Advanced Research Integrated Avionic (ARIA) System for Fault-Tolerant Flight Research

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This paper describes the development of an Advanced Research Integrated Avionics (ARIA) system for a research effort at West Virginia University (WVU) focusing on the design of fault-tolerant control systems toward improving aviation safety. The system seeks to improve upon WVU’s existing avionics system by incorporating more functionality, flexibility, and computational performance while imposing more stringent constraints with respect to size, weight, and power consumption. The system features nine independently controllable/"fault-able" channels making it ideal for use in test-beds for fault-tolerant flight controls research. Furthermore, the design incorporates a novel dual Remote Control (R/C) receiver configuration that aims to decrease potential failures due to R/C signal loss. The hardware architecture is comprised of a network of logic gates and multiplexers, an embedded microprocessor, a general purpose Single Board Computer (SBC), as well as, a complex sensor suite featuring a Global Positioning System / Inertial Navigation System (GPS/INS) navigation solution.

I. Introduction

As of 2009, there are a large number of Unmanned Aerial Vehicles (UAV) of different sizes and for different purposes being manufactured by over 220 institutions in 44 nations. While commercially available autopilots have been extensively used for UAV research applications, advanced flight controls research often leads researchers to develop custom UAV avionic systems to meet their specific requirements. These custom system architectures vary depending on their operational requirements, and also due to constraints such as size, weight, power consumption and budget. The Advanced Research Integrated Avionic (ARIA) system, being developing at West Virginia University (WVU), meets several complex research requirements, along with strict power, weight, size and cost limitations.

Extensive technical literature describes several customized avionic systems designed by various universities, industries, and federal agencies. For example, the Airborne Subscale Transport Aircraft Research Test bed (AirSTAR) program at NASA Langley uses dynamically scaled vehicles equipped with customized avionics capable of faster dynamic responses than the full-scale aircraft counterpart within a research program focused on improving aviation safety. The AirSTAR system utilizes computational resources at a ground station to receive state information from Radio Frequency (RF) telemetry downlink and to send control commands through an RF uplink. This architecture has the benefit of relying on ground station computational power that is not limited by size, weight and power consumption, but could potentially experience problems due to communication interference leading to latency, packet loss, etc. Another example, researchers at Stanford University developed an avionic system to test sensor fusion techniques using a customized GPS receiver that features multiple antennas, and a Honeywell’s HG-1700 Inertial Measurement Unit (IMU) with tri-axis ring laser gyroscopes. While providing an excellent platform for a specialized research topic, including ring laser gyroscopes may be beyond the affordability limitations of many research UAVs. A different system, the FCS20 developed at the Georgia Institute of Technology uses Digital Signal

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Processing/ Field Programmable Gate Array (DSP/FPGA) technology and has a credit card sized form factor. Using a totally different approach, the Massachusetts Institute of Technology (MIT) utilizes an indoor flight testing facility for flight controls research in which the laboratory environment known as Real-time indoor Autonomous Vehicle Test Environment (RAVEN) is outfitted with the necessary means of measuring the UAVs dynamic state. This approach has the clear advantage of being able to rapidly perform complex flight control tests on a large variety of low-cost platforms. However, with respect to up-front costs, this approach likely exceeds the affordability limitations of many within the research community, and does not provide a solution implementation outside of the research environment.

Researchers at West Virginia University (WVU) have been involved in UAV research since 1997. Developing customized avionics systems for flight controls research started with basic data acquisition and has since evolved to a full range of flight control applications, such as the system developed for WVU’s jet-powered YF-22 research aircraft used for validating GPS-based formation control laws and fault-tolerant flight control laws. In recent efforts, WVU researchers have developed a small autopilot as part of a Modular Avionics Platform (MAP) that weighs only 3 oz. and features attitude determination via GPS/INS sensor fusion. Furthermore, flight data from the formation flight project has been used offline to demonstrate the potential of GPS/INS data fusion for attitude determination using Extended Kalman Filter (EKF) within WVU’s YF-22 research UAV. The development of the ARIA system has evolved from the lessons learned throughout WVU’s decade of UAV avionic system development as well as adapting the latest technological advances to address new research requirements. This new system provides the necessary upgrades for expanding the capabilities of potential flight controls research applications within a variety of advanced topics, which are discussed in the Design Requirements section of this paper.

