Flight Data Acquisition Platform Development, Integration, and Operation on Small- to Medium-Sized Unmanned Aircraft

Conference Paper · January 2019

DOI: 10.2514/6.2019-1262

2 authors:

Or Dantsker
University of Illinois, Urbana-Champaign

Renato Mancuso
Boston University

Flight Data Acquisition Platform Development, Integration, and Operation on Small- to Medium-Sized Unmanned Aircraft

Or D. Dantsker *
Al Volo LLC, Urbana, IL 61801

Renato Mancuso†
Boston University, Boston, MA 02215

Unmanned aerial vehicles (UAVs) are rapidly increasing in popularity for civilian, military, and research applications, and as part of this uptrend, significant effort has been undertaken to integrate an increasing amount of sensing into these vehicles. This sensing, or in other words, acquisition of sensor data, is part of the core functionality of UAVs — without the ability to sense, an unmanned aircraft is unable to function. By intelligently integrating sensors into a vehicle and properly interfacing with them, one is able to derive streams of data from these sensors, which allow the aircraft to fly and the desired mission to occur. In just the past several years, along with the uptrend in UAV use, there has been an increase in the research to evaluate and improve aircraft performance and flight characteristics. All of these efforts depend on the ability to acquire and utilize high fidelity data from a large range of sensors and devices. This paper will first provide an overview for the development of a data acquisition system. It will then focus on the design aspects involved including system architecture, sensing interfaces, common sensors, and user interface. Next, the paper will present a study of data acquisition systems and flight control systems that have been used in UAV research, with their specifications. Finally, avionics integration examples will be provided to demonstrate application in an unmanned aircraft.

Nomenclature

ADC	=	analog-to-digital converters
AHRS	=	attitude and heading reference system
CPU	=	central processing unit
DOF	=	degree of freedom
ECU	=	engine control unit
ESC	=	electronic speed controller
GPS	=	global positioning system
GNSS	=	global navigation satellite system
IC	=	integrated circuit
IMU	=	inertial measurement unit
INS	=	inertial navigation system
I/O	=	input output
PCB	=	printed circuit board
PWM	=	pulse width modulation
PPM	=	pulse position modulation
RC	=	radio control
UAV	=	unmanned aerial vehicle

* Aero-Mechanical Engineer. ordantsker@alvolo.us
† Assistant Professor, Department of Computer Science. rmancuso@bu.edu

I. Introduction

Unmanned aerial vehicles (UAVs) are rapidly increasing in popularity for civilian, military, and research applications. As part of this uptrend, significant effort has been undertaken to integrate an increasing amount of sensing into these vehicles. This sensing, or in other words, acquisition of sensor data, is part of the core functionality of UAVs — without the ability to sense, an unmanned aircraft is unable function. By intelligently integrating sensors into a vehicle and properly interfacing with them, one is able to derive streams of data from these sensors, which allow the aircraft to fly and complete the desired mission.

In just the past several years, along with the uptrend in UAV use, there has been an increase in the research to evaluate and improve aircraft performance and flight characteristics. For example, significant effort has been put into studying their aerodynamic qualities,[1,2] especially in high angle-of- attack conditions,[3–5] as well as the development of new control algorithms.[6–11] In addition, unmanned aircraft are often used as low-cost stand-ins for experiments that are too risky or costly to perform on their full scale counterparts.[12–14] They are often also used to explore new aircraft configurations[15–18] or flight hardware.[19–21] All of these efforts depend on the ability to acquire and utilize high fidelity data from a large range of sensors and devices.

This paper will first provide an overview for the development of a data acquisition system. It will then focus on the design aspects involved including system architecture, sensing interfaces, common sensors, and user interface. Next, the paper will present a study of data acquisition systems and flight control systems that have been used in UAV research, with their specifications. Finally, avionics integration examples will be provided to demonstrate application in an unmanned aircraft. The paper will conclude with a summary.

II. Development Overview

Capturing data is a fundamental component of conducting flight research with unmanned aircraft and doing so requires the acquisition of high fidelity flight data from a large range of sensors and devices. This naturally leads one to either attain and utilize an existing data acquisition platform or to develop their own if they are unable to find a system that can satisfy their needs. This process, as do many others, generally follows the engineering design process, shown in Fig. 1. At the start, one has to understand the underlying problem: what type of data needs to be collected; this will depend on the intended research that will be conducted. This often involves performing an extensive study of platforms currently available as well as those that have been developed at universities and research agencies, as will be presented in the following section. This research then leads to an extensive list of desired and/or required specifications, most often based on what is state of the art. The first and likely most critical consideration that must be taken into account is that of the intended uses of a platform and the sensors required. Essentially, what data must be captured and why? From this point forth, it will be assumed that the interested party was unable to find an existing system that satisfies their requirements and has decided to develop their own.

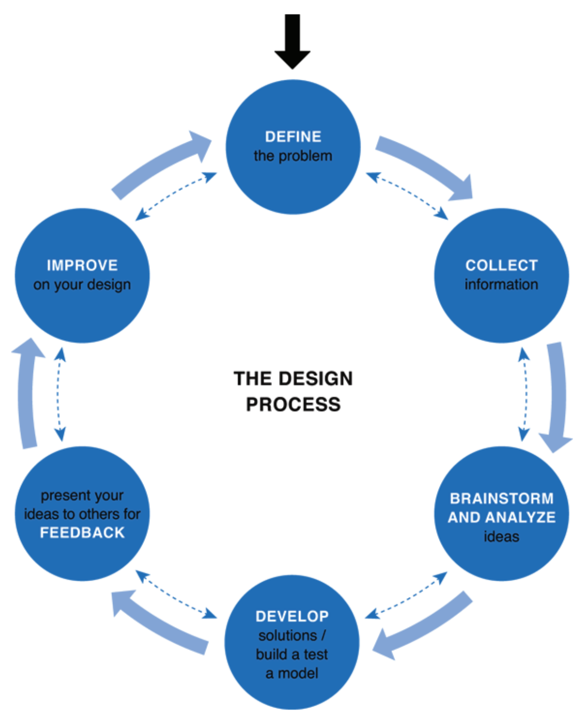


Figure 1. The engineering design process.

The next consideration is that of platform integration, i.e., how will it be integrated into the aircraft and whether there are size, weight, access constraints. This is especially important on small unmanned aircraft, which leads to the notion that a platform must likely be highly integrated; however, at the same time, such tight integration can be restrictive, especially if modifications must be made. Should the platform designer, for example, split the data acquisition between multiple logical devices, sending all of the measurements back into a central device? This could be advantageous in distributing the work, especially if some logical devices can be given the task of handling high-level tasks while others handle low-level tasks. Yet implementing such a platform design may lead to sensory streams having undesirable temporal properties, which in turns affects the quality of produced data. Alternately, the platform may be made up of a single logical device prudently managing all of the sensors and measurement devices. Generally, performing benchmark testing of a platform will help determine which approach should be used.

In order to reach design maturity, testing is key. Initial development is often performed by piecing together and interconnecting a set of mostly independent, integrated circuit (IC) components, each on their own printed circuit board (PCB). The strict segregation of components is initially used to test each and every subsystem individually, while designing the software/hardware infrastructure with the integration goal in mind. The *divide et impera* approach has shown to produce highly reliable sensor-processor communication. Then, as the system is miniaturized, these components moved into close proximity with each other. Apart from the obvious hardware integration, subtle signal interplay and similar issues arising from circuit-level integration must be extensively investigated and addressed. Many issues are largely software dependent, as timing properties of software-hardware interaction routines need to be re-calibrated once all the subsystems are contemporarily active. For other issues, new revision of the hardware layout are often required and yield the most reliable solution in terms of reliability and robustness. Flight testing, throughout the whole miniaturization process, also reveals several other challenges that cannot be discovered on the ground.

Minimizing the time required to develop and integrate a platform into an aircraft is also very important and thus a crucial design driver that must be taken into account. Effectively, there is little point to perform system development if the end results will either be too late to meet a project timeline or be impossible to integrate. Therefore, significant effort should be put into developing a self-contained system that could be assembled, installed, and controlled. Regarding control, the end use researcher must be able to interface with the platform in order to communicate required commands. This can mean a wired or wireless connection; however, extra care should be taken with the later for some applications, especially those with possible RF interference or other limitations. Thus, the goal of this particular design effort is to ensure that in a complex environment, as most aircraft testing setups are, the platform can be self-contained, not cause interference, and finally be controllable. Effectively, this describes the deployability of the platform solution, which is especially difficult on small electric unmanned aircraft.

III. Design Aspects

The design of a data acquisition system requires careful consideration and forethought. In this section we discuss a variety of design aspects, which should be considered during the development process.

A. Architecture

A data acquisition system designed to operate on board in a UAV is required to define two main sub-systems. The first essential sub-system is comprised of a set of sensor-side I/O interfaces that goes under the name of *low-level sensor interface*. The second fundamental building block is the *data aggregation and storage* unit, which, as the name suggests, aggregates what is collected via the low-level interface into a single data stream. It then performs a minimum set of format conversion operations, on each sample of the data stream, intended to optimize the aggregated data for long-term storage.

While the subsystems described above represent the bare minimum for a data acquisition system, a number of additional modules can be added to increase functionality, in-the-field deployability, and composability with the rest of the onboard avionics. An important module that is usually implemented is a *command & control unit* to direct acquisition and logging operations. Apart from local storage of the acquired data, the system may also provide a set of live feed *data streaming communication units*. Communication interfaces can be used to provide a sensor feed to other on-board sub-systems (e.g. an autopilot), to establish a telemetry channel with a ground station, and to allow in-flight access to the command control interface. Finally, a data acquisition system may offer a *graphical user interface* that internally leverages the communication and the command control interface. The goal of the graphical interface is to simplify in-the-field configuration and operation.

Given the required and optional modules described above, the mapping of these modules onto computation units dictates a number of important properties of the final acquisition system, such as: (1) maximum acquisition rate; (2) degree of user-level interactivity; (3) degree of integration with other on-board avionics; (4) degree of inter-operability with different UAVs. We now delve into typical design trade-offs between system complexity and the four properties mentioned above.

1. Processing Domains

In this work, we refer to a *processing domain* as a self-contained processing system. This includes one or more processors (CPUs), memory resources and communication interfaces. A processing domain also defines a power and clock domain. It follows that different processing domains are also tolerant with respect to power and/or clock loss that occurs in a different processing domain.

The multiple components of a data acquisition system mentioned above operate at very different time scales. On the one side of the spectrum, the low-level sensor interface needs to be precise at a micro-second scale. On the other hand, the communication with the user can be carried out few times every second. Components like data aggregation unit, command control, and communication have their own timescale. In principle it is possible to consolidate all these components onto the same general-purpose processing domain. In practice, however, this choice leads to unstable performance and sub-optimal maintainability.

A system design where both necessary and optional units are implemented onto the same processing domain will be sub-optimal for two main reasons. First, low-level communication with sensors often involve handling a large number of short-lived I/O events to/from the sensor pool. While each event generally requires few processor cycles, a context-switch from other processing flows (e.g. user interface handling) is required. Unfortunately, in a general-purpose processing system, context-switches are not only costly, but introduce significant latency. As such, it would be necessary to deploy a high-performance CPU to achieve sampling rates in the order of 50-100Hz. High-performance CPUs, however, are not power-efficient and may require active cooling, which directly impacts the minimum power and weight that can be achieved with such an approach. In order to lower the power and weight requirements, an embedded CPU can be used. The lower operating frequency of traditional embedded CPUs, however, imposes a hard cap on the achievable sampling rate. It can be noted in the previous sections that solutions that are compact in weight and power are characterized by sampling rates in the 20-50Hz range. Achieving higher rates is possible only by playing careful workload optimization.

