SUBSCALE FLIGHT TESTING AT LINKÖPING UNIVERSITY

Ingo Staack, David Lundström
Linköping University, 58183 Linköping, Sweden

Keywords: *flight testing, data acquisition, subscale demonstrator*

Abstract

At Linkoping University aeronautical research is focusing on design methodologies in early stages of aircraft design. Rapid design and evaluation of prototypes is considered an important branch of this work. In this paper flight test activities at the university are described, the design of a light weight affordable data acquisition system is explained and some flight test results including flow visualization are presented.

1 Introduction

The use of radio controlled models for validation and data acquisition in early stages of aircraft design is getting an increased interest in the aircraft industry around the world. Modern low cost electronics allows these types of tests to be carried out cost effectively yet providing valuable data for improving or validating a design.

One axis of the current research in aircraft design at Linköping University is focused on fast concept evaluation in early conceptual design stages. This covers multidisciplinary optimization using computational tools of different level of complexity [1][17][14], and also subscale flight testing.

1.1 Subscale flight testing

Subscale flight testing is a mean to evaluate the free flight characteristics of an aircraft design prior to building a full-scale prototype. It is a convenient way to investigate extreme, high risk portions of the flight envelope without exposing a pilot to risk. It is especially interesting for demonstrating the feasibility of unconventional and innovative designs without the cost and risk of a manned, full-scale vehicle. There are several recent examples of this: the NASA funded McDonnell Douglas X-36 [9][18], Rockwell HiMAT [7], Saab UCAV [16], NASA X-43A-LS [10] and the proposed Gulfstream Quiet Supersonic Jet [19]. Subscale flight testing has also been used for civil aircraft development. An example is the NASA AirStar research program [12], where a dynamically scaled model is used to explore a larger then normal flight envelope for a civil transport aircraft. For the Boeing blended wing body concept, the X-48 project, Boeing and NASA have been using a scaled model to demonstrate the concept and obtain more data without going to full scale. Recently NASA also announced the plans to have a subscale demonstrator of a green twin-aisle airliner concept flying in 2015 [29].

Testing of free flying subscale models is not a new practice. The restrictions imposed by a rigid connection as in a wind tunnel is prohibitive for high angle of attack test, and to study departure modes. As a solution free flying, and often uncontrolled, models is regularly used as a compliment to standard wind tunnel measurements. Spin models for updraft wind tunnels have been a standard practice since the 1940s and remotely controlled models dropped from helicopters have often been used to test departure and spin characteristics. Free-flight models have also been built for conventional wind tunnels, such as the NASA Langley Free Flight Facility [11]. Also for fighter configurations, drop models have been widely used; recent examples being the X-31 [13] and F/A-18E/F [6]. Subscale drop models of space vehicles, such as the Lockheed Martin X-38 and Japanese HOPE-X [31], have also been employed.

2 Platforms

Currently the research team has access to 3 aircraft for subscale flight testing. The business jet “Raven”, a 1:8 scale Dassault Rafale, and lastly a concept of a low signature fighter “GFF”.

