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SDAC-UAS: A Sensor Data Acquisition Unmanned Aerial System for Flight State Monitoring and Aerodynamic Data Collection

Or D. Dantsker[*], Andrew V. Louis[†], Renato Mancuso[‡], Marco Caccamo[§], and Michael S. Selig[¶]
University of Illinois at Urbana–Champaign, Urbana, IL 61801

This paper presents a sensor data acquisition unmanned aerial system (SDAC-UAS) for flight state monitoring and aerodynamic data collection research on small to mid-sized unmanned aerial vehicles (UAVs). The SDAC-UAS was developed to provide the ground-based human (safety) pilot an easily discernible display of sensor and state data for aircraft monitoring along with providing the ability to remotely start and stop on-board logging. The system is composed of three elements: an unmanned aerial vehicle, the sensor data acquisition system (SDAC), and ground interface. The SDAC is a low power and low weight unit that is fitted onto the UAV and acts as the sensor data distribution hub—the SDAC combines at 100 Hz a large variety of sensor streams into a unified high-fidelity state data stream that is simultaneously: recorded for post-flight analysis, transmitted to the ground to provide telemetry, and forwarded to a separate processing unit, such as an autopilot. Commands are given to the SDAC either locally using a simple interface or remotely using the down-link transceiver connected to the ground interface. The ground interface is a portable computer setup that runs a custom graphical user interface (GUI), which displays the sensor and state data and is used to transmit commands to the SDAC. The entire SDAC-UAS is completely fabricated from commercial-off-the-shelf (COTS) components, which reduced cost and implementation time; and it is designed such that it can be used with almost any small to mid-sized UAVs.

Nomenclature

ADC	=	analog-to-digital converter
ARF	=	almost ready-to-fly
CANbus	=	controller area network bus
COTS	=	commercial off the shelf
CG	=	center of gravity
DOF	=	degree of freedom
GPS	=	global positioning system
GUI	=	graphical user interface
IMU	=	inertial measurement unit
I/O	=	input/output
I2C	=	inter-integrated circuit
Lipo	=	lithium polymer
PFD	=	primary flight display
PPM	=	pulse position modulation
PWM	=	pulse width modulation
RC	=	radio control
RSSI	=	received signal strength indicator
SPI	=	serial peripheral interface
UART	=	universal asynchronous receiver/transmitter
UAV	=	unmanned aerial vehicle

[*]Graduate Research Fellow, Department of Aerospace Engineering, AIAA Student Member. dantske1@illinois.edu
[†]Undergraduate Research Assistant, Department of Computer Science. avlouis2@illinois.edu
[‡]Ph.D. Candidate, Department of Computer Science. rmancus2@illinois.edu
[§]Professor, Department of Computer Science. mcaccamo@illinois.edu
[¶]Associate Professor, Department of Aerospace Engineering, AIAA Associate Fellow. m-selig@illinois.edu

I. Introduction

This paper presents a sensor data acquisition unmanned aerial system (SDAC-UAS) for flight state monitoring and aerodynamic data collection research on small to mid-sized unmanned aerial vehicles (UAVs). The SDAC-UAS was developed to provide the ground-based human (safety) pilot an easily discernible display of sensor and state data for aircraft monitoring along with providing the ability to remotely start and stop on-board logging. The SDAC-UAS is composed of three elements: an unmanned aerial vehicle, the sensor data acquisition system (SDAC), and ground interface. The entire SDAC-UAS is completely fabricated from commercial-off-the-shelf (COTS) components, which reduced cost and implementation time; and it is designed such that it can be used with almost any small to mid-sized UAVs. A test implementation of the SDAC-UAS can be seen in Fig. 1.