The route of performing ad-hoc optimization to reconcile the activity of system components with different characterizing time-scales, however, highlights the second main weakness of the single processing domain approach. A system implemented following this approach is hard to maintain and expand. This is because while certain system components are almost immutable (e.g. the low-level sensors interface), others undergo continuous refinements and expansions (e.g. a graphical user interface). Often, a revision/expansion of a high-level component can break an ad-hoc optimization that is crucial for temporal sampling stability. As such, a costly re-consolidation of all the system components is required.

Following an approach that is the opposite of what described above (consolidation of all the system units onto the same processing domain), one can first assign each system unit onto its own processing domain. Then, the multiple domains can be integrated with the specification of appropriate inter-domain communication channels. We refer to this as the *composite* approach. The main advantage of the composite approach is that hardware resources can be ideally tailored to match the computation needs required by each and every sub-system.

Unfortunately however, the additional burden introduced by synchronization and the increased overall system complexity make the composite approach not necessarily cost-efficient. This is particularly true for high-end units that implement all the auxiliary sub-systems descried above.

A hybrid approach, known as the dual-domain design, appears to strike the best compromise. In the dual-domain design, two processing domains are used. A first *time-sensitive* domain handles all the low-latency communication with the sensor pool which occurs at the nanosecond/microsecond time-scale. A second *compute-heavy* processing domain handles all the data processing, storage and external communication workload at the millisecond/second time-scale.

2. *Communication Interfaces*

In a minimal setup, a data acquisition system only performs local storage of acquired flight data for offline analysis. It is not uncommon, however, for modern data acquisition systems to also output a live feed of sensor data during flight. Two main communication interfaces are usually provided. The first is directed towards a ground station and uses either a high-power point-to-point radio link, or a wireless network infrastructure (e.g. 4G). A second is usually provided for other onboard avionics that are co-located on the same aircraft. A typical example is an autopilot.

When data is relayed using a wireless channel to a ground station, the data bottleneck is typically represented by the channel itself. Commercial point-to-point radios with a transmission range of few miles have a typical bandwidth that does not exceed a few hundreds of Kbps. As such, heavy data compression is required. Moreover, the refresh rate for streamed data needs to be in the few tens of Hz. Leveraging a network infrastructure can provide significantly higher transmission rates. For instance, by exploiting 4G networking it is possible to transmit up to 50 Mbps under ideal conditions. The downside of this approach is that contact with the ground can be lost if the aircraft temporarily enters an area with poor network coverage. Additionally, since the available bandwidth is strictly dependent on the congestion level of the network, sudden sags in available bandwidth can cripple ground-to-aircraft communication.

A data acquisition unit has a global view of all the sensor streams in the aircraft. As such, it is convenient to implement an autopilot since the acquired data feed can be used to compute aircraft attitude and actuation decisions. Based on this observation, a number of different designs have been provided, surveyed in the next section. For systems that do implement an autopilot system, there exist two main design choices.

A first option consists in implementing the autopilot on the same processing system as the data acquisition. In this case, we refer to a *unified* implementation, where the autopilot and data acquisition sub-systems use internal resources and interfaces to communicate. These can be a shared memory channel, or a message-passing interface, such as a socket network interface. A shared memory channel offers benefits in terms of performance — the two sub-systems generally pay little overhead to synchronize over the shared sensor data pool. Nonetheless, message-passing interfaces provide benefits in terms of robustness, because they decouple the behavior (and misbehavior) of the two sub-systems.

A second common approach is to implement the autopilot on an entirely separated processing domain. As such, we say that such designs implement a *split* paradigm. In this way, both the autopilot and data acquisition systems have their own processing and memory resources, and exclusive interfaces to actuators and sensors. This approach guarantees maximum isolation between the two sub-systems, but it comes at the expense of additional complexity, weight, and power consumption. In systems that are designed according to the split paradigm, a dedicated, physical interface is used to provide sensing data from the data acquisition side to the autopilot side of the system. Typical interfaces include serial connections (e.g. UART, RS-232, RS-485), or wired network interfaces (e.g. Ethernet). While serial connections can be supported easily in data acquisition systems implemented on simpler processors, these interfaces provide relatively low bandwidth, topping at few Mbps. Conversely, significantly higher bandwidth (few hundreds of Mbps) can be achieved using network interfaces, but their support is limited to platforms that feature a full networking stack.

B. Sensing Interfaces

A data acquisition system needs to aggregate sensor data produced by a number of different sensors. Depending on the type of sensor and on the rate at which sensor data is available, a number of interfaces are used for raw data acquisition. We hereby provide a short summary of the most common interfaces, along with their main strenghts and shortcomings.

1. Synchronous and Asynchronous Serial

Serial communication with sensing devices is commonplace in many data acquisition systems. The RS-232 standard is widely used to implement inter-device serial communication. The standard defines a variety of communication bandwidths and can be used for both asynchronous and synchronous communication. In spite of its versatility, the RS-232 interface requires 5 wires (a ground line, 2 data lines, 2 flow control lines) to be fully supported. For this reason, many embedded systems implement only a subset of the full RS-232 features, namely a UART interface. UART communication is always asynchronous and only requires 3 lines for full-duplex communication (1 ground line, 2 data lines).

Communication using traditional serial interfaces can sustain a maximum bandwidth in the order of few hundreds of Kbps. In fact, the most commonly supported maximum bit-rate is 115.2 Kbps. Newer controllers and devices support rates up to 921.6 Kbps. Newer revisions of the RS-232, such as the RS-485 standard, introduce support for higher bandwidth, up to 10 Mbps. Nonetheless, their support in embedded devices and sensors is limited.

Using serial interfaces to communicate with external sensors requires little-to-none OS-level support. As such, serial communication represents a low-overhead, reliable channel for low/mid-bandwidth sensors. The main limitation of this interface is that a dedicated controller is required for each individual device that needs to be interfaced. The hard cap on how many devices can be attached to a data acquisition system using serial interfacing is imposed by the number of UART/RS-232 controllers available in modern embedded platforms. Our survey highlighted that this number is typically between 2 and 4.

2. SPI

A popular interface for communication with off-chip sensors is the Serial Peripheral Interface (SPI). SPI consists in a master-slave interface where the master is in charge of selecting which slave is the receiver of the communication, and the clock frequency for sending/receiving data. The typical SPI interface requires 5 wires (1 ground line, 2 data lines, 1 clock line, 1 slave select line). The data rate that can be achieved via SPI strictly depends on the clock frequency that can be generated by the master controller. Nonetheless, our survey indicates that typical embedded controllers support up to few Mbps of data throughput.

The structure of a SPI-based bus follows a centralized structure. Multiple slaves/devices can be connected at the same time to the same master, as long as a dedicated slave-select line is available per each device in the master. If we indicate with N the number of SPI controller in an typical embedded platforms and with S the number of slave-select lines per controller, it follows that the number of devices that can be interfaced via SPI is $N \times S$. Our survey indicates that the typical values of N and S are 2-4 and 1-2, respectively.

Implementing support for an SPI interface is straightforward. It follows that, despite the inherent limitation in the number of devices that can be supported, SPI represents a good trade-off between achievable data throughput and ease of implementation.

3. *I^2C*

The Inter-Integrated Circuit (I^2C) communication interface is comparable in adoption with respect to SPI. The great advantage of I^2C over SPI is in the number of wires required to establish communication, and in its capability to support a large number of devices. Only 3 lines are required to establish communication between a master and a slave device (1 ground line, 1 data line, 1 clock line). Moreover, multiple devices can share the same three line.

Similarly to SPI, I^2C follows a master-slave approach for communication. But unlike SPI, a slave on the I^2C bus is assigned a unique address. Any given slave can transmit data only after a read or write request with a matching address has been generated by the master. Data from/to the slaves is transported over the same single data line, which needs to be properly arbitrated for successful communication.

I^2C slaves have 7-bit addresses, meaning that, theoretically, up to 128 devices could be attached to the same I^2C bus. In practice however this number is much smaller because it is common for I^2C devices from the same vendor to have overlapping addresses, with only 1 or 2 configurable address bits. Additionally, it is often the case for I^2C buses having more than 16 attached devices to exhibit electrical instability, making the data exchange error-prone.

Three main standards are followed by manufacturers in their I^2C interfaces. These are commonly referred to as Standard-, Fast-, and High-speed I^2C. Standard-speed mode supports 100 Kbps, but it is largely considered obsolete. Fast-speed mode is typically implemented in the vast majority of modern sensors and embedded controllers, providing data rates up to 400 Kbps. Devices that can operate in High-speed mode can reach data rates of 1 Mbps.

Implementing support for I^2C communication is more difficult compared to SPI and UART, because bus arbitration requires more complex logic.

4. *USB*

The Universal Serial Bus (USB) interface is the most widespread in general-purpose computing system for I/O and device interfacing. Nonetheless, its adoption in data acquisition systems is limited. Interfacing a device via USB allows reaching data rates up to 480 Mbps. Support for USB devices typically requires a full-fledged OS, as small footprint embedded solutions often do not implement the complex set of drivers required to support the USB interface stack. Additionally, few sensor devices provide USB as a native I/O interface. Those devices that do include USB interfacing are generally high-bandwidth devices that would be unusable otherwise. Some examples are RGBD cameras and 3D LIDARs.

While comparatively less commonplace to interface a data acquisition system with individual sensors, USB represents a valid option for high-speed communication between multiple processing domains. For instance, in data acquisition systems that follow split approach, USB represents a viable option for reliable synchronization and data aggregation between the fast- and slow-timescale processing domains. In this case, the complexity of implementing a full USB stack is largely hidden because a traditional OS (e.g. Linux) can be deployed on the slow-timescale side of the system; while the fast-timescale side of the system only needs to implement a partial device-side USB stack.

5. *Ethernet*

An even smaller number of sensing devices provides a full-fledged network interface like Ethernet. Like USB, it is possible to achieve large data transfer bandwidths if Ethernet interfacing is available and supported. The typical bandwidth ranges between 100 Mbps and 1 Gbps (gigabit Ethernet). Technically only one device can be connected to a given Ethernet port, but by adding switching elements it is possible to extend the number of devices that can be simultaneously connected.

Due to its similarity with USB, few sensors are usually interfaced via Ethernet. It is also not common for Ethernet to be used for communication across multiple processing domains of the same system. Nonetheless, Ethernet is largely adopted to interface data acquisition systems with third-party autopilot systems.

C. Common Sensors

It is crucial to select the appropriate sensors needed for each application. Generally, most vehicular applications will require some type of motion logging, involving an inertial and/or global positioning system. It is also important to monitor the vehicle's propulsion and energy generating or storage devices as well as other components. Often component states are measured using sensors that provide a voltage output proportional to their state. On aircraft, air data, including air density, velocity, and direction is rather important.

1. Inertial

Inertial sensors allow for motion of a vehicle to be measured. Inertial sensors arrive in the form of accelerometers and gyroscopes: accelerometers are used to determine acceleration and gyroscopes are used to determine rotation rate. These sensors are often combined together in all 3 axes, and in combination with a 3-axis magnetometer, to form an inertial measurement unit (IMU). An IMU is the basis of an inertial navigation system (INS), which utilizes raw measurements from the IMU sensors to calculate linear and angular position and velocity with respect to a global reference frame. The raw data produced by the accelerometer and gyroscope is combined using filtering with attitude reference data from the magnetometer and position reference data from the global positioning system (addressed in the next section), to generate motion state solutions. There is extensive literature regarding how to best fuse inertial data to provide the best solution for a given environment.