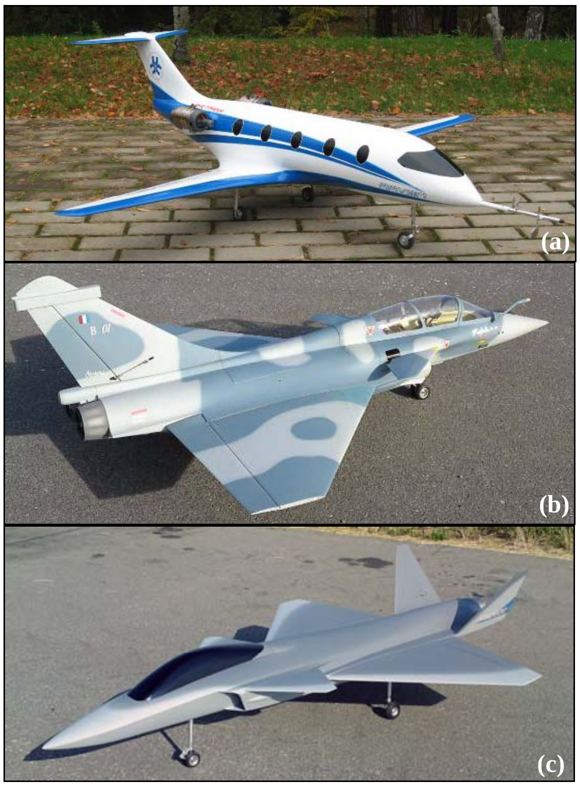

Fig. 1. Platforms for subscale flight testing: (a) The Raven business jet, (b) Dassault Rafale, (c) GFF.

The Raven aircraft is a University in-house designed business jet aircraft [15]. The model of Raven is dynamically scaled in the sense that its inertia and weight is adjusted to correspond to the theoretical full scale design. The Rafale aircraft is a commercial RC scale model of a Dassault Aviation Rafale and has been acquired for high angle of attack testing and to serve as a general test bench. The last aircraft is the result of a study for a generic future fighter (GFF) involving the following partners: Saab AB, the Swedish Defense Research Agency (FOI), Volvo Aero [2] Linköping University and the Royal Institute of Technology (KTH). All 3 aircraft are powered by miniature gas turbines and are remotely controlled using standard RC equipment and within visual range.

3 Data Acquisition System Design

The miniaturization and reduction in price of modern electronics allows for affordable light weight and accurate data acquisition systems to be assembled. This enhances the utility of subscale flight testing and opens up the door for smaller companies and universities for such activities. There are some off the shelf systems available, such as Eagletree [27] targeting the hobby sector, that could be used for some simpler flight tests. For advanced testing a more flexible and powerful solution is needed. Initial work on a custom data log system was carried out at Linköping University in 2008 [15]. This system was based on a diamond systems PC board “Athena” with a Pentium III class processor running a streamlined Linux kernel as operating system [3]. Because of an undeclared malfunction of this unit, and the experiences gained under development, this project was stopped and a decision was taken to start the development of a new system based on microcontrollers and without any operating system. This reduction of hardware to an absolute minimum should fulfill the main requirements affordability, small size and minimum power consumption. Furthermore, this approach facilitates better timing control than with the non real time operating system but with the disadvantage of loosing multitasking capability.

3.1 System layout

The system is separated into four functional parts, a core unit, the sensors, a telemetry link and the ground station with a graphical user interface (GUI). The core unit manages the timing, performs the data handling between the peripherals and should have excessive processing performance in order to support latter extensions of the system such as an auto pilot function.

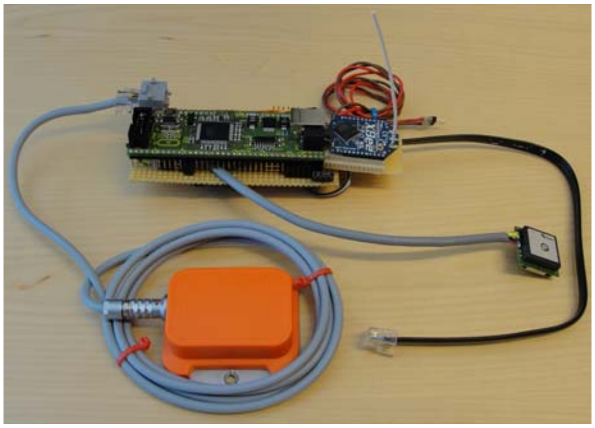

Fig. 2. Data acquisition system.

The telemetry link is primary intended for system control and to provide the pilot with important flight condition information such as velocity or attitude and may be used in a later version to transport the onboard buffered logging data to the ground station and vice versa. This will enable the implementation of complex data calculations on the ground station which could send back control commands e.g. rudder deflection.

