AIRBORNE SYSTEMS LABORATORY FOR AUTOMATION RESEARCH

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Abstract

This paper presents an Airborne Systems Laboratory for Automation Research. The Airborne Systems Laboratory (ASL) is a Cessna 172 aircraft that has been specially modified and equipped by ARCAA specifically for research in future aircraft automation technologies, including Unmanned Airborne Systems (UAS). This capability has been developed over a long period of time, initially through the hire of aircraft, and finally through the purchase and modification of a dedicated flight-testing capability. The ASL has been equipped with a payload system that includes the provision of secure mounting, power, aircraft state data, flight management system and real-time subsystem. Finally, this system has been deployed in a cost effective platform allowing real-world flight-testing on a range of projects.

1 Introduction

The objective of this paper is to describe the design, manufacture, maintenance and operation of a unique and cost-effective flight testing capability which is used to support the research and development of future avionics, sensor and automated airspace management technologies at ARCAA. In particular, this capability has been used extensively in the Smart Skies project [1, 2]. This capability is referred to as the ARCAA Airborne Systems Laboratory (ASL).

ARCAA has for some time been hiring light aircraft to use in various automation experiments, usually as a surrogate or proxy Unmanned Aircraft System (UAS). As the need for such an aircraft grew more frequent, ARCAA began investigating the purchase of a dedicated flight test aircraft capability. The ASL is the culmination of that effort and is documented in this paper.

ARCAA required an aircraft that could cater for a wide variety of research tasks related to automation, which differs substantially to many other university research aircraft which are quite often focused on aerodynamics, stability and control or atmospheric research. This paper begins by describing the technical requirements and operational considerations taken into account when designing the ASL's systems. A detailed discussion of the implementation on the aircraft is then presented. Finally a summary of the ASL's operations to date is made demonstrating the system as a practical and efficient flight test capability for automation research.

2 Requirements Overview

Over the years of operating hired aircraft for research projects, ARCAA had a good understanding of what would be required in a research aircraft platform.

The key features of the ASL that are considered essential are: 1) the ability to carry a wide range of research payloads safely and securely, with a minimum of certification effort; 2) provide reliable and continuous power to the payload and minimise the carriage of storage batteries which are potentially unsafe and inevitably run low at the most interesting point in the experiment; 3) have access to good quality aircraft state data (position, velocity, attitude and other derivatives) which can be readily synchronised in time with the research data; 4) the ability to 'close-the-loop' on aircraft control inputs (i.e. interface to the aircraft's autopilot); 5) provide a number of different communications links to the outside world; 6) include a modular and pluggable software framework for implementation of experimental software quickly and reliably; 7) be safe, simple and cost effective to operate.

One of the roles of the ASL is as a proxy-UAS. In developing new payloads for small UAS, it is often much quicker to first test on a larger platform, to avoid the need for miniaturisation and autonomous operation early in the development cycle. The ASL has been used in this role, particularly for the development of machine vision based payloads.

The next section describes the systems that have been considered and developed into the ASL to satisfy each of these requirements.

3 ASL Design and Implementation

3.1 The Aircraft

The base aircraft for the ASL is a Cessna 172R as shown in Figure 1. This is a single, naturally aspirated, piston engine aircraft with a fixed pitch propeller. The aircraft has a fixed undercarriage. The basic specifications of the aircraft are listed below.

Takeoff Weight (max) 1109kg
Engine .... 160 HP
Cruise TAS (typ.) .... 110 knots
Wingspan 11m
Overall Length 8m
Operating Altitude (max typ.) .... 10,000 feet
Fuel Economy .... 38 Litres/Hour
Stall Speed .... 54 knots
Crew 1
Passengers 3

This platform was chosen due to its proven ease and simplicity of operation, low operating and maintenance costs. A larger aircraft (Cessna 182 and 206 were also considered), whilst being more sophisticated and being able to carry a larger payload, was deemed to be not desirable due to higher maintenance costs and higher demands on pilot training and proficiency.

3.2 Physical Modifications

A number of physical modifications were initially made to the aircraft. The major structural modification made to the aircraft was the installation of air-transport style seat tracks normally only found on much larger aircraft (sometimes referred to as Douglas rail). This modification allows the secure fitment of a wide range of payloads, thus satisfying the requirement of flexibility in payload carriage.