Inertial sensors can be integrated into a data acquisition system in several ways. First, the sensors can be directly incorporated into the design - this can be very developmentally expensive as proper support for the sensor is needed, including power and/or signal regulation and shielding. The next option is to integrate a *ready-to-use* development (”dev”) board, which already includes all the sensor specific support, onto the data acquisition system; such development board integrations are common in custom research systems, where size and weight constraints are relatively loose. Finally, the last option is to place the sensor off of the data acquisition board and connect it. This option comes with inherent advantages, where the sensors can be placed in an optimal spot, away from interference and error sources; however, this can introduces communication challenges - connecting the sensor and the main system board. Some of the systems presented in Section IV feature multiple IMUs, on- and off-board to get the best of both options.

2. Global Position

Global positioning is an integral part of modern inertial navigation systems and provide the basis for determining aircraft position, in conjuction with inertial sensors. Global positioning systems (GPS) or global navigation satellite system (GNSS) provide geolocation and time information by trilaterating location in 3-dimensions. Basic positioning requires a minimum of 3 satellites while the addition of time, through receiver clock time offset calculations, requires a minimum of 4 satellites; additional satellites can increase precision of a positioning system. It should be noted that base systems are only passive receiving units. However, GPS and GNSS systems can be enhanced, for added precision, using augmentation including the popular Wide Area Augmentation System (WAAS) or other differential GPS (DGPS). Position systems can also be enhanced using other methods such as carrier phase tracking and real-time kinematic (RTK) positioning.

3. Air Data

Air data sensors are crucial in aircraft research and flight control. These will include barometric pressure sensors, temperature sensors, humidity sensors, and differential pressure sensors as well as wind vanes. The output from these sensors highly vary from simple analog voltages to complex digital signals; sensors interfaces are described above in Section III.B and analog-input sensors are discussed below in Section III.C.5.

Barometric pressure sensors can help augment the altitude estimation of an inertial navigation systems. Barometric pressure sensors can also be used to determine the air density in conjunction with temperature sensor; humidity sensors may also be added for better air density determination if operating in high humidity environments.

Differential pressure sensors are used to determine airspeed using pitot probes. These probes come in a variety of flavors ranging from simple pitot tubes, static tubes, or pitot-static tubes, with different geometries, and number of holes, commonly: 1, 5, or 7. 5 or 7 hole probes also provide the angle-of-attack and side-slip angle of the the probe. Calibration is needed for pitot probes in order to accuracy and their data output is often integrated in to the inertial navigation system filter in order to account for pressure altitude, climb rate, and Mach effects as well as tubing distance lag. It is very important to great care of pitot probes as malfunctioned probes have shown to cause devastating results if integrated with a flight control system.

Wind vanes are another option for measuring angle-of-attack and side-slip angle rather than using multi-hole probes. The vanes can be mounted stand alone, however, are often integrated into an air data boom, with a pitot probe on the tip and two vanes on the mast. Wind vanes can vary in construction and are most often mounted on ball bearing, with the angle measured by a 'friction-less' encoder or hall effect sensors.

4. Propulsion

Integrating a data acquisition system with the propulsion system of an aircraft can be challenging, however, can provide a great deal of information. For example, in order to compute the aerodynamic forces and moments at play, one needs to subtract the force and moment created by the thrust force(s) (as well as the gravitational force) from the total force and moment measured by the inertial navigation system. This often requires knowing the rotation rate of the propulsion unit(s), whether it be an internal combustion engine, electric motor, or turbine. The rotation rate of these propulsion systems can be measured using optical, magnetic, or electrical sensors. In the case of an electric motor, the electronic speed controller (ESC) can be interfaced in order to extract this rotation rate information, along with other parameters such as voltage, current, and throttle percentage; these later parameters are vital for calculating motor electrical to mechanical conversion efficiency or for monitoring the voltage of the energy source (battery, solar panel, etc.). For a turbine, an interface can be developed that communicates with the engine control unit (ECU), also called the 'full authority digital engine control' (FADEC).

5. Analog or Digital

A great number of sensors and devices output a simple analog or digital signal that are designed for easy acquisition. Analog measurement is performed using the analog-to-digital (ADC) converters, which will then interface with the data acquisition system. Potentiometers as well as other types of linear or angular position sensors output a voltage or current that is proportional to their measure inputs; these sensors will allow for aircraft component positions to be measured such as control surface deflections. As discussed earlier, air data sensors will often output data using an analog signal. Analog measurement is also important for determining aircraft system voltages or currents, which may require amplification or indirect methods of measurement (e.g. a hall effect based current transducer sensor to measure current rather than direct measurement). An additional example is a load or torque cell, which require analog amplified measurement.The rate at which analog signals need to be acquired will highly depend on the specifications of the device as well as the expected noise - sampling at a higher rate can allow for time averaging.

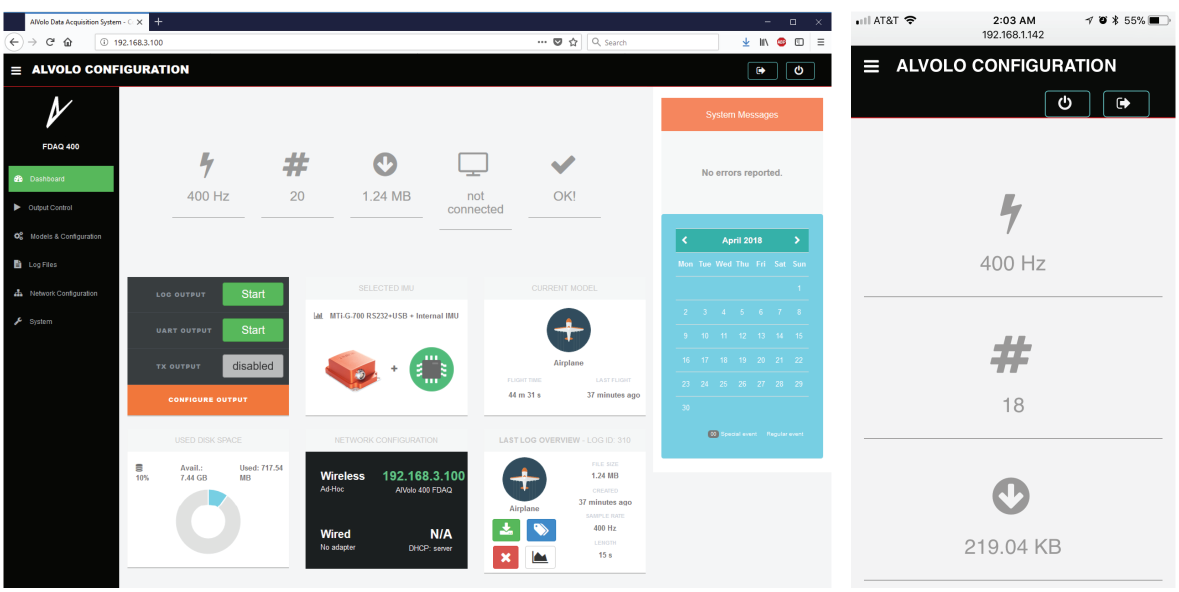
On the other hand, these sensors may also output simple digital signals such as a pulse-width modulation (PWM) or pulse-position modulation (PPM) signal. Servo actuators, which are often used on UAVs to drive the control surfaces or other mechanisms, use PWM signals as input; these signals directly correlate to an intended value, however, in some cases, the amplitude of the spacing of the signal may be reversed. PWM signals are also integral parts of brushless (stepper) motor and their measurement can therefore allow the system to determine position or rotation rate. Similarly, optical or magnetic rotation rate sensors can output an amplified or non-amplified PWM signal, which would need to be measured. Analog and digital signals measurement can occur within the main unit of the data acquisition system or can be done so externally. Moving the signal acquisition off-board is often beneficial because losses may otherwise occur during transmission, especially though long signal wires or within wires that pass in close proximity to wires with high and/or alternating current. However, depending on the complexity of the integration and the types and number of interfaces available on the data acquisition system main unit, moving signal acquisition off-board may be overly difficult and/or time or cost prohibitive, and therefore impractical.

D. User Interface

As mentioned earlier, data acquisition systems often provide a command & control interface. The minimal set of commands provided by this interface include: start/stop of logging and data forwarding on the various communication interfaces; a set of commands to assess the sanity of the current hardware configuration; and a way to inspect and download the stored flight logs.

The command & control user interface is typically bound to one of the external communication interfaces, such as UART and Ethernet. In order to make interfacing more convenient, graphical user interfaces that internally use the command-based interface are often provided for easier in-the-field operation. The drawback of this approach is that only a few devices can be used for interfacing with a data acquisition system in the field. This is because defining the same graphical interface while supporting multiple systems represents an extra development burden. A recent trend is in the definition of graphical user interfaces that are web-based. In this case, the interface is provided by the data acquisition system itself via a network interface (wired or wireless). But the burden of rendering the actual interface is put on the client, which is typically a general purpose desktop/laptop machine. The additional advantage of this approach is that little development effort is required to support mobile devices (e.g. smartphones and tablets).

For instance, Figure 2(a) depicts the dashboard of the command & control graphical user interface available on the Al Volo FDAQ. The interface is entirely web-based and dynamically refreshed. When a mobile client is detected, the same information is displayed in a mobile-frienly layout, as depicted in Figure 2(b).



(a) (b)

Figure 2. The Al Volo FDAQ data acquisition system user interface dashboard on (a) PC and (b) iPhone.

IV. Existing Systems

Researchers have performed flight data acquisition on unmanned aircraft using a variety of data acquisition systems and flight control systems. In order to choose or develop a data acquisition platform, it is important to survey existing systems. Here we evaluate existing systems, which are differentiated into several overlapping categories: commercial products, custom-solutions, flight control systems, and data acquisition systems. The writing and tables below provide information on these system along with references to use cases by researchers. This is not a comprehensive study of autopilots or data acquisition systems, however, it is done so to provide a general survey of what is available. It should be noted that the information presented in the tables was extracted completely from the sources cited.

There are two types of commercially produced autopilot solutions available: closed-sources and open-source. Closed-source commercial autopilots presented include the Collins Aerospace Cloud Cap Piccolo II,[22] MicroPilot MP2128g,[23] Lockheed Martin Kestrel Flight Systems Autopilot v2.4,[24] Embention Veronte,[25] and the Al Volo FC+DAQ.[?] The specifications for these systems are given in Table 1.

Open-source commercially-produced autopilots examined include the Emlid NAVIO2/RPi3,[26] Intel Aero Compute Board,[27] Paparazzi Lisa/M,[28] 3D Robotics APM 2.6,[29] and Pixhawk Autopilot.[30] All of these autopilots use the open-source Ardupilot.[29] The specifications for these systems are given in Table 2. It should be noted that open-source commercially-produced autopilots presented mostly use the ArduPilo UAV Autopilot Software Suite[29] as that has been how the open-source environment has evolved to. There is extensive documentation, which has allowed researchers to often adapted the software or completely change some or all of the software.

Next are the commercial data acquisition systems, which include the RCAT Systems Industrial UAV datalogger,[31] Eagle Tree Systems Flight Data Recorder Pro,[32] National Instruments CompactRIO,[33] and Al Volo FDAQ.[34] The Eagle Tree Systems Flight Data Recorder Pro is a high-end hobby / prosumer data acquisition system while the RCAT Systems Industrial UAV datalogger, NI CompactRIO, and the Al Volo FDAQ are industrial- / research-grade data acquisition systems. It should be noted that there are not many commercial data acquisition systems available that are intended to or could be used on small- to mid-sized unmanned aerial vehicles; as an example of this, due the NI CompactRIO's size and mass, it is not suitable for smaller aircraft. The specifications for these systems are given in Table 3.