3.2 Core Unit

According to the minimalistic approach, the first design was supposed to use the Atmel 8-bit microcontroller family “AVR Mega” [24], programmed direct in Assembler for maximum system performance an timing accuracy, with the intended change to a newer, at this time just announced controller series “AVR XMega” with of their extended number of interfaces and direct memory access (DMA). The Atmel AVR series was chosen because of the free available integrated development environment (IDE) and the availability of an inexpensive programmer/debugger.

First tests with the AVR Mega series indicated a lack of peripheral interfaces und a very limited calculation capacity, especially for floating point numbers. At this point, the system was modified to use the AVR32UC3A series [24], a 32-bit microcontroller family from Atmel with on-chip Flash program memory. This type provides a much higher CPU performance with up to 66MHz clocking, a more complex interrupt controller with different priority levels (instead of one at the Mega series) and enables data throughput without CPU load with help of the peripheral DMA controller (PDCA). Drawbacks using the AVR32UC3A family in this project is the low maximum system voltage of 3.3 V only (but most of the I/O pins are 5 V level compatible) and the lack of internal EEPROM memory for system parameter storage. But this lack can be dodged by using a page of the program Flash memory.

In order to skip the production of a custom printed board for the prototype, a commercial of the shelf development board were used, connected with a hand-made adapter board for sensor and memory connections.

Programming the microcontroller was done in C in the freeware IDE “AVR32 Studio”, which use the open source C-compiler avr-gcc, adapted from the Linux C-compiler gcc [20] and the well known open source IDE Eclipse. The device can then be programmed directly over the USB with help of a Bootloader (called Device Firmware Upgrade, DFU [4]) which enables the programming of these devices directly from a standard PC without the need of any programmer. This feature therefore makes it especially interesting for open source / low budget projects and –like intended in this project- for later usage in student courses.

Data storage occurs in a sequential access memory “AT45DB321D”[5], from atmel, connected by serial peripheral interface (SPI) with a frequency of 33MHz. This 4 Mbyte big storage has two onboard 528 byte data buffers which enables continuous write or read operations without the need of data buffering in the microcontroller´s memory. Minimizing the logging data by parsing all input signals from the sensor and storing only the required values, partly in binary format, the storage size is enough for approximately 5 minutes logging which equates to the average flight endurance of a jet driven remote controlled airplane.

Device	Interface	Clocking	Update rate
IMU	USART	230400Baud	100Hz
GPS	USART	115200Baud	10Hz
Engine	USART	9600Baud	2Hz
Air-Link	USART	115200Baud	n/a
Dataflash	SPI	33MHz	n/a
ADC	SPI	20MHz	50Hz

Table 1. Interfaces.

3.3 Instrumentation

The sensor instrumentation consists of the following components:

- Attitude and Heading Reference System (AHRS)
- GPS receiver
- Noseboom, including:
    - Alpha & Beta vanes
    - Dynamic & Static pressure
    - Temperature Sensor
    - ADC converter
- Turbine engine interface

The AHRS is a commercial of the shelf (COTS) component, including a sensor conglomerate of three Micro-Electro-Mechanical System (MEMS) accelerometers, three gyrometers, three magnetometers and a built-in sensor fusion algorithm, which enables a direct output of the attitude of the IMU in Quaternion, Euler angles or Rotation Matrix [30].

The GPS signal receiver is a low cost 65 channel receiver “Venus6T” with a maximum update frequency of 10Hz, alternatively with NMEA or binary data output. At the current state, the NMEA protocol is used but should be substituted with the binary data format in order to get a constant data length backing the usage of DMA also with the GPS data.

The only none-COTS-device is the nose boom containing the angular flow and pressure measurement sensors. It is an in-house design made of a 12mm aluminium tube, a Pitot tube and two vanes. The latter are ball bearing pivoted and the position readout occurs contact less by hall sensors (Honeywell HMC 1501) in order to minimize friction. The analogue signal of the hall sensors is amplified and converted to digital signal by a four channel, 24bit resolution analogue to digital converter (ADC) MAX11040 which communicates via SPI with the microcontroller. This setting should gain a high resolution of the vane position but in practise, the resolution and especially the curvature of the signal is distorted by the bearing clearance and the misalignment of the magnets. In order to gain a better result, theses sensors should be replaced by programmable magnetic angle decoders from the AS5X series from Austrian Microsystems [25]. These devices offer an 8 element hall sensor array with integrated digital signal processing and are connected with the microcontroller over a serial port or pulse width modulation output signal. This solution should gain a vane angle position resolution up to 14bit.

