busses, requiring a minimum of approximately 17VDC, but the TG-16A operates on a 12VDC bus. During the prototype phase the data recorder was powered from the aircraft bus, while the production recorders include their own 12V battery. In both cases, a 12V to 24V converter is used to provide sufficient voltage supply to the KAM-500. The major components of the data recorders by volume are the DAS, the 12V to 24V converter, and the 12V battery. Those components are organized to fit within the volume of the O_2 tube and a unique chassis built around them to secure the system as shown in Figure 3.

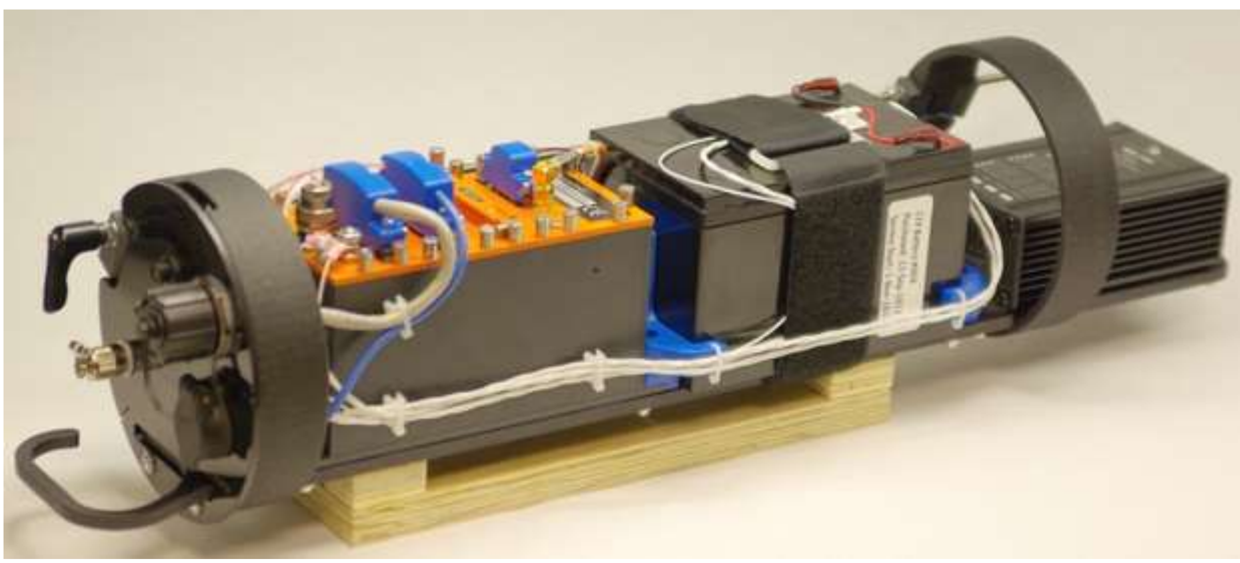

Figure 3: CAStLE data recorder for TG-16A.

The chassis incorporates a handle for ease of installation, removal, and carrying. There are 2 split rings that expand to grip the inside of the O_2 tube when wedges are driven together by rotating the tightening handle. When installed, this interface to the aircraft provides sufficient static load carrying capability to secure the 16.8 lb data recorder during the 9g forward crash load case of JAR22, yet requires no tools for installation nor traditional fastening methods that would require documentation and approval of airframe modification. The chassis includes lightening holes to reduce weight and a stiffener to ensure natural structural frequencies of the system do not interfere with the range of frequencies of interest to the data collection effort.

The use of in-house rapid prototyping and manufacturing capabilities saved significant time and cost throughout the development process. Fused-deposition rapid prototyping technology can produce extremely durable complex parts and these parts were used not only for the prototype unit but also for the production versions of the data recorders as shown by the ABS labeled parts in Figure 4.