To securely carry research payloads, a custom designed 19” equipment rack was manufactured and installed in these seat tracks, replacing the two rear seats (Figure 2). The rack is certified to safely carry up to 55kgs of payload. In this configuration, the aircraft is operated with only a single passenger plus pilot.

The other physical modifications included running aircraft power (28VDC) to a convenient connector on the rear bulkhead for powering the research payload; GPS and communications antennas and associated cabling for the research communications links; and a 10.4” daylight readable LCD screen in the cockpit. These are discussed in further detail below.

Figure 1: ARCAA Airborne Systems Laboratory Cessna 172 aircraft.

3.3 Power System

Power for research equipment is provided by a power conditioning system installed in the lower-most bay of the equipment rack. The power system provides continuous 12V DC power to research payloads from the aircraft's power system via a TSO[1] certified DC-DC converter. The system also includes a storage battery for ground operations and in-flight backup.

3.4 Payload System

The payload system on the ASL is very simple consisting only of the physical interface specification and some basic requirements on airworthiness. Payloads are required to be housed in a standardised Aluminum 19" rack enclosure. Payloads are provided with 12V DC power up to 10A continuous each, which is adequate to run a typical desktop or embedded computer and peripherals.

Payloads are required to conform to some basic airworthiness requirements for structural soundness and use standard aircraft wiring materials and practices to ensure there is no extraordinary risk of fire or other hazard in flight or on the ground. Basic electromagnetic interference (EMI) and compatibility (EMC) checks are carried out on all payloads prior to flight. Finally, especially since research payloads are necessarily atypical, all payloads are subject to a specific risk analysis to identify any unusual or unmitigated risks to safe flight.

The next section will discuss the standard payloads available on the ASL.

4 Standard ASL Payloads

The standard ASL payloads include a Truth System, Camera and Image Capture System and Flight Computer and Flight Management System. Crew interfaces and communications for these systems are also available. Each of these systems is discussed in this section.

4.1 ASL Truth System

Research payloads typically require good knowledge of the aircraft state (position, velocity and attitude), which can be synchronised with the payload, either in real time or for post processing. The ASL has been equipped with a Novatel SPAN integrated GPS-INS navigation system to provide this reference trajectory (or "truth") data. The SPAN data is collected and logged on an embedded computer by a real-time subsystem running on the ASL flight computer and then distributed to the payload systems via Ethernet. Most payloads only require precisely time-stamped truth data for post-processing, however recently the need for real-time data for automated Detect, Sense and Act (DSA) experiments has led to the expansion of the real-time data feed from the truth system.

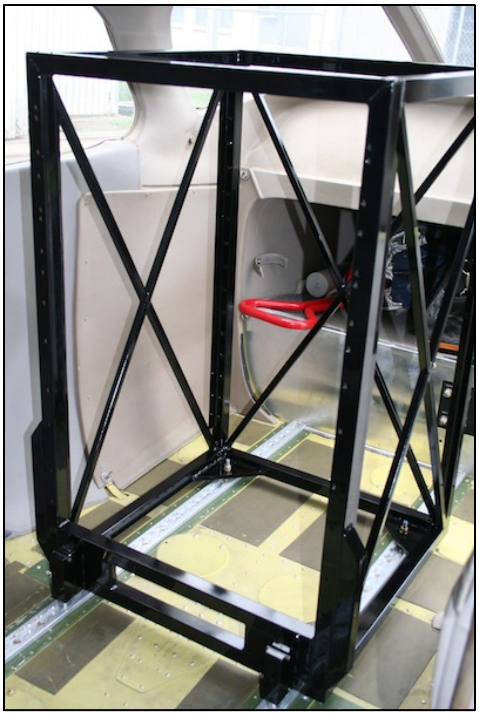

Figure 2: Empty Equipment Rack allowing the safe carriage of up to 55kg of payload.