The rest of the paper is organized as follows. Section II briefly describes existing UAV avionic systems developed by WVU. Section III discusses the design requirements of the ARIA system. Section IV describes the ARIA’s hardware and software system development. Section V summarizes the initial flight testing results of the ARIA system onboard the YF-22 test-bed. Finally, Section VI concludes the paper and summarizes plans for future development.

II. Existing Systems

A. YF-22 Avionic System

The existing WVU YF-22 avionic system consists of an On-Board Computer (OBC) based on a PC-104 stackable system that consists of a 300 MHz Central Processing Unit (CPU) board, a power supply, and a data acquisition module with 32 A/D channels. The sensor suite features a high quality vertical gyro for direct measurement of the vehicle’s roll and pitch angle, a GPS receiver, and a solid-state six degrees of freedom Inertial Measurement Unit (IMU). In addition, the current system provides six independently controllable channels allowing for multi-controllable channel configurations, such as the control of the left/right ailerons and stabilators independently along with dual rudder control and throttle. Within the six controllable channels, actuator failures can be ‘injected’ during flight maneuvers, where the vehicle can be either flown under pilot control, operate autonomously, or operate partially autonomous. A layout of the current YF-22 vehicle and payload hardware configuration are shown in Fig. 1 [reproduced from 9].

![Fig. 1: WVU YF-22 Avionics System [9]](image-url)
B. Modular Avionics Platform Autopilot

To address the need of avionics systems that can serve a large variety of UAV research requirement with a limited budget and development time, a Modular Avionics Platform (MAP) was introduced by researchers at WVU based on a layered architecture and interchangeable Commercial-Off-The-Shelf (COTS) components. At its minimum configuration, a small autopilot has the ability to perform GPS-based waypoint navigation. The attitude reference is provided by the fusion of information collected from GPS/INS, based on a low cost Micro-Electrical-Mechanical System (MEMS) IMU. This baseline configuration has a small footprint with low weight along with minimum power-consumption and Electro Magnetic Interference (EMI); as shown in Fig. 2[reproduced from 13].

![Autopilot System](image)

**Fig. 2: Autopilot System [13] Design Requirements**

Table 1, as developed by Gu in [13], describes a list of common research topics and their specified requirements for UAV avionic systems.

<table>
<thead>
<tr>
<th>Research Topic</th>
<th>Specific Avionics Requirements</th>
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<tbody>
<tr>
<td>Flight Dynamics</td>
<td>High quality sensor measurements; fast update rate; and the ability to measure pilot control commands.</td>
</tr>
<tr>
<td>Flight Controls</td>
<td>Additional ability to control individual aircraft control effectors.</td>
</tr>
<tr>
<td>On-Board Excitation for aircraft Parameter IDentification (PID)</td>
<td>The ability to automatically apply pre-specified waveform inputs to control effectors during flight maneuvers.</td>
</tr>
<tr>
<td>Fault-Tolerant Flight Control</td>
<td>The ability of ‘injecting’ and ‘removing’ pre-specified sensor and/or actuator failures during flight tests.</td>
</tr>
<tr>
<td>On-line PID / On-line Training Neural Networks /Real-time Machine Vision</td>
<td>Extended on-board computational resources.</td>
</tr>
<tr>
<td>Formation Flight /Multiple vehicle coordination /Collision avoidance</td>
<td>Multipoint communication or wireless mobile networking.</td>
</tr>
<tr>
<td>Micro Aerial Vehicles (MAV)</td>
<td>Extremely low weight and power consumption.</td>
</tr>
<tr>
<td>Agricultural /Surveillance /Air Sample Collection</td>
<td>Autonomous waypoint navigation capabilities; low weight and power consumption; ability to integrate aircraft flight data with scientific instrument measurements.</td>
</tr>
<tr>
<td>Pilot-In-The-Loop Control</td>
<td>Ability to monitor ground pilot input so that the pilot and controller can work together</td>
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Based on avionic development experience at WVU, the development of the ARIA system is intended to meet all the research requirements listed in Table 1, with the exception of the MAV research topic, by taking advantage of the latest advancements in microprocessors, sensors, and sensor fusion technologies.