At the heart of the sensor data acquisition unmanned aerial system is the sensor data acquisition system (SDAC),[1–3] which is installed onto the UAV. It is both low weight and low power, operates at 100 Hz and features: a high-frequency, high-resolution six degree-of-freedom (6-DOF) inertial measurement unit (IMU) with a global positioning system (GPS) receiver, a 3-axis magnetometer, a pitot probe, an electronic tachometer, seven 10-bit analog-to-digital converters (ADC), thirty-two 12-bit analog-to-digital converters, a 14-bit analog-to-digital converter, twenty digital input/outputs (I/O), twelve pulse width modulation (PWM) signal inputs, a 40 mi downlink transceiver, an open serial, an open CANbus port, and up to 64 GB of onboard storage. The SDAC is fitted onto the UAV and acts as the sensor data distribution hub—the SDAC combines the large variety of sensor streams into a unified high-fidelity state data stream that is simultaneously: recorded for post-flight analysis, transmitted to the ground to provide telemetry, and forwarded to a separate processing unit, such as an autopilot. Commands are given to the SDAC either locally using a simple interface or remotely using the down-link transceiver connected to the ground interface.

Figure 1. A photograph of the entire system used in the test implementation of the SDAC-UAS: the aircraft instrumented with an SDAC (internal - not visible) and ground interface.

The ground interface is a portable computer setup that has a bi-directional data link. The computer interfaces with the bi-directional data link over a serial connection to receive data and transmit commands. A custom graphical user interface (GUI) runs on the computer and displays sensor and state data and is used to transmit commands to the SDAC. The GUI has 5 sub-displays that visually show: the physical state of the aircraft, the control inputs, the location of the aircraft; a primary flight display; and a raw input data feed. With the displays, the GUI has input buttons to start and stop onboard logging and make adjustments to the sub-displays. The GUI was implemented such that all the aircraft specific data is input into a configuration file, thereby not requiring any modifications to the code to go from aircraft to aircraft.

This paper presents an implementation of the SDAC-UAS on a fixed-wing UAV. First, the paper provides background and motivation behind the development of the SDAC-UAS, including similar work from other research institutions and will also present the goals set for the development of the system. Then the next part of the paper provides details of the implementation including descriptions of air and ground facilities. Descriptions of air facilities include information on the airframe and instrumentation while descriptions of the ground facilities will include details of the ground interface and graphical user interface. The paper concludes with a summary and description of future work.

II. Background and Motivation

Situational awareness is a must for a pilot to maintain safe control of an aircraft. This becomes especially true in the case of a ground-based human (safety) pilot flying an unmanned aerial vehicle. The pilot must see the aircraft, judge its orientation, and detect if anything on the aircraft is faulty, all while flying the vehicle. The difficulty to do so increases as the aircraft and/or flight path complexity increase. Often there is the added challenge of relinquishing control to an autonomous on-board system and recovering control when needed, either planned or when the aircraft flies itself into a dangerous situation. Sometimes the pilot may need to fly the aircraft in a holding pattern or harder yet, following a path to way points. The difficulties in all these situations stem from the fundamental fact that the pilot is located on the ground, outside of the aircraft, and must therefore visualize what the aircraft is doing.

Observing the motion of an aircraft is often not enough. Due to the increasingly complex nature of unmanned aircraft, monitoring systems must be integrated into an aircraft in order to gain a better view of the aircraft subsystems and if all are functioning properly. There are a handful of commercially made datalogging telemetry systems available,[4,5] however, they do not really offer the level of customization needed to monitor complex unmanned aircraft and their subsystems. Similarly, there are many autopilots, both open[6–8] and closed-source,[9–11] that offer down-link and therefore monitoring capabilities, yet similar limitations still exist. To this end, many research institutions and agencies have developed their own data logging and down-link systems,[12–17] which are sometimes based on existing systems. Specifications for cited systems are found in Tables 1-4. By comparing the systems available, both commercial and developed, the best option in terms of feature flexibility and cost seems to come from developing one's own monitoring system; there will, however, be a penalty in terms of time.