4.2 Camera and Image Capture System

The ASL has been fitted with a dual machine vision camera system (Figure 3). To date, this camera system has been used for a variety of research topics including aircraft state estimation [3], automated Detect, Sense and Act (DSA) research [4], automated forced landing, aerial photography [5] and power line detection. The fitted cameras are deliberately small and lightweight as they are designed eventually to

[1] U.S. Federal Aviation Administration Technical Standard Orders. These define technical standards for aircraft equipment.

be fitted in small UAS. In this case, the ASL is simply used as a proxy UAS.

The image capture payload is designed to capture precisely timed images for use in navigation and sense-and-avoid experiments. The system is capable of simultaneously capturing two IIDC[2] machine-vision cameras outputting uncompressed images at full frame rate (30Hz) and resolution (1024 x 768). The cameras currently certified for the ASL are the Point Grey Flea, Sony DFW-SX900 and the Basler Scout.

The image camera payload consists of several components; (1) A commodity x86-64 computer with 3x 500GB hard disk drives, and an additional Firewire card, running Ubuntu 9.04 Linux with the real-time kernel patches; (2) A commercial 160W power supply designed to interface a 8-26V input to a motherboard power supply and Serial ATA power; (3) A Novatel OEMV-1 receiver providing absolute time data and a 1 Pulse-Per-Second (PPS) signal to the system; (4) A custom electronics board that synchronises to the GPS PPS signal and triggers the shutters of the camera at the desired frame rate; (5) A custom-designed mechanical mounting system to protect the system from vibration and shocks housed in a standard aluminum 3U 19” rack mount case.

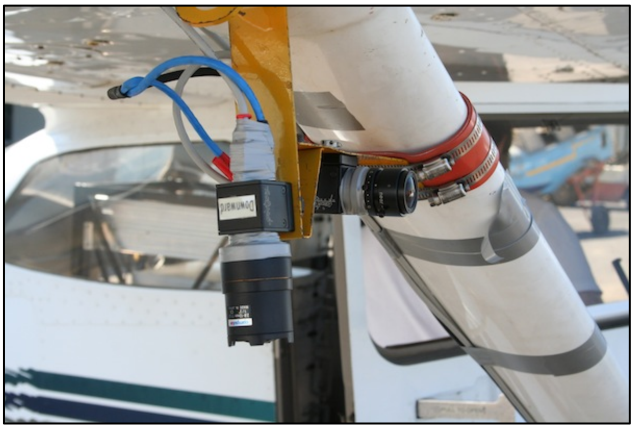

Figure 3: Dual camera system showing forward and downward pointing cameras.

As the cameras are triggered externally by electronics synchronised to the GPS PPS and the Firewire latency is well characterised, it is possible to precisely timestamp the images, which essential for comparing the camera-derived aircraft state against the reference provided by the ASL truth system. The kernel time of the PC is matched to the GPS time using the time data from the GPS receiver and the PPS signal, which is time stamped via the Parallel Port interrupt.

The image capture software was designed specifically for the Image Capture Payload. The software, called Videography, utilises the low-level DC1394 libraries [6] to create a command-line utility that can setup and capture the cameras from a configuration file and can be run without human intervention. The latter property is especially important for a UAS, where it may be started from the initialisation scripts and run until the entire system is shut down without any manual intervention.

Modern desktop hard disks are capable of capturing the very large amounts of data generated by two uncompressed cameras, but the unpredictable latency of the I/O system can cause Videography to block on a write to disk and on occasion drop a frame. This is particularly noticeable on smaller (and generally more robust) laptop-style hard disks, which are not always capable of saving the required amount of data, especially if fragmentation or concurrent access on the drive leads to a large number of disk seek activity.

To get around this problem, an additional program known as FileDistributor has been developed. FileDistributor moves files saved in a known location and distributes them across several hard disks. It will also manage the process of creating sub-directories to prevent potentially hundreds of thousands of images from being saved to the root directory of any single hard disk. File distributor also contains scripts for assembling the images “scattered” across several hard disks to a single place after the flight has been completed.

Videography still needs to save the frames to a designated location. By creating a RAM Disk, which emulates a hard disk in RAM, the images from Videography can be saved quickly and in constant time, removing the problem of dropped frames. The RAM Disk also acts as a

[2] The 1394 Trade Association Instrumentation and Industrial Control Working Group, Digital Camera Sub Working Group

buffer, preventing frames from being lost if I/O to a particular hard disk is blocked for a period of time. The full image capture pipeline of the image capture system is shown in Figure 4.