An additional design requirement of the system derives directly from an issue encountered during the designs of the existing WVU avionic systems. Particularly, a potential problem for any avionic system design for unmanned research vehicles is the presence of EMI. Within UAVs, the issue of EMI is recurrent due to the close proximity of
electrical components within a relatively confined space. A combined approach using a RF spectrum analysis along with the use of conventional ferrite chokes and metal shielding provided a adequate reduction in EMI problems for the design of the WVU YF-22 avionics payload. However, an improved R/C range is highly desirable to ensure a safer operation, which requires a systematic approach of designing a low noise system during every step of the avionics design.

Another design requirement of the ARIA system consists of increasing degrees of freedoms for simulating aircraft sub-system failures, compared to the 6-channel design of the existing YF-22 avionic system. To be able to split all the conventional control surfaces into their left and right counterparts while also controlling throttle, nine controllable channels are required for this research.

III. System Development

A. Hardware Architecture

The ARIA system consists of a stack of three Printed Circuit Boards (PCBs). The 1st (top) board of the stack is a general purpose Single Board Computer (SBC) featuring integrated data acquisition. The 2nd (middle) board is a standard PC/104 power supply that also provides two additional serial ports. The 3rd (bottom) board of the stack is a custom developed board that serves as a sensor interface and signal distribution controller. Within the custom PCB an embedded microprocessor is included and a MEMS IMU is mounted in the center. The overall dimensions of the ARIA system when compared to the current YF-22 avionics system resulted in a 50% reduction in total volume. In addition, the total weight of the new avionic system is approximately 3 lbs, with an approximate 5 lbs weight saving with respect to the previous avionic system. This is partially due to the replacement of a mechanical vertical gyro with EKF-based GPS/INS sensor fusion algorithm for Euler angle estimations. A photo of the ARIA system with enclosure removed is shown in Fig. 3.

![Fig. 3: ARIA System (Right) and Current YF-22 Avionics System (Left)](image-url)

A 32-bit 66 MHz Freescale ColdFire MOD 5213® microprocessor with a real-time operating system is integrated into the custom PCB and used to tackle much of the communications workload within the system. The MOD 5213 allows task prioritization with seven interrupt levels. Its tasks include interfacing with the MEMS IMU, reading control command signals from the ground pilot generated by the R/C receiver, and writing control commands as prescribed by the on-board flight control software. The microprocessor receives inertial information through a serial peripheral interface (SPI) from Analog Device’s ADIS-16355 High Precision Tri-Axis IMU. The inertial information recorded includes three-axis acceleration, and angular rates. The entire function of reading and writing control command signals is described in detail in the next section of this paper.

The Diamond System’s 800 MHz Athena II general purpose SBC with sixteen 16-bit integrated A/D serves as the main flight computer within the ARIA system. Along with a PC/104 compatible power supply, a total of 6 serial ports are available for communicating with various devices. Two serial ports are devoted for communication with the embedded microprocessor, while an additional two are utilized to interface with a GPS unit and a RF modem leaving two available for auxiliary external devices. One proposed expansion would be the use of multiple GPS receivers. Using the general-purpose SBC effectively enhances the on-board computational resources and provides additional interfaces without the need for customized hardware design.
Sensors outside of the main ARIA enclosure consist of a GPS receiver, nose probe sensors, and control surface deflection indicators. The Novatel OEMV-1® GPS receiver is used to provide position and velocity measurement at a 20 Hz update rate. The analog sensors include potentiometers that measure control surface deflections, vaned potentiometers that measure the angle of attack and sideslip flow angles, a thermister that measures air temperature, and pressure transducers that measure both the static and dynamic pressures at the nose probe. The angle of attack and sideslip measurement vanes and the pitot tubes are part of a high-quality SpaceAge® Probe affixed at the nose of the test-bed. Fig. 4 shows the general hardware layout and indicates the various signal types for each signal input/output.

**Fig. 4: Avionics Hardware System Layout**

Fig. 5 displays the custom developed PCB with each component and interface labeled.

**Fig. 5: ARIA System Main PCB**

In order to maintain the maximum number of 16-bit A/D channels on the CPU’s main DAQ card, an embedded A/D converter with SPI output interface is utilized to acquire the five analog nose probe signals. The embedded A/D
The system utilizes a converter that is Analog Devices AD7699 which provides 8-Channel at 16-bit resolution. A photo of the nose probe signal processing board is displayed in Fig. 6.