Beyond the shear specifications of a monitoring system, usage requirements must also be considered. A ground-based human (safety) pilot can only glance away from the aircraft for a short period of time. The commercially made datalogging telemetry systems mentioned[4,5] do not require any additional personnel to operate, rather they display all the information downlinked on a laptop screen in a mostly predefined way. The open- and closed-source autopilot systems mentioned[6–11] provide output in a similar way, however, as the name implies, open-source autopilot system ground interfaces can be modified. The display formats for all of the systems thus far mentioned do not lend themselves to the pilot using them during flight. Custom avionic solutions[12–14,17] have similar usage requirements. Some groups that use custom solutions even describe how a large team is required to operate and monitor the instrumented aircraft.[15,16,18] The goal in developing a monitoring solution would be to make the system easy for the pilot use, specifically allowing the pilot to glance at a screen and know the state of the aircraft along with having the system alert the pilot of any ongoing or potential failures. Additionally, some form of feedback, to command the instrumentation, would be beneficial.

In order to minimize development time, the sensor data acquisition unmanned aerial system (SDAC-UAS) was to be directly based on the previously developed sensor data acquisition system (SDAC).[1–3] The SDAC, which had performed very well in testing and use, provided a good starting point in both hardware and software development in terms of the onboard system. The SDAC was however lacking proper integration into the rest of the aircraft and a ground interface. There were two important additions that needed to be made beyond the original SDAC. The first addition was the inclusion of motor pulse counting tachometers to measure the rotation rate of electric motors used. The second was not placing additional sensors boards, such as the ADC boards and the newly added tachometer(s), on the SDAC board and using the I2C protocol to transmit data, thereby minimizing the number of wire leads running from aircraft components to the SDAC board. An example would be wiring all the potentiometers in wing panel, which measure the control surface deflection, to an ADC board and running a single I2C lead to the SDAC board; if motors were to be placed on that wing panel, the tachometers could also be connected to that same I2C lead, which would highly simplify the problem of wiring a wing, especially in the case of a tiltrotor.[19,20] The ground half of the SDAC-UAS system, which would be developed from scratch, would need to be modular, quick to set up, and provide easy viewing of important information in any light setting.

Table 1. Commercially-made datalogging telemetry units

Unit	**RCAT Systems Industrial UAV[4]**	**Eagle Tree Systems Flight Data Recorder Pro[5]**
Sensors		
Inertial sensors	1-axis, ±8 g accelerometer	2-axis, ±38 g accelerometer
Magnetometers	-	-
Altimeter (barometric)	8 ft resolution	1 ft resolution
Airspeed (pitot probe)	10–290 mph	9–350 mph
GPS	1 Hz	10 Hz
Digital I/O	-	-
Analog inputs	2	2
Other inputs	2 Thermocouples, current and voltage measurement, optical RPM measurement	2 Thermocouples, current and voltage measurement, optical RPM measurement, 4 CH PWM measurement
Data Handling		
Sampling rate	20 Hz	40 Hz
Local output	-	-
Storage	up to 512 MB SD	10 kB on-board
RF link	15 mi	14 mi
Estimated cost	$2,500+	$650–1,500+

Table 2. Open-source commercially-made autopilots

Unit	**Paparazzi Lisa/M[6]**	**3D Robotics APM 2.6[7]**	**Pixhawk PX4 Autopilot[8]**
Sensors			
Inertial sensors	3-axis, ±2-16 g accelerometer 3-axis, ±250-2000 deg/s gyroscope	3-axis, ±2-16 g accelerometer 3-axis, ±250-2000 deg/s gyroscope	3-axis, ±2-16 g accelerometer 3-axis, ±245-2000 deg/s gyroscope
Magnetometers	3-axis ±8 G	3-axis ±8 G	3-axis ±2-12 G
Altimeter (barometric)	1 ft resolution	1 ft resolution	0.3 ft resolution
Airspeed (pitot probe)	Add-on supported	Add-on supported	0–223 mph
GPS	5 Hz	5 Hz	5 Hz
Digital I/O	3	0-12	0
Analog inputs	7	0-12 (same pins as Dig I/O)	2
Other inputs	1x CANbus, 1x SPI, 1x I2C	8 PWM signals, 1x I2C, 2x serial	Up to: 1x PPM sum, 1x RSSI, 6x UART, 2x SPI, 3x I2C, and 1x CANbus
Data Handling			
Sampling rate	50 Hz	50 Hz	50 Hz
Local output	Serial	Serial	Serial
Storage	512 KB on-board	16 MB on-board	2 MB on-board
RF link	Add-on supported	Short	15 mi
Estimated cost	$210	$240+	$200