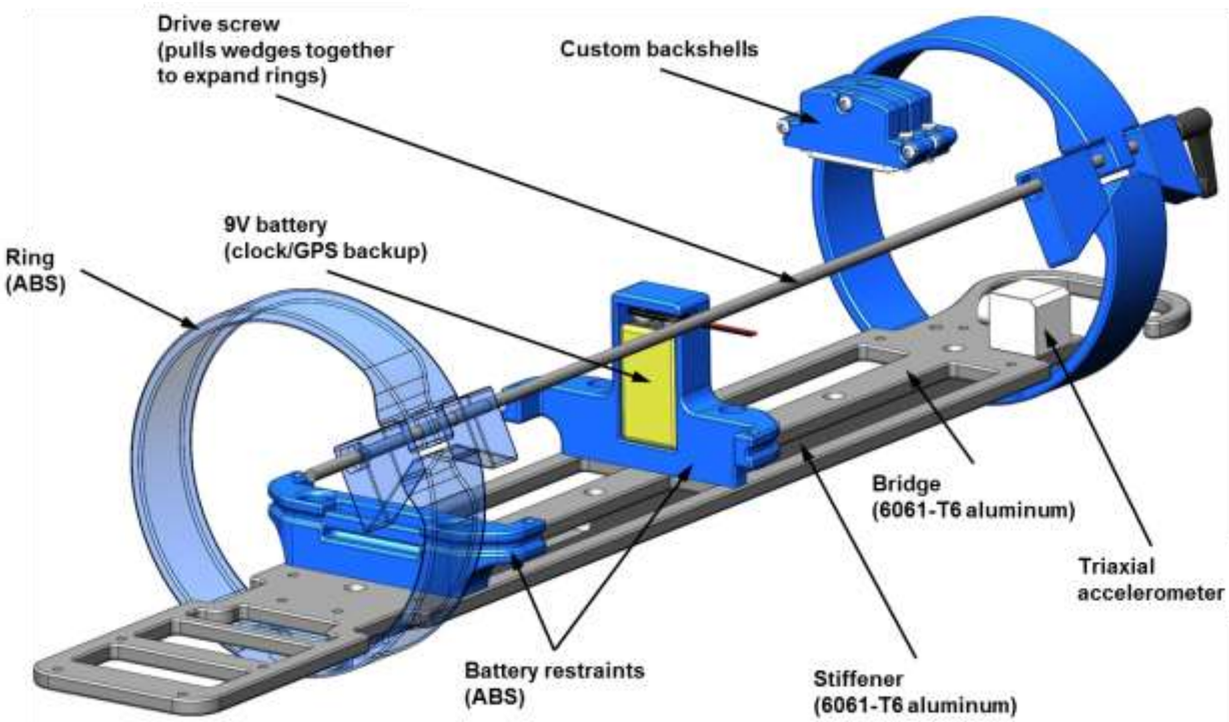

Figure 4: Data recorder chassis and materials.

Rapid prototyping also filled in when COTS components weren't available. As an example, the space constraints imposed by fitting the system inside the O_2 tube meant that there was no room to accommodate standard MIL-SPEC backshells. No other commercial backshells could be found to fit, so a custom version was designed and printed in a matter of hours.

Figure 4 also shows the location of the Kistler 8395A triaxial accelerometer. In order to meet the portability goal, the accelerometer was located on the recorder chassis even though the system is away from the centerline of the aircraft. This will result in some level of measurement error and needs to be accounted for in the analysis. Quantifying this error is planned future work that will be accomplished by wiring a second accelerometer to the DAS and mounting it near the CG of the aircraft while capturing several hours of flying. Differences between the 2 accelerometers will be calculated and quantified as the measurement error.

Figure 5 shows the faceplate layout. It has a power switch, an LED power indicator, a circuit breaker, an Ethernet port (for DAS programming and real-time data analysis), a battery charging port, and a connection for the external GPS antenna.

Figure 5: Faceplate layout.

The production system is powered by a 12V 12Ah valve-regulated lead acid battery. It provides up to 11 hours of runtime, sufficient for capturing a full day of flying. A 9V alkaline battery provides backup for the GPS clock to maintain time when the data recorder main power is switched off.

In an effort to keep the system self-contained, attempts were made to locate the GPS antenna on the data recorder. However, the GPS receiver was unable to maintain a satellite lock, requiring an alternative location. Field testing revealed the optimum accessible location for the antenna to be positioned behind the front seat headrest. It is affixed with hook and loop tape between the headrest support and cushion for quick transfer between aircraft. The position of the GPS antenna and its connection to the recorder can be seen in Figure 6.