The pressure sensors are high precision pressure transducers of the BSDX series from Sensor Technics [28] with an analogue output signal and a pressure range of 800 to 1100mbar (static pressure) respectively 0 to 99mbar (dynamic pressure).

3.4 Data Link and Ground Station

A rudimentary data link is realized by using two radio frequency transmitters within the ISM 868 MHz frequency band (XBee-PRO®868 OEM [8]). These units are connected by asynchronous serial interface with the microcontroller respective USB port with the ground station (standard laptop).

In the current state, this data link fulfills two functions: system control and (pseudo) real time data transmission for flight attitude monitoring. The system controls functions such as logging start/stop, set marker, show status information, readout logging data, erase storage, system reset, sensor settings, and can be executed with single character commands through any serial port terminal program. A more intuitive way to control these functions is to use the developed graphical user interface. The GUI is a QT application [22] written in C++. It comprises the control of the measurement system with help of graphic elements and a status feedback terminal, as well as a graphical presentation of the airplane attitude, velocity and position with help of an animated artificial horizon for the pilot. Additionally, this program provides plotting functionality for the downloaded logging data. All this functions are programmed by using freeware only: Qt, a cross-platform application and UI framework for the graphical user interface, QextSerialPort [21], a cross-platform serial port class for the virtual serial port (data link) and QWT [23], a GUI component and utility class library supporting technical 2D plot widget for graphical logging data presentation.

4 Flight Testing

At the time of writing the logging system is still in beta testing. It has been tested in flight at two occasions, installed in the Rafale Jet. Initial experience shows that the logging and telemetry works fine, but there are some issues with the AHRS not always giving reliable data. Interference from the surrounding components in the tight RC jet seems to be the issue.

4.1 Flow visualization

Apart form the work with the logging system, experiments with flow visualization techniques on subscale aircraft in free flight is also carried out. Using small onboard cameras it is possible to visualize flows in ways similar to what is common on full size aircraft. While this is a rather obvious possibility it is a method that rarely has been investigated or presented in other subscale flight research projects. In flight flow visualization has become possible thanks to the small, low cost, yet high quality video cameras that are available today. As a test the Rafale aircraft was fitted with wool tufts on its right wing. A 640x480 resolution video camera with onboard memory was mounted on the fin facing the wing and wool tufts. The setup is shown in Fig. 3.

Fig. 3. Test setup with camera and wool tufts.

The aircraft was then flown at high alpha while recording the flow pattern. Several high alpha passes were made where the aircraft was aligned with the wind and flown at constant altitude while slowly increasing angle of attack until control authority was compromised. Some screenshots from the video are shown in Fig. 4.

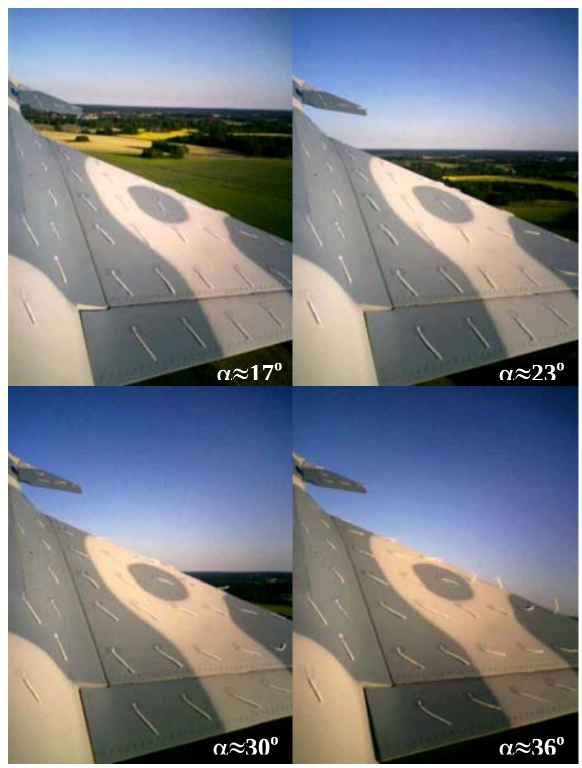

Fig. 4. Flow visualization at high angle of attack.