Table 3. Closed-source commercially-made autopilots

Unit	Cloud Cap Piccolo II[9]	MicroPilot MP2128g[10]	Kestrel Autopilot v2.4[11]
Sensors			
Inertial sensors	3-axis, ±10 g accelerometer 3-axis, ±300 deg/s gyroscope	3-axis, ±5 g accelerometer 3-axis gyroscope	3-axis, ±10 g accelerometer 3-axis, ±300 deg/s gyroscope
Magnetometers	Add-on supported	Add-on supported	2-axis and 3-axis
Altimeter (barometric)	1 ft resolution	1 ft resolution	0.8 ft resolution
Airspeed (pitot probe)	up to 180 mph	up to 300 mph	0–130 mph
GPS	4 Hz	4 Hz	4 Hz
Digital I/O	16	8	12
Analog inputs	4x 10 bit	32x 24 bit at 5 Hz	3x 12 bit
Other inputs	CANbus	-	4-8 PWM signals, 4 Serial Ports (Std, SPI, I2C)
Data Handling			
Sampling rate	20 Hz	5–30 Hz	100 Hz
Local output	LPT	Serial	Serial
Storage	-	1.5 MB on-board	512 KB on-board
RF link	25 mi	3 mi	15 mi
Estimated cost	$20,000+	$6,000+	$2,500+

Table 4. Custom avionic system solutions

Unit	Higashino and Sakurai[12]	Beard et al[13]	FCS-20[14]
Sensors			
Inertial sensors	3-axis, ±5 g accelerometer 3-axis, ±90 deg/s gyroscope	3-axis, ±2 g accelerometer 3-axis, ±500 deg/s gyroscope	3-axis, ±10 g accelerometer 3-axis, ±300 deg/s gyroscope
Magnetometers	-	-	-
Altimeter (barometric)	-	(yes)	(yes)
Airspeed (pitot probe)	(5-hole)	(yes)	(yes)
GPS	-	1 Hz	4 Hz
Digital I/O	-	-	12
Analog inputs	16x 12 bit	16x 12 bit	2x 16 bit, 8x 16 bit
Other inputs	-	4x serial	4x RS-232
Data Handling			
Sampling rate	20Hz	130 Hz	100 Hz
Local output	-	-	-
Storage	12 MB on-board	up to 512 KB on-board	64 MB on-board
RF link	Serial communication line	3 mi	Supported

Unit	NASA EAV[15]	NASA AirSTAR[16]	Brusov et al. PRP-J5[17]
Sensors			
Inertial sensors	3-axis, ±10 g accelerometer 3-axis, ±200 deg/s gyroscope	3-axis, ±10 g accelerometer 3-axis, ±600 deg/s gyroscope	3-axis, ±2-6 g accelerometer 3-axis, ±300 deg/s gyroscope
Magnetometers	-	-	-
Altimeter (barometric)	-	(yes)	(yes)
Airspeed (pitot probe)	(5-hole)	(yes)	(yes)
GPS	(yes)	5 Hz	-
Digital I/O	-	2	0
Analog inputs	16x 12 bit	48x 16 bit	24x 12 bit
Other inputs	8x PWM signals, 4x RS-232, 8x serial, 1x CANbus	3x serial	4x PWM signals
Data Handling			
Sampling rate	10Hz	50 Hz	100 Hz
Local output	-	-	-
Storage	2x 8 GB CF	up to 512 KB on-board	Up to 512 MB SD
RF link	(yes)	(yes)	-

III. Test Implementation

The SDAC-UAS was implemented on a fixed-wing trainer-type radio control model airplane in order to test the system. The SDAC, which had previously been installed onto the aircraft,[1,2] was upgraded and then modified to communicate with a newly developed ground interface. This section provides information about the tested system, particularly the air facilities, the aircraft and on-board instrumentation; and the ground facilities, the ground interface and graphical user interface.