Finally, a variety of custom-solution avionics systems are examined and organized by year developed. Tn 2006 Christophersen et al. at Georgia Institute of Technology developed the FCS-20 flight control system[8,35] in order to serve as the backbone for their control development flight campaigns. NASA's EAV[36,37] and AirSTAR[12] programs produced testbed platforms that included avionics systems which are able to perform data collection and control. Next in 2011, Brusov et al. developed the PRP-J5 flight data acquisition system for small UAVs.[38] Then in 2013, the Flight Control Systems Laboratory at West Virginia University developed a Gen-V avionics system in order to support their Phastball research into simplifying and reducing the cost of flight testing.[39–41] Afterwards in 2013, researchers at the University of Illinois developed the SDAC data acquisition for subscale aerodynamics flight testing;[5,42–44] this system was the basis for development of the Al Volo FDAQ and FC+DAQ.[34] Then in 2014, Stockton and Vuppala at Oklahoma State University developed a flight control system and hardware in the loop testing environment to demonstrate new control strategies.[45–47] In 2017, Bingler and Mohseni at the University of Floriday a minature dual-radio autopilot system for swarm research, based on their previous design at the University of Colorado - Boulder.[48] Also in 2017, researchers at the University of Minnesota developed their third generation flight control system to study body freedom flutter and flutter suppression strategies;[18,49] this system was commercialized by Bolder Flight Systems.[50] Finally in 2018, McCrink and Gregory at the Ohio State University developed a custom inertial navigation system to enable record setting beyond visual line-of-sight operations, as well as allow high-frequency logging of flight and RF system data and demonstrate real-time adaptive control techniques.[51] The specifications for these units are given in Table 4.

Table 1. Closed-source commercially-produced autopilot comparison

System:	Cloud Cap Piccolo II[22]	MicroPilot MP2128g[23]	Kestrel Autopilot v2.4[24]	Embention Veronte[25]	Al Volo FC+DAQ[34]
Internal Sensing					
Inertial	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary
Accelerometer	10 g	5 g	10 g	16 g	16 g
Gyroscope	300 deg/s	Yes	300 deg/s	300 deg/s	2000 deg/s
Magnetometers	Add-on	Add-on	Yes	6 G	6 G
Global positioning	u-blox GPS	u-blox GPS	Proprietary GPS	Proprietary GNSS	u-blox GNSS
Rate	4 Hz	4 Hz	4 Hz	4 Hz	10-18 Hz
Differential	Available	Available	-	Available	Available
Altimeter (barometric)	1 ft resolution	1 ft resolution	0.8 ft resolution		0.3 ft resolution
Analog voltage	4x 10 bit	32x 24 bit at 5 Hz	3x 12 bit	5	32x 12 bit
Servo position (PWM)	8-13	-	4-8	up to 16	up to 22
External Sensing					
Ext. IMU/INS/AHRS	-	-	-	-	XSens , MicroStrain 3DM, or VectorNav
Airspeed	up to 180 mph	up to 300 mph	up to 130 mph	up to 240 mph	up to 130 mph
Propulsion	optical or magnetic RPM and fuel flow	-	RPM and fuel flow		Castle ESC (voltage, current, RPM, %) and optical RPM
Interfacing					
Digital I/O	16	8	12	up to 16	up to 22
Peripheral interfaces	CANbus	-	4 Ports: UART, SPI, and/or I2C	CANbus, RS232, RS485 UART, I2C, and USB	UART, I2C, and USB
Data Handling					
Processing	MPC555 40 MHz Embedded Power PC w /26K RAM	unknown	29 MHz CPU w/ 512K RAM	unknown	2 or 4 core, 500 MHz to 1 GHz CPU w/1-4GB RAM
Sampling rate	20 Hz	5–30 Hz	100 Hz	200 Hz	100-400 Hz
Storage	448 KB	1.5 MB	512 KB	unknown	8 GB+
RF link	25 mi	3 mi	15 mi	20-75 mi	30 mi
Physical					
Size	142.0 x 46.0 x 62.6 mm	100.0 x 40.0 x 15 mm	57.7 x 35.6 x 12.7 mm	63 x 39.6 x 67.9 mm	110.0 x 58.0 x 25.4 mm
Weight	220 gr	24 gr	21 gr	190 gr	100 gr
Power	4 W	1.3 W		5 W	1 W
Estimated cost	$15,000+	$6,000+	$2,500+	$6,000+	$9,500+
Use cases	UIUC,[52] NPS/UCSC,[53] U. KS,[19,54] U. ND[55] NASA[56]	NASA,[57] MITRE Corp[58]	U. Toronto[59]		UIUC[60–62]

Table 2. Open-source commercially-produced autopilot comparison

System:	Emlid NAVIO2/RPi3[26]	Intel Aero Compute[27]	Paparazzi Lisa/M[28]	3D Robotics APM[29]	Pixhawk Autopilot[30]
Internal Sensing					
Inertial	MPU9250 and LSM9DS1	BMI160 and BMI150	MPU-6000 and HMC5883	MPU-6000	MPU 6000, L3GD20, and LSM303D
Accelerometer	2-16 g	2-16 g	2-16 g	2-16 g	2-16 g
Gyroscope	250-2000 deg/s	125-2000 deg/s	250-2000 deg/s	250-2000 deg/s	250-2000 deg/s
Magnetometers	4-48 G	13/25 G	8 G	8 G	2-12 G
Global positioning	u-blox M8N GNSS	-	-	uBlox LEA-6	u-blox GPS
Rate	5 Hz (GPS) or 10 Hz (GNSS)	-	5 Hz	5 Hz	
Differential	-	-	-	-	-
Altimeter (barometric)	0.3 ft resolution	-	0.8 ft resolution	1.0 ft resolution	0.3 ft resolution
Analog voltage	4	5x 12 bit	7	up to 12	2
Servo position (PWM)	8	12	-	8	0
External Sensing					
Ext. IMU/INS/AHRS	-	-	-	-	-
Airspeed	-	-	-	-	-
Propulsion	-	-	-	-	-
Interfacing					
Digital I/O	2	25	3	up to 12	-
Peripheral interfaces	UART, I2C, USB, and Ethernet	UART, I2C, SPI, and USB	CANbus, UART, I2C, SPI, and USB	I2C and UART	CANbus, UART, I2C, SPI, and USB
Data Handling					
Processing	4-core 1.2 GHz Broadcom BCM2837	4-core 2.55 GHz Intel Atom x7-Z8750	STM32F105RCT6 (Cortex M3) 72 Mhz w/ 64K RAM	16 MHz Atmega2560 and 16 MHz Atmega32U-2	168 MHz Cortex M4 w/256K RAM
Sampling rate	100 Hz	200 Hz	50 Hz	50 Hz	200 Hz
Storage	4-32 GB microSD	32 GB + microSD	512 KB	16 MB	2 MB + 8 GB microSD
RF link	-	-	-	-	-
Physical					
Size	96.0 x 70.0 x 25.0 mm	88mm x 63mm x 20mm	60.0 x 33.7 x 10.0 mm	70.5 x 45 x 13.5mm	81.5 x 50.0 x 15.5 mm
Weight	76 gr	60 gr	10 gr	31 gr	38 gr
Power	4 W	1.3 W	1 W (est.)	0.5 W	1.1 W
Estimated cost	$200+	$399	$199	$160-340	$199
Use cases	NCSU,[63] U. MO-KC/NPS,[64] UIUC[65]		Stanford,[66] U. KS,[67] Delft,[68] U. Toulouse[69]	Techn. Univ. Sofia,[70] Cal Poly,[71] OKSU[72]	OSU,[73] Embry-Riddle,[74] U. TX-Arl,[75] Linkoping[76,77]

Table 3. Closed-source commercially-produced data acquisition systems comparison

System:	RCAT Systems Industrial UAV[31]	Eagle Tree Systems Flight Data Recorder Pro[32]	National Instruments CompactRIO[33]	Al Volo FDAQ[34]
Internal Sensing				
Inertial	Proprietary	Proprietary	-	Proprietary
Accelerometer	1-axis 16 g	-	-	16 g
Gyroscope	-	-	-	2000 deg/s
Magnetometers	-	-	-	6 G
Global positioning	Proprietary	Proprietary	Add-on	u-blox GNSS
Rate	1 Hz	10 Hz	-	10-18 Hz
Differential	-	-	-	Available
Altimeter (barometric)	8 ft resolution	1 ft resolution	Add-on	0.3 ft resolution
Analog voltage	2	2	4, 8, 16, or 32	32x 12 bit
Servo position (PWM)		4	-	up to 22
External Sensing				
Ext. IMU/INS/AHRS	-	2-axis 38 g	Add-on	XSens, MicroStrain, or VectorNav
Airspeed	up to 290 mph	up to 350 mph	-	up to 130 mph
Propulsion	RPM, voltage, current, and thermocouple	RPM (optical, magnetic, or ESC), voltage, current, thermocouple, and EGT	Add-on	Castle ESC (voltage, current, RPM, %) and optical RPM
Interfacing				
Digital I/O	-	-	4, 8, or 32	up to 22
Peripheral interfaces	-	-	RS232, Ethernet, and USB	UART, I2C, USB, and Ethernet
Data Handling				
Processing	20 MHz microcontroller	unknown	Intel or ARM 400 MHz to 1.33 GHz	2 core, 500 MHz CPU
Sampling rate	20 Hz	40 Hz	100-400 kHz	100-400 Hz
Storage	512 MB SD	10 KB on-board	2x 4 GB SD	8 GB+
RF link	10 mi+	14 mi	Add-on	30 mi
Physical				
Size	101.6 x 95.3 x 44.5 mm	50.0 x 35.0 x 17.0 mm	179.6 x 88.1 x 88.1 mm+	110.0 x 58.0 x 25.4 mm
Weight	unknown	28 gr	1580g	100 gr
Power	4 W	1 W	6-25 W+	1 W
Estimated cost	$2,495	$299-1,500	$2,000-8,000 base plus sensor modules	$4,950+
Use cases	U. FL[78] NASA[79,80]	U. FL[2,81] UIUC[13,82]	NRL[83]	UIUC[84,85]