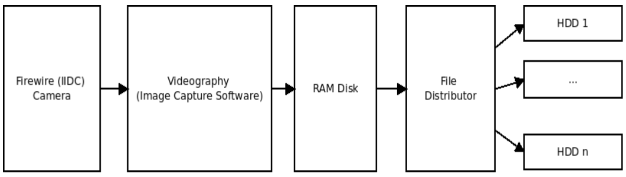

Figure 4: Real-time image capture pipeline.

Videography and FileDistributor have now been open-sourced under the GNU Public License and may be freely used [7]. Recently, the image capture sub-system has been more highly integrated into the ASL software architecture in readiness for automated DSA experiments involving the ASL.

4.3 Flight Computer and Networked Flight Management System

The ASL has been fitted with a standard Flight Computer and Networked Flight Management System developed at ARCAA. The Flight computer is a relatively standard industrial embedded computer featuring a solid state disk and PC104 bus for expansion. This computer is installed with Linux operating system with real-time patches enabling a real-time subsystem for time-critical tasks. The most important of these real-time tasks is the logging of the ASL Truth system data for post processing, however can be configured for other tasks if required.

The Networked Flight Management System (N-FMS) has been developed entirely in-house at ARCAA to suit unique research needs. The term 'Networked' FMS is used to highlight the connectivity to the outside world that the N-FMS employs in the research projects that it is used in, particularly Smart Skies [8].

In the Smart Skies project, the ASL, along with the other ARCAA flight platforms, is used as a test-bed for next-generation airspace management technologies. It communicates with a centralised airspace controller, the ground-based Automated Dynamic Airspace Controller (ADAC), which is located in another part of the world. ASL state and intent information is transmitted to the central controller, which may elect to transmit trajectory commands back to the ASL for action. This behavior is implemented in the N-FMS in a module called the Predictive Flight Management System (pFMS). For more detail on this architecture, refer to [1].

The N-FMS is built upon ARCAA's modular and pluggable software framework shown in Figure 5. This framework implements a scheduler executive allowing multiple tasks to run at the desired rates. Shared memory and event manager interfaces are implemented allowing modules to communicate with each other.

The N-FMS integrates the command and control all of the common payloads used on the ASL. It implements the features found commonly on commercial Flight Management Systems including navigation and guidance, and interfaces to the ASL's autopilot for closed loop control. New research payloads which are deployable in software can be easily integrated into the N-FMS as a 'plug-in[3]'. The payload plug-in is then automatically provided with scheduling, event management and shared data via a common interface.

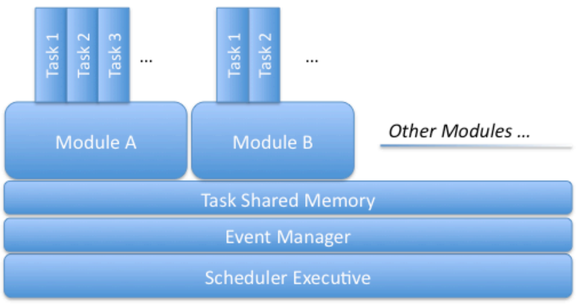

Figure 5: Software Architecture

One particularly useful feature of this framework is that it allows simple hardware in the loop testing of payloads by using a Flight Simulator plug-in in place of the ASL Truth system plug-in. In this way, the payload plug-in can be simulated without any modification prior to flight. This approach has been used extensively in the Smart Skies project where separation scenarios are rehearsed in the

[3] A plug-in is a software module that has a defined interface and can be dynamically loaded into a host application.

laboratory using flight simulation prior to actual flight.

The same N-FMS deployed onto the ASL is also deployed on ARCAA's Unmanned Aerial Systems (UAS). Software re-use is maximized and the primary difference between the two platforms is the interface to the autopilot system. ARCAA UAS use a Micropilot and an interface module for this has been written for the N-FMS.

Figure 6: ARCAA Flamingo UAS

4.4 Crew Interfaces

The N-FMS includes two primary crew interfaces. The first of these is a 10.4" daylight readable LCD installed in the right hand side cockpit panel (Figure 7). This is in the primary field of view of the right hand seat crewmember. For research purposes, this crewmember operates the aircraft whilst the pilot-in-command (in the left hand seat) maintains a situational awareness lookout and takes over if required.