A. Air Facilities

The air facilities of the SDAC-UAS are made up of the aircraft and the instrumentation integrated into the aircraft. The aircraft is a standard COTS RC trainer airplane that is structurally unmodified. The instrumentation installed into the aircraft is based on the previously developed SDAC system and was integrated into the aircraft proving measurements of all aircraft inputs and motion.

1. Aircraft

A radio control model airplane was built to test the sensor data acquisition unit.[1–3] The aircraft used was a Great Planes Avistar Elite,[21] which is a 62.5 in wingspan, 7-8 lb fixed-wing trainer-type airplane. It is equipped with an electric propulsion system that uses an AXI 4120/14 600 W motor,[22] a Castle Creation Phoenix ICE 75 Amp electronic speed controller,[23] and a Thunder Power 14.8 V, 5 Ah lithium polymer (Lipo) battery.[24] The model is actuated using Futaba S3004 ball-bearing standard-torque servos and is controlled by a 2.4 GHz R6014HS spread spectrum receiver.[25] The radio control system is powered by a Castle Creations CC BEC regulator, which uses a Thunder Power 7.4 V, 450 mAh lithium polymer battery. The completed flight-ready aircraft is shown in Fig. 2, its physical specifications are given in Table 5, and its airframe component specifications are given in Table 6.

Figure 2. Flight-ready Great Planes Avistar Elite model aircraft.

Table 5. Great Planes Avistar Elite unmanned aircraft physical specifications

Geometric Properties	
Overall Length	55.0 in (1395 mm)
Wingspan	62.5 in (1590 mm)
Wing Area	672 in^2 (43.3 dm^2)
Aspect Ratio	6.62
Inertial Properties	
Weight	
Empty (w/o Battery)	7.53 lb (3.415 kg)
4S LiPo Battery	1.17 lb (0.530 kg)
Gross Weight	8.70 lb (3.945 kg)
Wing Loading	29.8 $\mathrm{oz/ft}^2$ (90.9 $\mathrm{gr/dm}^2$)

Table 6. Great Planes Avistar Elite unmanned aircraft airframe component specifications

Construction	Built-up balsa and plywood structure, aluminum wing tube, aluminum landing gear, ABS canopy, and plastic-film sheeted.
Flight Controls	
Controls	Ailerons (2), elevator, rudder, throttle, and flaps (2)
Transmitter	Futaba T14MZ
Receiver	Futaba R6014HS
Servos	(8) Futaba S3004
Regulator Distribution	Castle Creations CC BEC
Receiver Battery	Thunder ProLite 20c 2S 7.4V 450 mAh
Propulsion	
Motor	AXI 4120/14 Outrunner
ESC	Castle Creation Phoenix ICE 75 Amp Brushless Speed Controller
Propeller	APC 13x8E
Motor Flight Pack	Thunder Power ProPower 30c 4S 14.8 V 5 Ah lithium polymer battery
Flight Time	10–20 min

2. Instrumentation

The testbed aircraft was instrumented with an updated version of the sensor data acquisition system (SDAC),[1–3] which can be seen in Fig. 3. The SDAC was developed from COTS components and is plug-and-play, meaning that it could easily be installed into almost any aircraft. As mentioned earlier, the unit operates at 100 Hz and includes: a high-frequency, high-resolution six degree-of-freedom (6-DOF) inertial measurement unit (IMU) with a global positioning system (GPS) receiver, a 3-axis magnetometer, a pitot probe, an electronic tachometer, seven 10-bit analog-to-digital converters (ADC), thirty-two 12-bit analog-to-digital converters, a 14-bit analog-to-digital converter, twenty digital input/outputs (I/O), twelve pulse width modulation (PWM) signal inputs, a 40 mile downlink transceiver, an open serial, an open CANbus port, and up to 64 GB of onboard storage. Given the included sensors, the system is able to simultaneously log and transmit: 3D linear and angular accelerations, velocities, and position along with GPS location; pitot probe airspeed; 3D magnetic field strength and heading; control surface inputs; and control surface deflections. The performance specifications for the updated SDAC are given in Table 7. A description of the software architecture used in the implementation is given in Mancuso et al.[1]