Table 4. Custom avionics system solution comparison

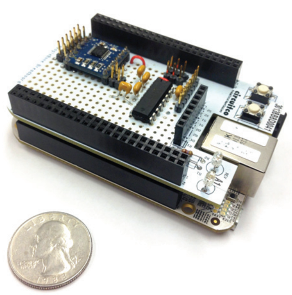
System:	Georgia Tech FCS20[8,35]	NASA EAV-2/3[36,37]	NASA AirSTAR[12]	Brusov et al. PRP-J5[38]	WVU RED "Phastball" Data Logger[39–41]
Year Developed	2006	2007	2008	2011	2013
Internal Sensing					
Inertial	Analog Devices ADXL210E and ADXR300	Rockwell Collins Athena GS111m INS/GPS Unit	Microbotics MIDGII and Memsense MAG	ST LIS344ALH and LPY530AL	(3) ADIS16405 and (1) ADIS16355
Accelerometer	10 g	8 g	10 g	2-6 g	10 g
Gyroscope	300 deg/s	200 deg/s	600 deg/s	300 deg/s	150 deg/s
Magnetometers	-	yes	yes	-	2.5 G
Global positioning	ublox TIM-LF GPS	RC Athena GS111m	Microbotics MIDGII	-	Novatel OEM-V1 GPS
Rate	4 Hz	yes	5 Hz	-	20 Hz
Differential	-	(ready)	-	-	-
Altimeter (barometric)	yes	yes	yes	yes	yes
Analog voltage	10x 16 bit	16x 12 bit	48x 16 bit	24x 12 bit	8
Servo position (PWM)	-	10	-	3	4
External Sensing					
Ext. IMU/INS/AHRS	-	-	-	-	-
Airspeed	yes	yes, 5-hole	yes, alpha-beta	yes	yes
Propulsion	-	-	Turbine throttle and RPM, fuel flow	-	-
Interfacing					
Digital I/O	12	-	2	-	-
Peripheral interfaces	4x RS232	2x CAN, 8x RS232	3x Serial	UART and SPI	-
Data Handling					
Processing	TI TMS320C6713 DPS and Altera EP1S40 Stratix FPGA	Diamond Athena 660MHz with 128MB RAM and Motorola DSP56807	PC104	Silicon Labs C8051F206	(2) Netburner MOD5213
Sampling rate	100 Hz	100 Hz	200 Hz (50 Hz IMU),	100 Hz	50 Hz
Storage	64 MB on-board	2x 8 GB CF	512 KB on-board	512 MB SD	microSD
RF link	-	yes	yes	-	yes
Physical					
Size	85.0 x 55.0 x 20.0 mm	239.8 x 160.0 x 121.4 mm	unknown	57.0 x 37.0 x 9.0 mm	71.1 x 45.7 x 25.4 mm
Weight	40 gr	2551 gr	unknown	17 gr	226 gr
Power	1-3 W	26 W	unknown	0.25 W	unknown

Table 4 (continued). Custom avionics system solution comparison

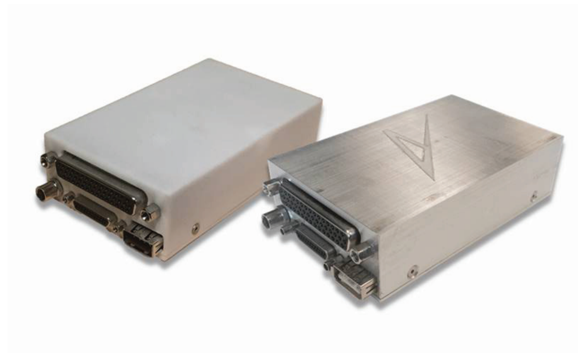
System:	**UIUC SDAC[5,42–44]**	**OK State Stabilis[45–47]**	**UFL AMP[48]**	**UMN Goldy III[18,49] / Bolder Flight Systems[50]**	**OSU Avanti INS/FMC[51]**
Year Developed	2013	2014	2017	2017	2018
Internal Sensing					
Inertial	XSens MTi-G	VectorNav VN-200 GPS/INS	MPU-9250	MPU-9250	(3) IMUs
Accelerometer	18 g	16 g	2-16 g	2-16 g	unknown
Gyroscope	300 deg/s	2000 deg/s	250-2000 deg/s	250-2000 deg/s	unknown
Magnetometers	750 mG	2.5 G	4-48 G	4-48 G	unknown
Global positioning	XSens MTi-G	VectorNav VN-200 GPS/INS	Linx TM GNSS	-	ublox RTK GPS
Rate	4 Hz	5 Hz	10 Hz	-	4 Hz
Differential	-	-	-	-	Yes
Altimeter (barometric)	1.0 ft resolution	1.0 ft resolution	0.5 ft resolution	yes	unknown
Analog voltage	”7x 10 bit, 16x 12 bit, 1x 14 bit”	6x 10 bit	yes, unknown	2x 10 bit 8-24x 13 bit	unknown
Servo position (PWM)	8	8	-	16 via SBUS (not PWM)	8 (est.)
External Sensing					
Ext. IMU/INS/AHRS	-	-	-	VectorNav VN-200 GPS/INS	-
Airspeed	external	external	-	yes	yes, 5-hole probe
Propulsion	RPM, Voltage, Current	-	-	-	ECU
Interfacing					
Digital I/O	up to 20	unknown	yes, unknown	2-14	unknown
Peripheral interfaces	CAN, UART, I2C, SPI, USB, and Ethernet	CAN, RS232, RS248, UART, I2C, SPI, USB, and Ethernet	I2C and SPI	CAN, RS232, RS248, UART, I2C, SPI, USB, and Ethern	unknown
Data Handling					
Processing	BeagleBone TI AM3358 720 MHz Cortex-A8	BeagleBoneBlack TI AM3359 1 GHz Cortex-A8	140 MHz dsPIC33EP	BeagleBoneBlack TI AM3359 1 GHz Cortex-A8 and (1-3) Teensy 3.6 Cortex M4	Parallax Propeller and ARM CPU
Sampling rate	100 Hz	10 Hz	100 Hz	50 Hz	256 Hz
Storage	8 GB+ microSD	2 GB on-board + microSD	512 MB on-board	2 GB on-board	unknown
RF link	25 mi	external	300 ft and 1 mi	yes	yes, 25 mi+ (900MHz) and SATCOM
Physical					
Size	90.5 x 54.3 x 26.8 mm	124.0 x 76.2 x 45.0 mm	32.5 x 30.0 mm (main board) 14 x 11 mm (sensor board)	96.0 x 70.0 x 25.0 mm	unknown
Weight	80 gr	80 gr	6.25 gr	76 gr	unknown
Power	0.45 W	2.0 W	unknown	4 W	unknown

V. Integration Cases

In order to better illustrate the development, integration, and operation of a data acquisition system in an unmanned aerial vehicle, we look at several integration cases that the authors performed in previous works. Two data acquisition systems, the UIUC SDAQ[42,43] and Al Volo FDAQ,[34] and one flight control and data acquisition system, the Al Volo FC+DAQ,[34] which can be seen below in Fig. 3, will be used as example. The aircraft used for demonstration will include the UIUC Subscale Sukhoi ,[5] the UIUC GA-USTAR ,[85] and the UIUC Solar Flyer ,[60,86] all of which are distinctly different types of aircraft and have different types of integration and operation challenges. Photos of the aircraft are shown below.



(a)

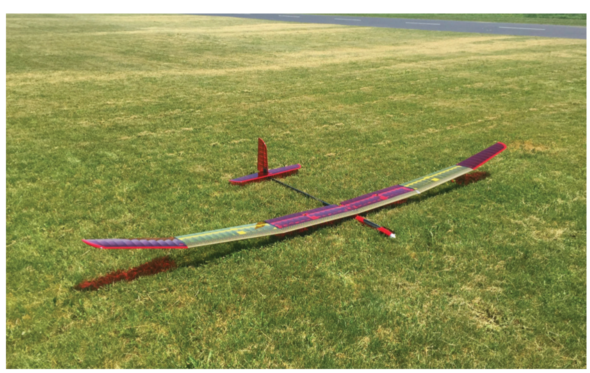


(b)

Figure 3. Data acquisition and flight control systems used as examples: (a) UIUC SDAC and (b) Al Volo FDAQ and FC+DAQ (photo taken from Al Volo[34]).

(a)

(b)



(c)

Figure 4. Aircraft used as examples: (a) UIUC Subscale Sukhoi, (b) UIUC GA-USTAR, and (c) UIUC Solar Flyer (baseline aircraft shown without solar panels).

A. UIUC Subscale Sukhoi

The UIUC Subscale Sukhoi was developed to perform aerodynamics research in the full-envelope flight regime, specifically to capture unsteady aerodynamic effects exhibited during high angle-of-attack flight. The unmanned aircraft was built from a 35% scale, 2.6 m (102 in) wingspan Sebart Sukhoi 29S electric radio control (RC) model, which provided a light yet robust structure that along with large control surfaces, that allowed the aircraft to perform aggressive aerobatic maneuvers. The aircraft used an electric propulsion system in place of an internal combustion gasoline engine to provide near constant performance, increased reliability, and low vibrations; a diagram of the propulsion system is given in Fig. 5. The completed flight-ready aircraft physical specifications are given in Table 5, and its airframe component specifications are given in Table 12.

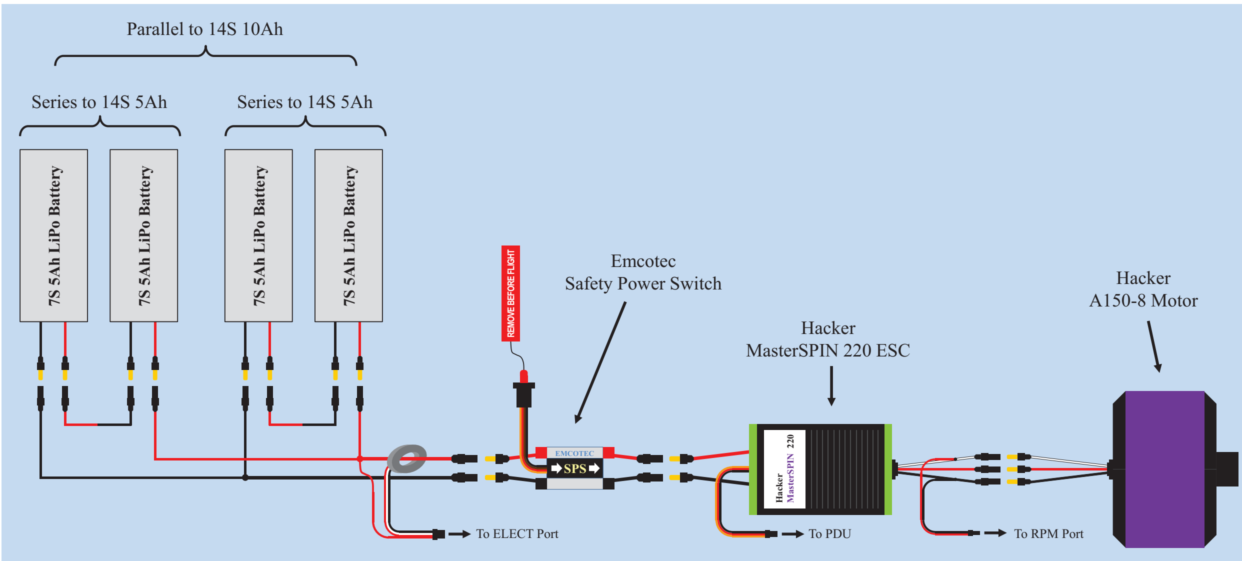


Figure 5. A propulsion system diagram for the UIUC Subscale Sukhoi unmanned aircraft

Table 5. UIUC Subscale Sukhoi unmanned aircraft physical specifications

Geometric Properties	
Overall Length	100.0 in (2540 mm)
Wingspan	102.4 in (2600 mm)
Wing Area	2015 in^2 (130.0 dm^2)
Wing Aspect Ratio	5.20
Inertial Properties	
Weight	
Empty (w/o Batteries)	27.16 lb (12.33 kg)
14S 2P 10Ahr LiPo Main Battery	8.13 lb (3.69 kg)
RC and Avionics Batteries	0.77 lb (0.35 kg)
Gross Weight	36.00 lb (16.37 kg)
Wing Loading	41.2 oz/ft^2 (126 gr/dm^2)

Table 6. **UIUC Subscale Sukhoi unmanned aircraft airframe component specifications**

Construction	Built-up balsa and plywood structure, foam turtle decks, carbon fiber wing and stab tube, aluminum landing gear, fiberglass cowl, fiberglass wheel pants, and styrene and fiberglass canopy.
Flight Controls	
Control Surfaces	Ailerons (2), elevator (2), rudder, and throttle
Transmitter	Futaba T14MZ
Receiver	Futaba R6014HS
Servos	(8) Futaba BLS152
Power Distribution	SmartFly PowerSystem Competition 12 Turbo
Receiver Battery	Thunder ProLite RX 25c 2S 7.4V 2700 mAh
Propulsion	
Motor	Hacker A150-8 Outrunner
ESC	Hacker MasterSPIN 220
Propeller	Mejzlik 27x12TH
Motor Flight Pack	(4) Thunder Power ProPerformance 45c 7S 5000 mAh in 2S2P config.
Motor Power Switch	Emcotec SPS 120/240

Based on previous experience gained in developing and operating the UIUC AeroTestbed, which was used for spin and upset testing,[13,82] the data acquisition system for the UIUC Subscale Sukhoi had to be able to simultaneously log: accelerations, velocities, position, angular rotation, Euler angles, pitot probe airspeed, propulsion system parameters, and control surface deflections. The new data acquisition system also had to be able to do so at 100 Hz as the system used on the UIUC AeroTestbed, which operated at 25 Hz, did not provide a sufficient acquisition rate to measure the effects of high control surface deflection maneuvers, especially during dynamic changes such as initial upset and non-constant spinning behavior. An additional requirement was that the IMU used on the UIUC Subscale Sukhoi be isolated in some way from the propulsion system as the magnetic field created by the UIUC AeroTestbed's propulsion system overwhelmed its IMUs magnetomer, and therefore severely interfered with its estimation of attitude.