Crew input to the N-FMS is achieved via a touch-screen PDA device attached optionally to the yoke or the crewmember's kneeboard. This is referred to as the Controller Display Unit (CDU). The CDU includes all of the controls necessary for interaction with the N-FMS including selecting, activating and deactivating flight plans, choosing waypoints, selecting display components etc. The CDU can also be configured to display custom inputs for research payloads. Some example CDU screens are shown in Figure 8.

Figure 7: ASL Cockpit Panel with N-FMS interfaces.

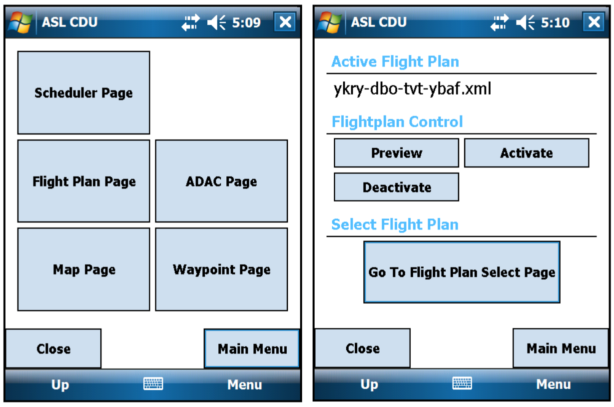

Figure 8: Example CDU Screens

4.5 Autopilot Interface

The aircraft is factory fitted with a Honeywell KAP140 analog autopilot which does not itself provide a convenient interface to the ASL flight computer. Fortunately there are certified devices known as Roll Steering Converters that provide a digital interface to this style of autopilot. Such an interface was designed, certified and installed in to the ASL, allowing the aircraft's Networked Flight Management System to command the aircraft's autopilot directly, without the need for crew interaction (other than actually engaging the autopilot in the correct mode). This is a significant capability as it allows true autonomous operation during cruise phases of flight (the autopilot is not certified for operations below 1000 feet above ground level).

4.6 Communications Systems

The ASL is fitted with a number of communications systems for research payload use. These comprise a Cellular High-Speed Packet Access (HSPA) data link, UHF (900MHz) data link and Iridium data links. Each link has its own advantages and disadvantages. The HSPA link provides high bandwidth internet access, however availability is limited to when in range of the cellular network. This is no problem when close to cities and towns, however coverage is more limited in the remote areas of Australia although coverage is continually improving. The Iridium data link provides low-bandwidth world-wide data link capability, however is extremely expensive and much slower than the HSPA link. Finally, the UHF data link provides low-latency, medium bandwidth point-to-point access over a short range.

At the altitudes at which the ASL typically operates, practical UHF data link range is 30 NM. For typical operations, the ASL uses the UHF data link to send the aircraft state back to a ground coordinator for experiment coordination with other assets (for example UAS). Of course as a certified aircraft, the ASL also carries dual VHF voice communications radios that are also used for ground coordination (with the appropriate frequency license).

5 Certification and Operations

This section discusses the certification considerations and operation of the ASL, including a summary of operations to date and lessons learned along the way.

5.1 Certification

The baseline aircraft, a Cessna 172, is a fully certified aircraft to U.S. Federal Aviation Regulations FAR 23. It was desirable to maintain this certification to the greatest extent possible. It has been possible to achieve this for the ASL by carrying out a compliance finding on the modifications against the regulations for certain phases of flight. This has resulted in a Flight Manual Supplement being issued which allows operation of the research payload during Day-Visual Flight Rules (VFR), whilst maintaining the aircraft's Instrument Flight Rules (IFR) capability when the research payloads are not operating. It may be possible to fully certify the research payload for IFR flight, however this is not a current requirement.

The flight manual supplement also covers operations with the N-FMS connected to the Aircraft's autopilot including abnormal operation and emergency procedures. Flight with the autopilot coupled to the N-FMS is limited to a minimum altitude of 1000 feet above ground level.