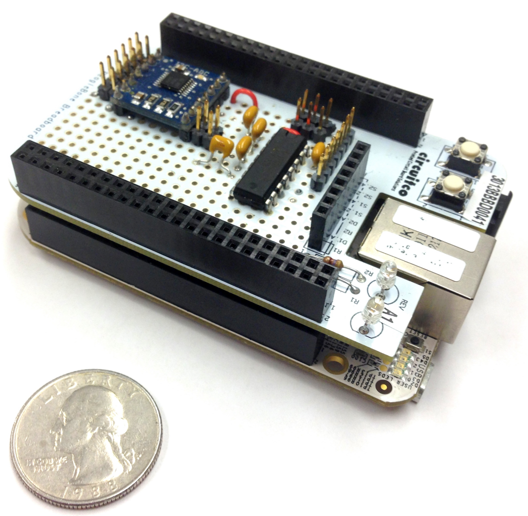

Figure 3. A photograph of the original sensor data acquisition system (SDAC) unit.

The updated SDAC was fitted onto the aircraft and acts as the sensor data distribution hub for the various sensors installed. A system diagram depicting the specific configuration of the instrumentation, along with the flight control and propulsion systems, is shown in Fig. 4. Starting from the top-left of the diagram, the RC receiver outputs PWM control signals to servos and ESC, while a duplicate stream of PWM control signals are sent to the SDAC. The receiver gets its power from a Lipo battery connected through a regulator. The ESC, which drives the motor, draws power from its own battery. In the center of the diagram, the SDAC is connected to a variety of devices: an IMU, 3D magnetometer, 4 ADCs, an RPM sensor and a telemetry radio. Three of the ADCs are connected to potentiometers to measure control surface deflections while the last is used to measure the voltages of each of the batteries. The SDAC acquires data from the sensors and from the stream of PWM control signals coming from the receiver and outputs a unified stream to the telemetry radio while simultaneously logging it. The output stream can also be transmitted to another on-board device. The last two systems in the diagram are the telemetry radio and the video system, camera and transmitter, which was added to simulate what would be found on larger aircraft. Each of these systems are powered by separate Lipo batteries with regulators to output the correct voltage. As mentioned before, one of the ADCs is being used to measure the voltages of all the batteries. This ADC is connected to the raw output of each of the batteries through voltage dividers circuits that scale the voltages of the batteries to the range the ADC can measure. The specifications of the components used in the updated, tested sensor data acquisition system are given in Table 8 and information about the installation of these components is described in Dantsker et al.[2]