The aircraft was instrumented with an updated version of the custom-made UIUC Sensor Data Acquisition System (SDAC),[42,43,87] which had recently been developed and made use of only commercial-off-the-shelf (COTS) components. Two photo of the installation can be seen in Figs. 6 and 7; note that the IMU is separated from the battery area by a thin steel plate to decrease the effects of propulsion system generated magnetic fields. A system diagram depicting the specific configuration of the instrumentation, along with the flight control and propulsion systems, is shown in Fig. 8. The specifications of the components used in the updated, tested sensor data acquisition system are given in Table 7. A description of the software architecture used in the implementation is given in Mancuso et al.[42]

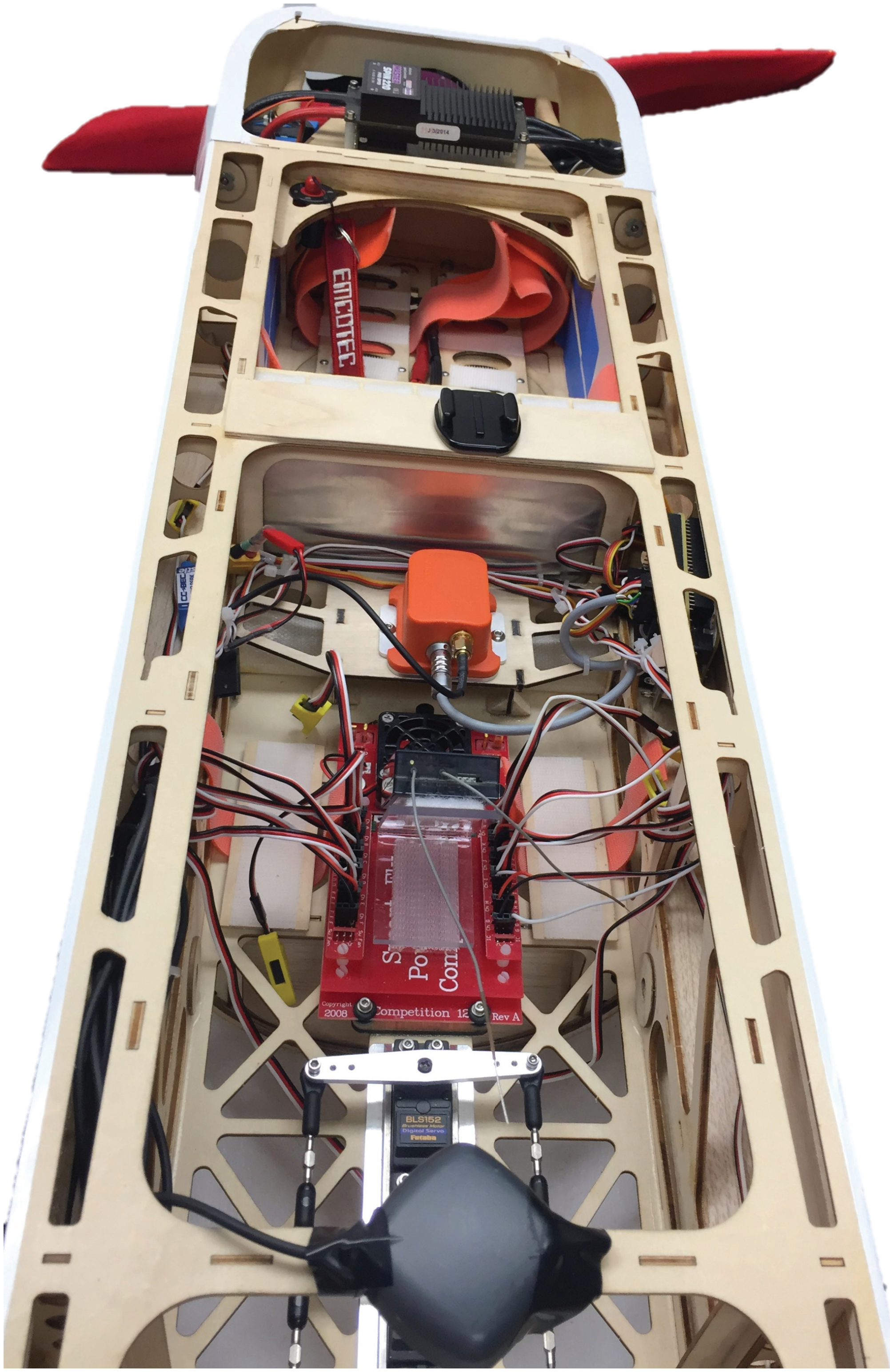


Figure 6. A photo of the fuselage of the UIUC Subscale Sukhoi showing (from front to back): the motor and controller, battery compartment, the avionics (XSens MTi-G IMU center and UIUC SDAC on the right), the flight control system (power distribution unit, RC receiver, and rudder pull-pull servo tray and servos), and GPS antenna.

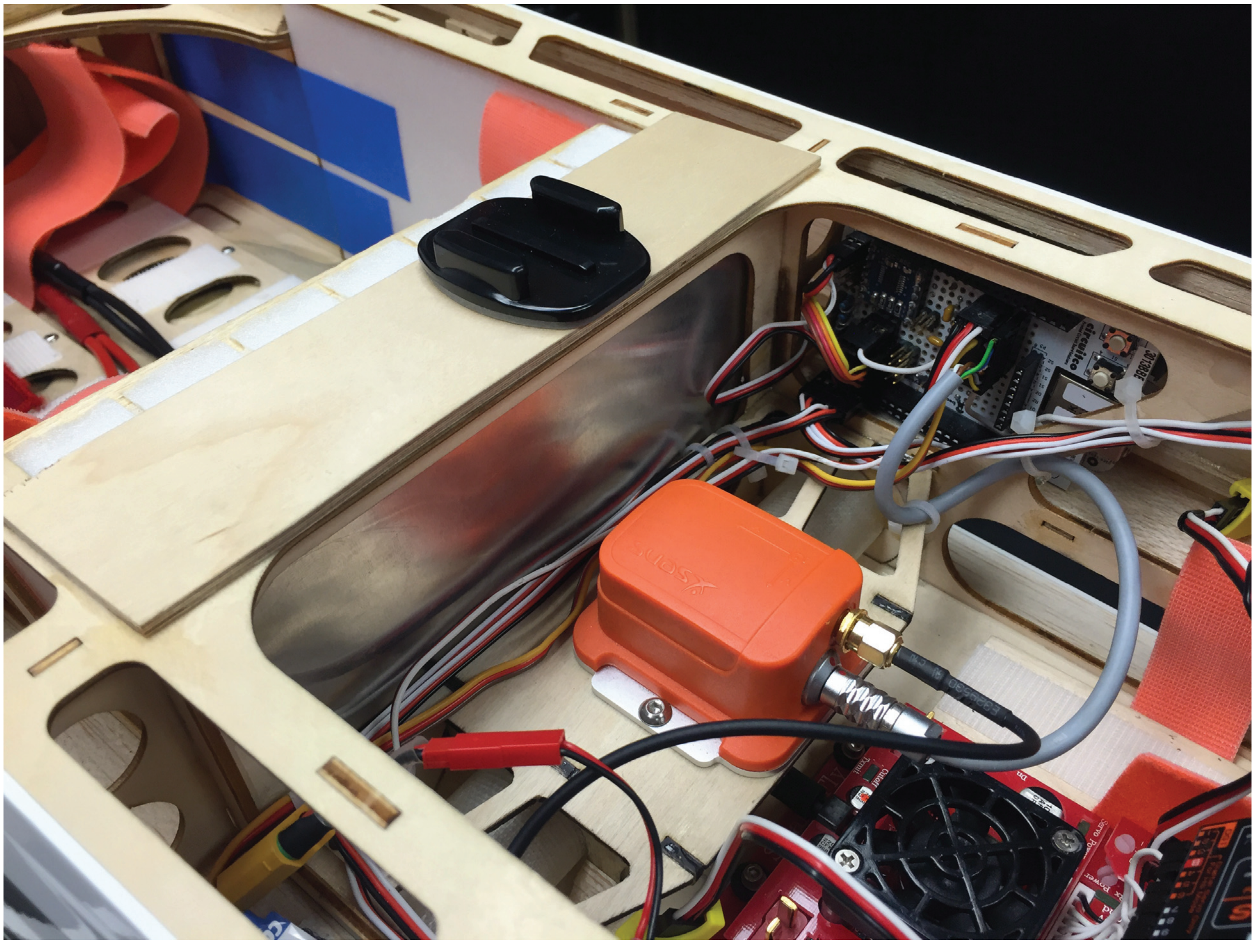


Figure 7. The center of the fuselage of the UIUC Subscale Sukhoi with the UIUC SDAC (top right) and XSens MTi-G IMU (center) visible; note the thin steel plate separating the IMU from the battery compartment in front.