![Fig. 6: ARIA Nose Probe Signal Processing PCB](image)

The potentiometer signals that monitor the control surface deflections of the UAV are collected, and the PWM signals that control the R/C Servos and the ECU of the UAV are distributed with the same PCB. This PCB is located in the back of the UAV and is shown in Fig. 7.

![Fig. 7: Actuator Command Distribution / Control Surface Deflection Collection Board](image)

Table 2 lists some common specifications of the primary sensors within the system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Signal</th>
<th>Range</th>
<th>Resolution</th>
<th>Nonlinearity (% of FS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADIS16355® IMU</td>
<td>Angular Rate</td>
<td>±150°/s</td>
<td>0.03663 °/s</td>
<td>±0.1</td>
</tr>
<tr>
<td></td>
<td>Acceleration</td>
<td>±10 g</td>
<td>2.522 mg</td>
<td>±0.2</td>
</tr>
<tr>
<td>SpaceAge® Probe Potentiometers</td>
<td>Alpha, Beta</td>
<td>±30°</td>
<td>9.16x10⁻⁴ °</td>
<td>±5</td>
</tr>
<tr>
<td>Honeywell ASCX15AN</td>
<td>Absolute Pressure</td>
<td>0-15 psia</td>
<td>0.069 mpsia</td>
<td>±0.1</td>
</tr>
<tr>
<td>Honeywell ASCX01DN</td>
<td>Dynamic Pressure</td>
<td>0-1 psid</td>
<td>1.03 mdsid</td>
<td>±0.1</td>
</tr>
<tr>
<td>Bourns® 10kΩ Potentiometer</td>
<td>Surface Deflections</td>
<td>0-10v*</td>
<td>16-bit</td>
<td>±10</td>
</tr>
</tbody>
</table>

*angular range varies per control surface type and are calibrated

B. Control Command Signal Processing

Using the embedded processor within the ARIA system, Pulse Width Modulation (PWM) signals are captured and measured using three 16-bit timer channels. Logging the ground pilot commands also allows for the possibility of human pilot-in-the-loop control in which the on-board controller and ground pilot collaborate. In addition, the
system also writes nine independent PWM signals based on commands produced by the on-board control algorithm. With respect to pilot inputs, a total of eight PWM channels are read with the two 16-bit timers by multiplexing the eight individual channels into two sets of four using a network of logic OR gates. Within this process, special care was given to PWM signal timing such that no information was lost by multiplexing the independent control channels into one signal. A 3rd 16-bit timer is used solely for reading the system “Mode Switch” that determines whether the ground pilot or the on-board software has control over the UAV. The full function of the “Mode Switch” is discussed in greater detail in the next section of this paper.

Upon establishing the low-level software for reading PWM commands, an issue was encountered with respect to signal synchronization. Within the counting algorithm that is used for demultiplexing the signal of four PWM channels into independent channels, the channels are read in the order in which they reach the 16-bit timer. Since it is common for the R/C system to be turned on prior to the rest of the ARIA system, it is possible for any of the four channels within the multiplexed PWM signals to trigger 16-bit timer first. Therefore, additional software was developed to ensure that the PWM channels are identified and recorded in the correct sequence each time the system is activated. The channel identification software takes advantage of the timing of the 50 Hz PWM signals. In particular, since the signal is updated at a rate of 50 Hz, and the four channels are spaced over a 0.02 s interval, two channels have a larger signal “low” gap between them then the other gaps. Using the fact that the largest “low” gap always occurs before a specific channel, all of the channels are then synchronized.

The microprocessor also produces nine PWM signals to control aircraft servos and the Engine Control Units (ECU). This function uses a Direct Memory Access (DMA) timer to activate digital output pins with 16-bit precision according to commands supplied by the on-board software. These commands are then fed to a network of duplexers and are available to control individual vehicle surfaces as well as the engine throttle.

C. Fault-Tolerant Architecture

The “Fault-Tolerant” nature of the ARIA system primarily refers to the aspects of the system allowing for advanced fault-tolerant flight control research within UAVs. However, the ARIA system also incorporates a novel dual R/C receiver feature that provides a fault-tolerant aspect within the system that heightens its own operational safety. This section describes both the ARIA features that allow for advanced fault tolerant research, as well as the dual R/C receiver function.