In these tests the nose boom and alpha beta vane was not used. An approximate angle of attack is instead computed from the AHRS, GPS trajectory and in flight measurement of the average wind velocity. The results are very encouraging and prove how simple and powerful it can be to visualize the flow in real flight. The method also has potential for refinement. In the above test only one camera was used. Using several cameras a larger part of the aircraft could be covered and with some video manipulation a composed video, or mosaic, of a larger surface could be created.

Another method to visualize flow is by using smoke generators. Two techniques are being investigated. Solid smoke cartridges or vaporized smoke liquid. Some initial experiments have been carried out using small smoke cartridges from Björnax [26], but these are rather bulky and can not be mounted to the airframe without disturbing the flow (Fig. 5).

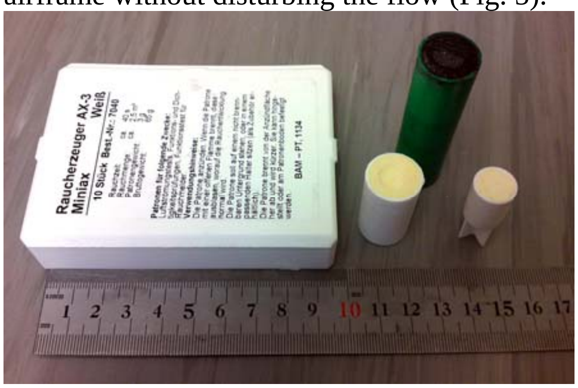

Fig. 5. Smoke cartridges.

A small system for ejecting vaporized smoke liquid through a nozzle in the aircrafts surface is there for under development.

5 Conclusions

With today's continuously increasing time between real aircraft projects, aeronautical engineers of today, and future, will never have the same experience as older generations. Obvious problems might be missed at a conceptual stage due to lack of knowledge and experience. Subscale flight testing offers the benefit of working with actual hardware, facing real problems, while still keeping cost at a minimum. This is not just valuable from a commercial perspective, but also as a means to improve aeronautical education as it is within the budget to easily be carried out at a university level.

The miniaturization of electronics is a key factor for the increased possibilities with subscale flight testing. Light weight low cost data acquisition systems can easily be assembled. Attitude heading and reference systems, GPS receivers, data links etc exists off the shelf. This paper has descried how such components can been used to design a micro controller based logging system. Further more miniature cameras with either video links or onboard memory can be used to complement measurements with in flight flow visualization. Flows can be visualized in a real dynamic environment much better representing the real world then a wind tunnel. A second very important factor that simplifies the development of subscale demonstrators is that RC hobby industry has become very advanced and offers high quality components at reasonable prices. Miniature turbine engines, precision servos, robust frequency hopping rc links, redundant power systems etc are good examples. The consequence of the mentioned factors is that sub scale flight testing can be made cheaper, with smaller aircrafts, and at an earlier stage in the design process then before.

One of the drawbacks with subscale flight testing is that the engineer has no control of the surrounding environment. A subscale aircraft will never fly at a proper Reynolds number, and even at the calmest of days there is always a little bit of turbulence interfering with measurements. It is therefore important to point out that subscale flight testing is only a method to come closer to reality. Just as there can be problems with wind tunnel measurements, CFD simulations etc, the results from subscale flight testing could some times be misleading and thus should be viewed with a critical approach. These are all just tools to "model" the real aircraft and the results are never 100% accurate.