Table 7. Updated UIUC SDAC system component specifications

Processing unit	BeagleBone running 32-bit Ubuntu Linux
Sensors	
IMU	XSens Mti-g 6-DOF IMU with Wi-Sys WS3910 GPS Antenna
Airspeed probe	EagleTree Systems pitot-static probe
Airspeed sensor	All Sensors 20cmH2O-D1-4V-MINI differential pressure sensor
Analog-to-digital converters	4x Gravitech 12 bit - 8 Channel ADC
Potentiometers	BI Technologies 6127
Tachometer	Sparkfun ProMicro
Magnetometer	PNI Corp MicroMag3
Power	
Regulators	Castle Creations CCBEC
Batteries	30cmThunder Power ProLite 3S 1350 mAh (avionics, telemetry and/or video)
Telemetry transceiver	Digi 9X Tend 900-MHz card
Data Storage	8GB microSD card

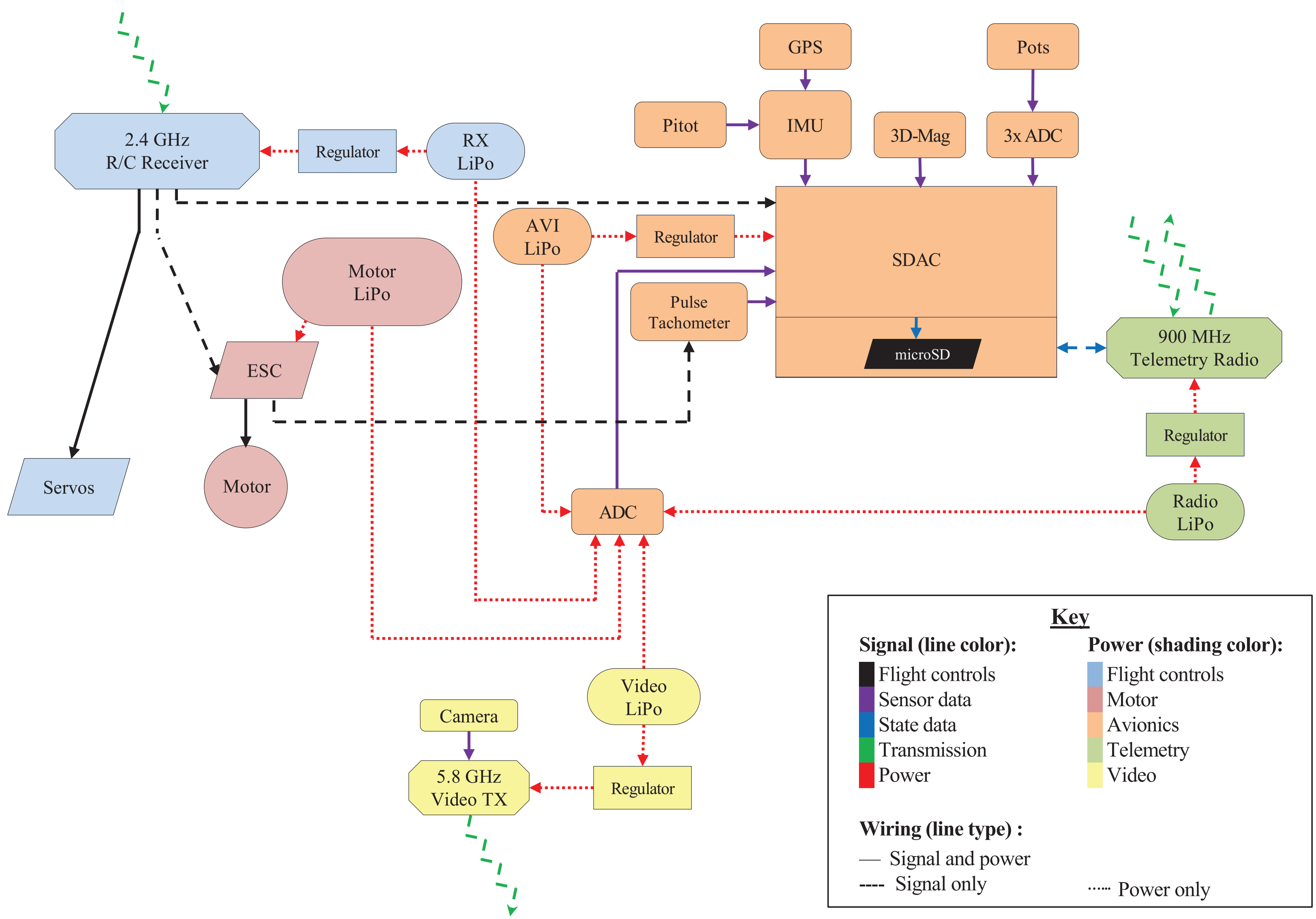


Figure 8. A block diagram of the UIUC SDAC as installed in the UIUC Subscale Sukhoi

B. UIUC GA-USTAR

The UIUC General Aviation Upset and Stall Testing Aircraft Research (GA-USTAR) project aims to ultimately reduce the number of general aviation (GA) incidents resulting from stall and upset by creating higher fidelity modelling tools to improve simulators and pilot training.[84,85] The GA-USTAR project therefore focuses on the development and flight testing of a sub-scale GA aircraft for stall/upset aerodynamic modeling. To design and build a correct model, research was conducted to determine the requirements, including dynamically scaling the aircraft, not only in terms of mass but also in terms of moments of inertia, Additional effort was put into researching a methodology to modify the aircraft flight surfaces to properly take into account Reynolds number effects.[88]

The aircraft developed to date was the first baseline aircraft, in series of three aircraft phases, which will ultimately take into account dynamic scaling and then Reynolds number corrections. The Phase 1 GA-USTAR aircraft was built, with the help of a team of undergraduate students, from a Top Flite 1/5-scale Cessna 182 RC model airplane, which had been slightly modified to increase aircraft safety, reliability, and ease of flight testing.[89] The completed flight-ready aircraft physical specifications are given in Table 8, and its airframe component specifications are given in Table 9.

Part of the design methodology employed in the aircraft development required the latest state-of-the-art sensors to be incorporated into the aircraft, which increased the integration challenge. Primarily, this included using a current-generation 400 Hz INS as well as interfacing with the ESC such that high-fidelity motor parameters could be acquired. The UIUC SDAC, which although provided excellent data for the high angle-of-attack flight testing research using the UIUC Subscale Sukhoi, was unable to meet these requirements. A full list of data acquisition requirements can be found in Ananda, et al.[84] An Al Volo FDAQ was used in the GA-USTAR project as it met the requirements. Component details of the aircraft can be seen in Fig. 10. The component specifications of the GA-USTAR aircraft instrumentation are given in Table 10.

Table 8. Baseline GA-USTAR unmanned aircraft physical specifications.

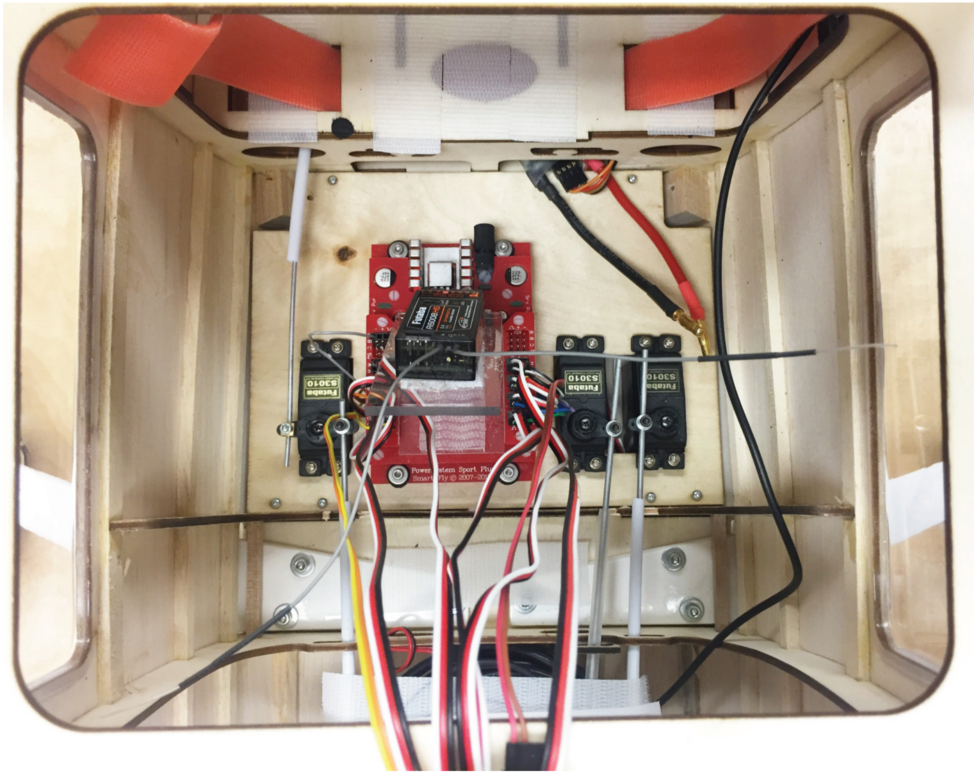
Geometric Properties	
Overall Length	64.0 in (1630 mm)
Wingspan	81.0 in (2060 mm)
Wing Area	898 in^2 (57.9 dm^2)
Wing Aspect Ratio	7.47
Inertial Properties	
Weight	
Empty (w/o Batteries)	12.08 lb (5.48 kg)
8S 6.6 Ahr LiPo Main Battery	2.74 lb (1.25 kg)
RC and Avionics Batteries	0.49 lb (0.22 kg)
Gross Weight	15.31 lb (6.94 kg)
Wing Loading	39.3 oz/ft^2 (120 gr/dm^2)

Table 9. Baseline GA-USTAR unmanned aircraft airframe component specifications.

Airframe	
Model	Top Flite 1/5-scale Cessna 182
Construction	Built-up balsa and plywood structure, aluminum landing gear, fiberglass cowl, fiberglass wheel pants, and styrene canopy.
Flight Controls	
Control Surfaces	(2) Ailerons, (2) elevator, rudder, (2) flap, and throttle
Transmitter	Futaba T14MZ
Receiver	Futaba R6008HS
Servos	(7) Futaba S3010
Power Distribution	SmartFly PowerSystem Sport Plus
Receiver Battery	(2) Thunder Power ProLite RX 25c 2S 7.4V 1350 mAh
Propulsion	
Motor	Hacker A50-14L Outrunner
ESC	Castle Creations
Propeller	APC Thin Electric 16x8
Motor Flight Pack	(4) Thunder Power ProLite 25c 8S 6600 mAh
Motor Power Switch	Emcotec SPS 60/120

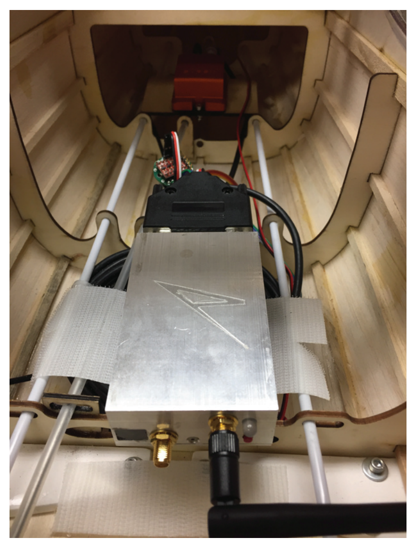
Table 10. Component specifications of the GA-USTAR aircraft instrumentation.

Data acquisition system	Al Volo FDAQ 400 Hz system
Sensors	
Inertial measurement unit	XSens MTi-G-700 AHRS with GPS
Airspeed sensor	Al Volo pitot-static airspeed sensor
Motor Sensors	Al Volo Castle ESC sensor
Power	
Regulator	Built into FDAQ
Battery	Thunder Power ProLite 3S 1350 mAh



(a)

(b)



(c)

Figure 9. Construction details in baseline GA-USTAR aircraft: (a) custom front tray holding the two elevator servos, rudder servo, Smart-Fly power distribution system, and the receiver, (b) nose with the motor, ESC, and safety power switch visible, and (c) Al Volo FDAQ flight data acquisition system and the XSens MTi-G-700 IMU mounted in the aircraft rear.

C. UIUC Solar Flyer

The UIUC Solar Flyer[60, 86] is currently in development with the ultimate aim of sustaining continuous flight for extended periods of time while performing on-board, real-time computation and to shift the paradigm of solar powered flight. The traditional approach for small size UAVs, is to capture data on the aircraft, stream it to the ground through a high power data-link, process it remotely (potentially off-line), perform analysis, and then relay commands back to the aircraft as needed. However, given the finite energy resources found onboard an aircraft (e.g. batteries and solar arrays), the traditional design greatly limits aircraft endurance, since significant power is consumed for transmission of visual data instead of being allocated to keeping the aircraft flying. The UIUC Solar Flyer is being developed to carry a high performance embedded computer system to minimize the need for data transmission. The process of reducing aircraft power consumption allows for decreasing aircraft size, prolonging flight time, and ultimately minimizing cost, therefore supporting the widespread adoption of UAVs for various types of missions.