Within the ARIA system a total of nine channels can be controlled independently by either a ground pilot or autonomously by the on-board software. Nine independent channels allow independent control of typical channels such as throttle, all the conventional control surfaces (rudder, aileron, and stabilator) as well as independent control of the flaps. However, the nine available channels are generic in that they can be utilized in application specific configuration. This aspect of the ARIA system uses both hardware and software components to provide a two-tiered signal control system. The logic diagram and participatory components for one single channel is illustrated in Fig. 8.

![Fig. 8: Controlled Channel Logic Diagram](image-url)
In Fig. 8, the signals indicated with dashed lines are PWM signals and the signals indicated with solid lines represent digital control signals (high or low). As indicated in Fig. 8, Receiver A sends the ground pilot command to a duplexer that acts as a double-throw switch. The default for the duplexer is to feed the ground pilot command from Receiver A directly to the actuator; therefore, in the event of a computer failure, the ground pilot will automatically regain control. Receiver A also sends a “Mode Switch” signal to the embedded microprocessor that is read by a timer and converted into a digital logic signal that is fed to a logic AND gate. The other input to the logic AND gate is a digital output signal from the main CPU, which serves as an “Individual Channel Mode Switch”. The output of the logic AND gate is used as a control signal for the duplexer. Thus, for the on-board software command to gain control over an actuator, both the “Mode Switch” activated by the ground pilot and the “Individual Channel Mode Switch” digital output from the CPU must be positive logic (both must be high voltage). The logic levels of the “Individual Channel Mode Switch” are user defined through software prior to each flight. This allows for the possibility of operating the UAV under partially-autonomous conditions, such as “injecting” an actuator failure on a specific control surface while the ground pilot is flying the UAV.

Also shown in Fig. 8 is the dual R/C Receiver (A and B) configuration. The purpose of integrating two receivers in the ARIA system is to develop a novel approach with the goal of limiting failure due to R/C signal loss. Specifically, both receivers are set-up to receive and interpret the commands from the ground pilot’s radio; however, they have a different antenna orientation. Receiver A is the default for ground pilot operation, and is wired to function properly even in the event of computer power loss. Receiver B’s primary purpose is to provide data for logging and recording pilot inputs using the embedded microprocessor. Each individual channel from the ground pilot is then sent from Receiver B to the embedded microprocessor; however, the “Mode Switch” channel from Receiver A is also sent to the embedded microprocessor. Therefore, since the microprocessor has access to signals from both Receivers A and B, the software gives priority to one set of ground pilot commands if a signal dropout is detected on the other receiver. The dual R/C receiver configuration relies on the Fail-Safe feature that is widely available on COTS R/C receivers. Ultimately, if one receiver is determined to be in Fail-Safe mode while the other has a valid signal, the valid receiver signals are fed through. Within this setup, the antennas of the two R/C receivers are arranged such that there is no overlapping RF “blind spot”. In the event that the RF links of both receivers are broken during flight, the UAV enters Fail-Safe mode II or III depending on the health status of the UAV as described in Table 3. This feature provides an element of redundant fault-tolerance capability within the ARIA system; furthermore, this feature carries a minimum cost, since it requires limited weight and power consumption to include two R/C receivers. Using the nine controllable channels the ARIA system can operate in any of the operational modes listed in Table 3, which is an updated version of a table presented in Gu [13].