References

[1] Amadori, K. *On aircraft conceptual design – a framework for knowledge based engineering and design optimization*. Licentiate Thesis No. 1366, Dept. of Mec. Eng. Linköping University, LiU Tryck, Linköping, Sweden, 2008.

[2] Amadori, K., Jouannet, C., Berry, P. Development of a subscale flight testing platform for a generic future

fighter. *27th international congress of the aeronautical sciences*, Nice, France, 2010.

[3] Athena Manual 1.40. High Integration CPU with Ethernet and Data Acquisition. Diamond System Corporation, 2004. www.diamondsystems.com.

[4] Atmel product document 7745C-AVR32-05/09 “AVR UC3 A0, A1, A3 USB DFU Bootloader”, 2009. www.atmel.com.

[5] Atmel product document AT45DB321, “32 Megabit 2.7-volt Only Serial DataFlash”. Rev. 1121E–01/01. www.atmel.com.

[6] Croom M, Kenney H, Murri D and Lawson K. Research on the F/A-18E/F using a 22% dynamically-scaled drop model. AIAA Paper 2000-3913, 2000.

[7] Deets D, DeAngelis V, Lux D. Himat flight program: test results and program assessment overview. NASA Technical Report, TM-86725, 1986.

[8] Digi International Inc. XBee-PRO® 868 OEM RF Modules, Datasheet, 2008, Minnetonka, USA.

[9] Dornheim, M. Mcdonnell douglas rolls out X-36. *Aviation Week & Space Technology*, 144(13), 1996.

[10] Gibson C, Neidhoefer J, Cooper S, Carlton L and Cox C. Development and flight test of the X-43a-Ls hypersonic configuration UAV, AIAA Paper 2002-3462, 2002.

[11] Hahne D, Wendel T and Boland J. Wind-tunnel Free-flight investigation of a supersonic persistence fighter. NASA Technical Report, TP-3258, 1993.

[12] Jordan T, Langford W and Hill J. Airborne subscale transport aircraft research testbed - aircraft model development. *AIAA Guidance, Navigation, and Control Conference and Exhibit*, August 2005, San Francisco, California, USA.

[13] Klein V and Noderer K. Aerodynamic parameters of the X-31 drop model estimated from flight-data at high angles of attack. AIAA Paper 92-4357, 1992.

[14] Krus P. Aircraft System Optimization and Analysis for Traceability in Design. *11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference.* September 2006, Portsmouth, Virginia, USA.

[15] Lundström D., Amadori K., ”RAVEN - A Subscale Radio Controlled Business Jet Demonstrator“, 26th Intl Congress of Aeronautical Sciences, Sept 2008, Anchorage, AK, USA.

[16] Saab Tests Subscale UCAV Concept. *Flight International*, 162, 2002.

[17] Tarkian M, Ölvander J and Berry P. Exploring parametric CAD-models in aircraft conceptual design. *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. April 2008, Schaumburg, IL, USA.

[18] Walker L. Flight testing the X-36 - the test pilot's perspective. NASA Technical Report, CR-198058, 1997.

[19] Warwick G. Gulfstream Unveils Concepts For Supersonic Business Aircraft. *Flight International*, 158(4751), 2000.

[20] website: gcc.gnu.org.

[21] website: qextserialport.sourceforge.net.

[22] website: qt.nokia.com/products.

[23] website: qwt.sourceforge.net.

[24] website: www.atmel.com.

[25] website: www.austriamicrosystems.com.

[26] website: www.bjornax.se.

[27] website: www.eagltree.com.

[28] website: www.sensortechnics.com.

[29] www.flightglobal.com. “NASA plans subscale green airliner tests in 2015”. Article by John Croft 07/06/2010.

[30] Xsens Technologies B.V.: MTi and MTx user manual and technical documentation. Document MT0100P, Rev.I, 2007, Netherland.

[31] Yanagihara M, Miyazawa Y, Alimoto T, Sagisaka M, Cretenet J and Venel S. HOPE-X high speed flight demonstration program phase II. AIAA Paper 2001-1805, 2001.

Copyright Statement