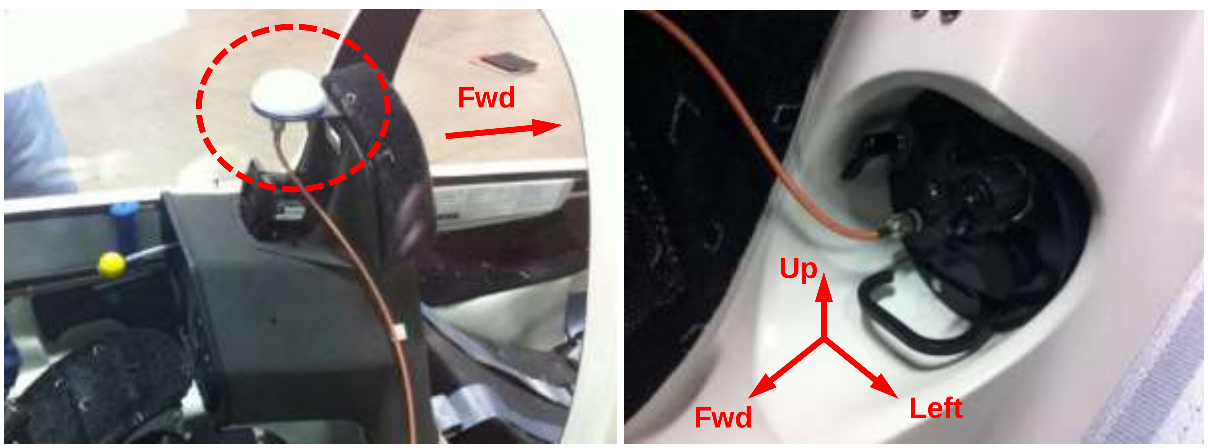

Figure 6: Data recorder GPS antenna installation.

The KAM-500 is programmed to record acceleration in 3 axes, temperature, and GPS parameters. The modular DAS is populated with 4 cards for this application:

- Ethernet controller

- GPS receiver and time code generator
- Analog-to-digital (A/D) converter
- Solid-state data storage device

The Ethernet module is a 100BaseTX Ethernet backplane controller used to program the system and packetize data for real-time analysis. The time code generator uses an onboard GPS receiver to provide the system with accurate time and navigation data. The A/D converter is an 8-channel module that is connected to the accelerometer and outputs temperature and triaxial acceleration. The solid-state storage device is a CompactFlash® card used to record the data. In addition, the KAM-500 has an independent power supply that provides the system ground and the 5V excitation required to power the triaxial accelerometer. The DAS has passed environmental testing for flight qualification, therefore additional ruggedization or environmental qualifications are unnecessary for this application.

SYSTEM CONFIGURATION AND DATA ANALYSIS

The DAS is programmed via the Ethernet interface with CWC-AE software, enabling quick configuration in the laboratory or in the field. On a routine basis, data from the CompactFlash® card is downloaded to a laptop computer using vendor software. The system can record approximately 100 hours on a 4GB card.

A CAStLE-developed FORTRAN program converts the raw data into engineering units and generates a comma-separated value (CSV) file of all recorded parameters, a National Maritime Electronics Association (NMEA) compliant GPS file, a Keyhole Markup Language (KML) map file, CSV files of calculated mission severity data, and various log files. Additionally, various CAStLE-developed scripts automate the repetitive file management and conversion tasks.

INSTALLATION, OPERATION AND LESSONS LEARNED

Initial installation of the data recorder requires 6 steps:

1. Place GPS antenna bracket in place between headrest and headrest support
2. Anchor GPS cable to cockpit with cable ties and anchors
3. Slide data recorder into O_2 tube
4. Level aircraft wings and data recorder; mark level line in O_2 tube
5. Turn data recorder handle until tight
6. Connect GPS antenna cable to port on faceplate

Initial installation requires approximately 10 minutes and subsequent installation or removal requires less than one minute to perform steps 3, 5, and 6 in the appropriate order.

The prototype unit was designed, built, and tested within a month of design kickoff. Unfortunately initial operation was delayed by a major wildfire in area of the USAFA that suspended flight operations for 3 weeks.

Once flight operations resumed and the prototype data recorder began service in late July 2012, radio interference was detected and traced to the data recorder. Field tests revealed the problem existed regardless of whether the unit was connected to the aircraft battery or a standalone power source so it was thought to be a radiated EMI problem. Further testing in the USAFA Department of Electrical and Computer Engineering anechoic chamber suggested the source as the KAM-500. The latest revision of the DAS included various EMI fixes so it was assumed that upgrading would solve the problem. Given the modularity of the system, it was a simple process to swap all the cards and reconnect for further tests.

The radiated EMI problem was solved, but a conducted EMI problem was still present. More testing revealed the external voltage converter as the source of the conducted EMI and an alternate converter was found. The lesson learned was that more aircraft ground testing would have uncovered the issue sooner. Given the fortunate proximity of the airfield to the CAStLE lab, subsequent hardware testing has relied more heavily on aircraft ground testing.