### Table 3 Operational Modes of the ARIA System [adapted from 13]

<table>
<thead>
<tr>
<th>Operational Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Mode</td>
<td>The ground pilot has full authority of the UAV. The pilot can switch to ‘Manual Mode’ instantaneously under any conditions as long as the RF link is operational. This mode can be used for aircraft manual takeoff and landing as well as the emergency recovery from other operational modes.</td>
</tr>
<tr>
<td>Autonomous Mode</td>
<td>The on-board flight control system has full control of the aircraft.</td>
</tr>
<tr>
<td>Manual/Autonomous Mode</td>
<td>A subset of the flight control channels is under autonomous control while other channels are still controlled by the ground pilot. This mode is very useful for incremental testing of flight control sub-systems.</td>
</tr>
<tr>
<td>Pilot-In-The-Loop Mode</td>
<td>The flight control system assists the pilot in controlling the aircraft. The pilot command is measured and supplied as inputs to the flight control system.</td>
</tr>
<tr>
<td>Actuator Failure Mode</td>
<td>A subset of the flight control channels is commanded to simulate various types of control effector failures (lock in place, floating, hard over etc.), while the rest control channels are under manual, autonomous, or pilot-in-the-loop control.</td>
</tr>
<tr>
<td>Fail-Safe Mode I</td>
<td>Switch to receiver B following receiver A loss of contact.</td>
</tr>
<tr>
<td>Fail-Safe Mode II</td>
<td>In the case that both RF links are lost during the flight, the autopilot system aborts the current mission and reset the waypoint back to the recorded initial launch position.</td>
</tr>
<tr>
<td>Fail-Safe Mode III</td>
<td>In the case that the aircraft is facing unrecoverable failure (such as engine failure or permanent loss of GPS reception) the autopilot can command to cut the engine throttle and put the aircraft into deep stall mode (if possible) to minimize the damage to ground personnel and surrounding facilities.</td>
</tr>
</tbody>
</table>
D. Real-Time Operating System

Using the general-purpose processor facilitates the use of the abundance of both commercially available and open source software products. The onboard Operating System (OS) utilized is a Linux kernel patched with Real-Time Application Interface (RTAI). With the approach outlined in [14] an RTAI target has been be implemented so that algorithms developed in the Matlab® and Simulink® can be compiled into real-time executables using the Real Time Workshop®. Currently, the real-time operating system (RTOS) is bootable on a Compact Flash (CF) card through an external IDE adapter, and future development is geared toward booting the OS from a USB flash drive. The current target environment is Linux kernel 2.6.9 patched with RTAI 3.2.

E. On-Board Power Supply

A total of six on board batteries are required within the ARIA system to power to YF-22 UAV. A single 14.8V 4S 3300mAh Li-Poly is used to power the main ARIA system, and GPS unit, a 7.2v 1250mAh NiCd pack is utilized for the ECU, propulsion starter, and fuel pump; and four 4.8v 1600mAh NiMN packs are use for the R/C system (specifically one for each R/C receiver, and two for the control actuators).

IV. Flight Testing Results

A. System Performance Validation

The initial flight of the ARIA system was conducted at the beginning of the 2009 flight season onboard the WVU YF-22 research test-bet. The primary goal of the flight was to verify the data acquisition performance, and to collect a set of data to facilitate the development of a GPS/INS sensor fusion algorithm. In order to evaluate its performance, both ADIS-16355 MEMs IMU and the Crossbow VG400A IMU - which has provided known quality flight data within the current YF-22 avionic system11,12 - were flown to provide a comparative flight data set. The data channels monitored to facilitate GPS/INS sensor fusion algorithm development included the tri-axis inertial information from the two IMUs, as well as the GPS receiver solution for Cartesian position and velocity. In addition, the direct measurement of the aircraft’s pitch angle was monitored with a high-quality vertical gyroscope to provide a truth data for the sensor fusion attitude estimation. Another goal of the initial flight was to verify that the system successfully mitigated EMI to provide acceptable R/C ground range.

The GPS track of the ARIA system’s first flight is shown in Fig. 9.

![GPS-Track of ARIA Flight](image)

Fig. 9: GPS Track of ARIA’s First Flight

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The flight had duration of approximately six and half minutes, and consisted of multiple loops in which the pilot performed doublet maneuvers on the stabilators. A clear outcome of the experiment is that the accuracy of the flight data from the ADIS-16355 MEMs IMU makes it very suitable for its application within a sensor fusion scheme. Fig. 10 (L) displays the angular rates around the 3 axes measured with the ADIS-16355 IMU, and Fig. 10 (R) displays the linear accelerations along the 3 axes measured with the ADIS-16355 IMU over a 50 sec. segment of data during the flight.

**Fig. 10(L): ADIS-16355 IMU Angular Rate Measurements**

One instance of the periodic doublet maneuver performed on the stabilators is most evident in the pitch rate signal within Fig. 10(L) and the Z-axis acceleration in Fig. 10 (R). Fig. 11 shows a comparison of an accelerometer signal from both IMUs.