5.2 Operations

The ASL has been designed for simple and safe operation. Even so, achieving safe operations is dependant upon a structured approach to flight testing. A safety management system has been developed which helps ARCAA to manage the research flight test process and ensure all operations are conducted safely and effectively. A process of careful risk assessment, mitigation, and post evaluation supports each flight test campaign.

Prior to each flight test campaign, the researcher prepares a Flight Trial Requirements document. This document details the specific research outcomes that are required, the resources that are available, and the time frame in which the trial is required. From this material, the ASL operators will develop a Flight Trial Scenario document, including a detailed Hazard Assessment. Typically this document is developed in conjunction with the researcher, and essentially is the test plan for the proposed flight trial. At this stage, the scenario and hazard assessment are reviewed independently, which is a critical step in the ASL Safety Management System. Depending on the complexity of the trial, a hazard identification workshop may also be undertaken. Following this process, the ASL crew undertakes final flight preparation, planning and conduct the trial.

To date, in the first 12 months of operation, the ASL has achieved over 160 operational hours, of which over 100 hours is engaged directly in research flying, with the remainder being capability development and other operations. During this time, the ARCAA ASL team has learnt a great deal about the operation of such a research asset. During this time, the ASL has proven the operational concept of a safe, simple, cost effective and efficient flight test capability.

5.3 Lessons Learned

There have been a number of important lessons learned along the way in developing the ASL capability. These lessons have been categorised into physical equipment, project management, operations and risk management.

Physical Equipment

The research team has sought to develop a flexible research payload system for the ASL. This has been largely successful, however operational experience has shown the need for some improvements.

The installation and removal of payloads currently requires a number of nuts and bolts to be used. For some payloads it would be beneficial to have a 'quick-release' system which would not only be easier to use and more reliable, but reduce the need for tooling on the aircraft.

In terms of computing hardware, initial experience with industrial ruggedized computers was promising. There were some early issues experienced using poor quality solid-state-disks in the flight computer, which have now been replaced with higher quality items. However after further operational experience, some computer hardware failures have been experienced. The team is currently working on moving to a CompactPCI computer architecture and ARINC-600 style chassis in an effort to improve computing hardware reliability. This is also related to the desire to have a 'quick-release' capability, which is facilitated by the ARINC chassis.

The ASL is not currently fitted with an air-data system and this has been a limiting factor for some research payloads. An independent air data probe and air data computer has been purchased and is to be fitted in the near future.

Project Management

From a project management perspective, communication with stakeholders was very important, particularly between engineering and maintenance staff. Good quality drawings and modification instructions were essential in communicating requirements to external organisations carrying out work on the aircraft. The team found that some General Aviation maintenance companies are not accustomed to working in a more structured engineering environment, and it took some time to find an organisation with the right skills and attitude.

Operations and Risk Management

The operations concept of the ASL calls for Day-VFR operation for research activities. This concept has proved acceptable for the research tasks themselves, however on occasion the operations team has been limited by poor weather that may impact a transit phase of flight. For example, the research task may call for a racetrack pattern to be flown at 5500 feet, however if there is a layer of cloud at 3000 feet, the crew may not be able to climb to altitude remaining VMC. Future operations concepts, crew training and equipment should therefore allow for parts of the flight to be completed under the Instrument Flight Rules (IFR) which would be safer and more efficient in certain circumstances.

Continuous communication with the University's risk management and workplace health and safety teams was also essential in the continuous development of a robust and effective safety management system (this is an ongoing effort). Since personnel in those departments were not necessarily familiar with aviation, a lot of effort was devoted to providing information about the general aviation regulatory environment. In addition to this, the team sought (and continues to seek) regular independent oversight and advice to ensure continued safe operations.

6 Conclusion

This paper has presented the ARCAA Airborne Systems Laboratory as a capable and cost-effective flight test capability. The ASL can be quickly and safely fitted with a range of experimental payloads used in automation research and this has been shown in a number of research projects at ARCAA. The ASL's modular Networked Flight Management System has been deployed for a number of research projects and is tested in real-world flying conditions in over 100 hours of research missions. The ASL's systems have been fully certified for Day VFR operation, hence there are no significant operational limitations. Finally, the operating costs of the ASL have been kept low which facilitates cost-effective operations allowing many research projects to take advantage of the ASL's capabilities.

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