After hardware swaps, the prototype data recorder became operational in late August of 2012. Final configuration decisions were made to have an onboard battery and locate the GPS antenna. The flight manual was updated to instruct the pilots to turn on the recorder before taking off and turn it off after landing. The production unit design was finalized, a design review was held in October, and the 4 production units were completed and installed in early November 2012. Thereafter, the prototype unit was scavenged for parts and converted into a spare production unit.

In the first 6 months of operation of the production units from November 2012 into May 2013, 59 hours of the basic mission type and 31 hours of the aerobatic mission were recorded for a total of 90 hours. When the hours captured by the data recorders were compared to flight logs, it was found that average capture rates were only 38%. Figure 7 shows the breakdown of hours recorded compared to the hours logged for each instrumented aircraft tail number.

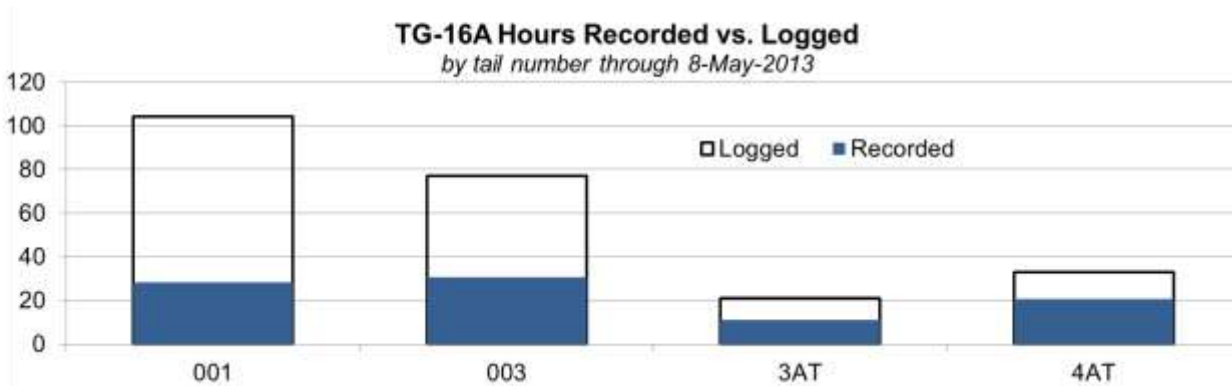

Figure 7: TG-16A capture rates by tail number.

It is assumed that there are 3 possible causes for the low capture rates:

1. The recorders are malfunctioning
2. The recorder batteries are not being charged by maintenance personnel
3. The recorders are not being turned on by pilots

Possible cause 1 is considered to be unlikely because the system has demonstrated great reliability in both the field and the lab, and on other past projects. Possible cause 2 is being addressed with reinforcement and formalization of the charging procedures, but we don’t currently have a way to know how often this is happening. Ideally, we would be able to monitor and record battery voltage as an estimate of state of charge for tracking purposes, but implementing this hasn’t been as simple as hoped. Possible cause 3 has been addressed with a modification to the recorders to automatically turn them on when aircraft bus is powered on. This was accomplished by adding a relay in the data recorder circuit that is plugged into a power socket on the TG-16A bus. When aircraft main power is switched on, the socket is energized and the relay turns on the data recorder. It is hoped that this modification and the formalization of charging procedures will greatly increase the capture rates. The lesson learned was to carefully monitor critical processes involving a person in the loop and consider whether or not it would be appropriate and cost-effective to automate the process.

CONCLUSIONS AND FUTURE WORK

In this paper we have described the development of an innovative data acquisition solution enabled by COTS technology. The use of COTS components allowed rapid deployment and capability expansion as the program matured. This effectively created a low-risk path into the production phase of development knowing that if issues arose (as they have) we could adapt the system with minimal downtime.

Future work at the time of writing includes quantifying the accelerometer measurement error due to location of the sensor relative to the aircraft CG, continuing to monitor capture rates, and strain gaging the wings of all the instrumented gliders. Research into the spectrum that formed the certification basis for the life of the gliders was not done until after the production units were built and flying due to schedule limitations. That research revealed that the fatigue spectrum was derived from strain gage measurements of wing bending moment. Wing bending load factors and CG acceleration load factors can agree, but not during all phases of flight. An example would be during landing when the accelerometer will measure a positive load factor while the wings will transition from positive bending (lift loading) to negative bending (inertia loading). The plan is to instrument the wings and determine if correlations can be derived such that all of the collected data can be used. Fortunately strain gage locations on the wing spar are easily accessible and another A/D card module can be easily installed into the DAS chassis.

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