**Fig. 11: Comparison of Crossbow VG400A and ADIS-16355 IMU Acceleration Channel**

As indicated in Fig. 11, the accelerometer signal from the ADIS-16355, which is part of the ARIA system, appears less noisy than the Crossbow IMU. This trend is confirmed by the calculation of the signal standard deviation over a segment of 100 sec. of data over a period in which the test bed was at rest on the runway. For example, for the Z-axis acceleration channel, the standard deviations for the Crossbow unit and the ADIS-16355 unit are 0.7731 m/s² and 0.2564 m/s² respectively. Fig. 12 shows a similar a comparison of an angular rate signal from both IMUs.
In this case the pitch rate signal on the ADIS-16355 signal is noisier than the same channel on the Crossbow unit. When considering the same segment of data the Crossbow IMU and the exhibits a standard-deviation of 0.751 deg./s while the ADIS-16355 shows a standard-deviation of 1.385 deg./s.

With respect to EMI, the ARIA system had acceptable R/C ground range (over 400 ft) without the need for RF-chokes or any elaborate EMI shielding techniques. In addition, the initial flight included the mechanical gyroscope for direct Euler angle measurement and its accompanying 28v DC-DC power supply. Therefore, it will likely enjoy better ground range performance once the GPS/INS navigation fully developed and the mechanical gyro is removed from the system.

**B. Implementation of Sensor Fusion Algorithm**

Within this work, the result of a direct implementation of the sensor fusion algorithm as formulated in the past work of WVU researchers is presented. The implementation of a 9-State EKF provides a navigation solution consisting of the triad of each position, velocity and attitude using data recorded during the initial flight of the ARIA system is shown. In addition, the pitch estimate is compared to the direct measurement of pitch with a mechanical gyroscope.

Figs. 13 displays the estimation of position and velocity as compared to GPS-measured data.

**Fig. 13(R): EKF Estimated and GPS Measured Position**

As shown in Fig. 13 the EKF estimate is nearly identical to the GPS measured position and velocity. Fig. 14 shows a closer view of 30 seconds of GPS receiver solution and EKF estimate of the vehicles Z-axis position.
Fig. 14: Zoomed View of EKF Estimated and GPS Measured Z-Position

The smoothness of the EKF position estimate in Fig. 14 illustrates how the low frequency INS fills position information gaps within the GPS measurement. Fig. 15 shows estimated pitch as compared to the measured pitch angle. The measured pitch angle was directly measured with a Goodrich Sensor Systems Vertical Gyroscope VG34®. It was also intended to measure the roll with the Goodrich gyroscope, but the roll channel was not recorded due to a simple connection problem on the day of the flight.

Fig. 15: EKF Estimated Pitch (L): Measured Pitch

As shown in Figure 15, the pitch estimate given by the GPS/INS is very closely correlated with the direct measurement of the pitch angle from the Goodrich gyro. The mean error of the pitch estimate over duration of the flight with respect to the measured pitch is 0.0329 degrees, and the standard deviation of the error is 5.7 degrees.

V. Conclusions and Future Work

In this paper, the development of an Advance Research Integrated Avionics (ARIA) developed by researchers at WVU has been discussed. The ARIA system improves upon existing WVU platforms by providing a smaller, lighter, and more powerful system suitable for a variety of research missions. Furthermore, the system provides both auxiliary RS-232 serial ports and 16-bit A/D channels for easy integration of additional sensors. To date the ARIA system has been flight tested on the YF-22 UAV and is scheduled to be flight tested on additional UAV platforms.

While GPS/INS has been widely studied and adapted into UAV navigation systems, in future work, the performance of different sensor fusion algorithms will be evaluated with the ARIA system based on estimation error with respect to attitude angles directly measured with a high-quality mechanical gyroscope. The algorithms will be evaluated with respect to required computational load due to their real-time operational requirement. The primary group estimation schemes that will be studied are Extended Kalman Filtering, Unscented Kalman Filtering, and Particle Filtering. In addition, it is envisioned to modify the algorithms with quaternion attitude reference, as opposed to the more conventional Euler angles, which could potentially provide a less computationally intensive and, at the same time, a more robust algorithm.
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VII. References


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