The UIUC Solar Flyer was designed using a mixture of trade studies and power simulations in order to enable a variety of missions to be performed while minimizing aircraft size. The aircraft is being built from a majority of commercial-off-the-shelf components in order to minimize both development time and cost. The completed 4.0 m (157 in) wingspan UIUC Solar Flyer aircraft is based on the F5 Models Pulsar 4.0 Pro, and once completed, should weight approximately 2.5 kg (88 oz). The aircraft will be powered by a 65 W gallium arsenide (GaAs) solar array from Alta Devices.[90] The aircraft configuration, sizing, and propulsion system were all chosen based on analysis of estimated solar power production and aircraft, instrumentation, and avionics power consumption, and therefore, efficient integration of avionics is critical. Flight testing is currently being done to increase aircraft efficiency, which requires high-fidelity data acquisition. The physical specifications for the instrumented, non-solar aircraft are given in Table 11. The specifications of the components used in the construction of the airframe is provided in Table 12.

Table 11. Instrumented (non-solar) UIUC Solar Flyer aircraft physical specifications.

Geometric Properties	
Overall Length	1815 mm (71.5 in)
Wing Span	4000 mm (157.5 in)
Wing Area	85 dm^2 (1318 in^2)
Aspect Ratio	18.8
Inertial Properties	
Gross Weight	1.966 kg (4.33 lb)
Empty Weight	1.739 kg (3.83 lb)
Wing Loading	23.1 gr/dm^2 (7.57 oz/ft^2)

Table 12. Instrumented (non-solar) UIUC Solar Flyer aircraft airframe component specifications.

Airframe	
Model	F5 Models Pulsar 4.0E
Construction	Fully-composite kevlar and carbon fiber fuselange and built-up balsa wood with carbon fiber and a kevlar-carbon fiber laminate reinforced flight surfaces.
Flight Controls	
Control Surfaces	(2) Ailerons, (2) elevator, rudder, (2) flap, and throttle
Transmitter	Futaba T14MZ
Receiver	Futaba R6208SB
Servos	(6) S3173SVi
Power	Castle ESC - BEC
Propulsion	
Motor	Model Motors AXi Cyclone 46/760
ESC	Castle Creations Phoenix Edge Lite 50
Propeller	Aeronaut CAM Folding 13x6.5
Motor Flight Pack	Thunder Power ProLiteX 3S 2800 mAh

A custom version of the Al Volo FC+DAQ flight control and data acquisition system was fabricated to meet the needs of the UIUC Solar Flyer. Part of the integration challenge is fitting the system within the aircraft geometry, which given the streamlined and narrow design, was very difficult. The components of the FC+DAQ have been stripped of their protective enclosures to save weight and are being split between location in the fuselage and the wings. Figs. 10(a) and 10(b) show the locations of the various control system elements. A top-view photo of the fuselage pod is shown in Fig. 11 and a photo of the entire center wing panel showing instrumentation components and servo actuators can be found in Fig. 12. The specifications of the instrumentation on the UIUC Solar Flyer are given in Table 13.

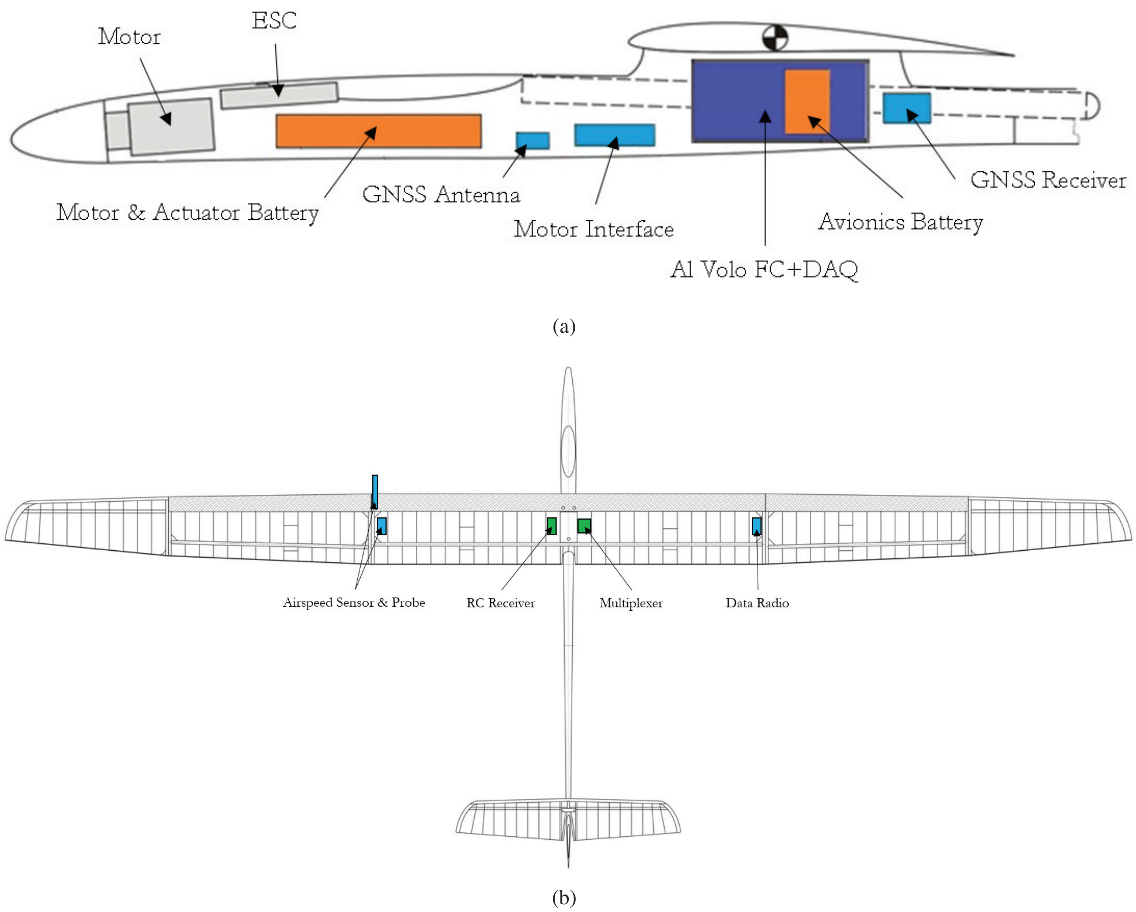


Figure 10. Current layout of the Al Volo FC+DAQ within the UIUC Solar Flyer: (a) fuselage and (b) wing.

Table 13. Instrumentation specifications.

Autopilot-DAQ system	Al Volo FC+DAQ 100 Hz flight control and data acquisition system
RF Module	Digi International 900 MHz XBee Pro S3B Module
Multiplexer	8-channel custom PWM multiplexer with redundant input
Sensors	
Inertial	100 Hz AHRS integrated into FC+DAQ
Positioning	10 Hz GNSS integrated into FC+DAQ
Airspeed sensor	Al Volo Pitot Static Airspeed Sensor
Motor sensor	Al Volo Castle ESC Interface
Power	
Regulator	Built into FC+DAQ
Battery	Thunder Power ProLiteX 2S 500 mAh

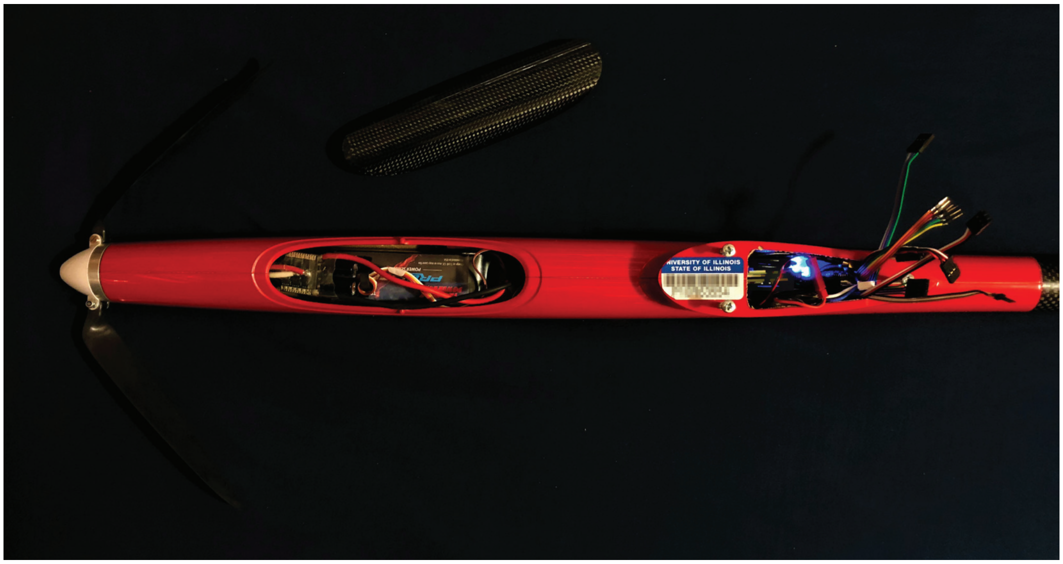


Figure 11. A photo of the top of the UIUC Solar Flyer fuselage pod showing propulsion system elements in the front of the pod and the instrumentation in the rear of the pod; note that the wires connect to the sensors and flight control actuation system located in the wing.

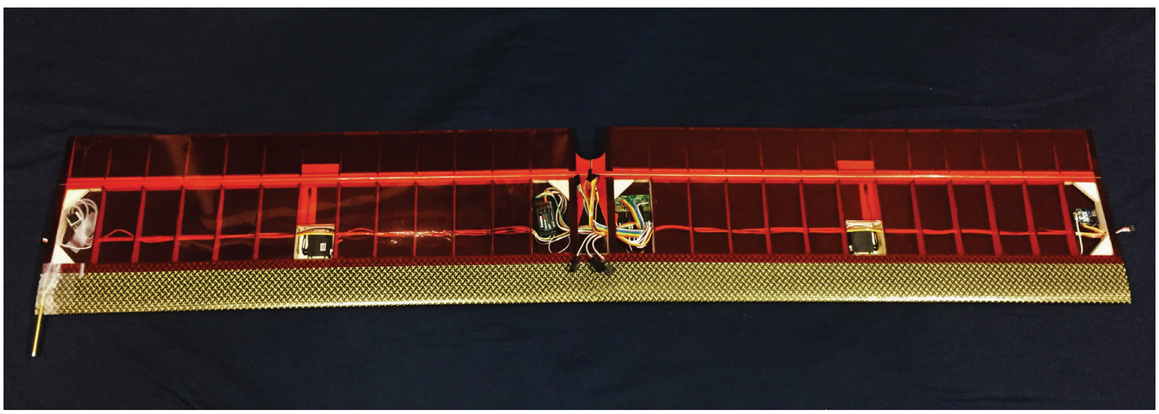


Figure 12. The center wing panel of the instrumented UIUC Solar Flyer airframe showing the instrumentation components and servo actuators.

VI. Summary

This paper focused on the development, integration, and operation of avionics platforms used to perform in-flight measurements, with specific emphasis for use on small- to medium-sized unmanned aircraft. First, the paper provided an overview of the development process followed by a discussion of design aspects involved in the process. Then, the paper presented a study of data acquisition and flight control systems that have been used in UAV research. Finally,three avionics integration examples were given that demonstrated application in an unmanned aircraft.

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