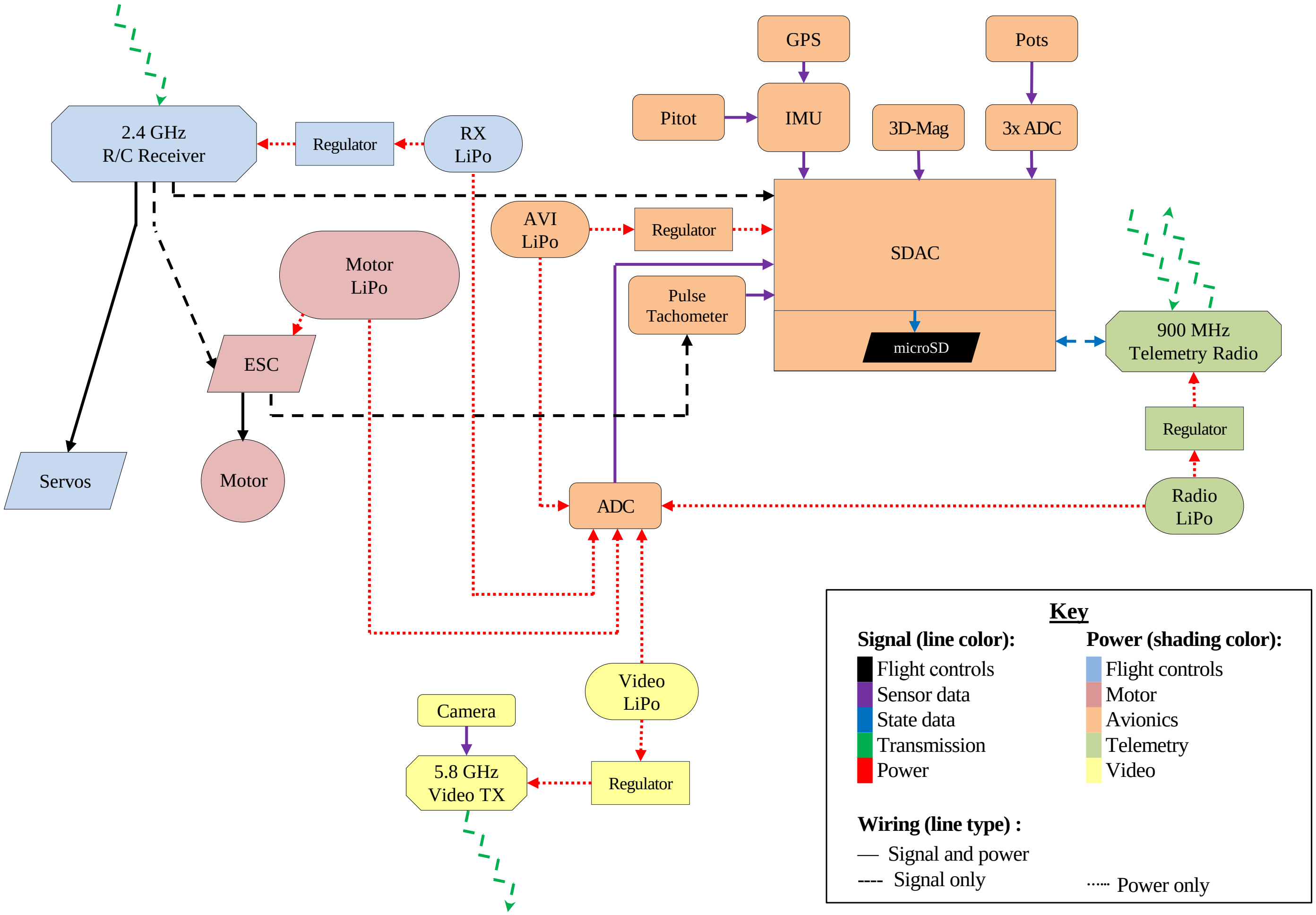

Figure 4. A block diagram of the aircraft systems.

Table 7. Updated sensor data acquisition (SDAC) system performance specifications

Sensors	
Inertial sensors	3-axis, $\pm$18 g accelerometer 3-axis, $\pm$300 deg/s gyroscope
Magnetometers	3-axis $\pm$750 mG and 3-axis $\pm$11 G
Altimeter (barometric)	1 ft resolution
Airspeed (pitot probe)	5–180 mph
GPS position	Up to 120 Hz (IMU assisted)
Tachometer	Up to 4 brushless motor pulse counters
Digital I/O	Up to 20
PWM inputs	Up to 12
Analog inputs	Up to 7x 10 bit, 32x 12 bit, 1x 14 bit
Further expansion capabilities	I2C, 1x serial port, CANbus
Data Handling	
Logging rate	100 Hz
Local output	Serial or Ethernet
Storage	Up to 64 GB microSD
RF link	40 mi
RF rate	10-25 Hz

Table 8. Tested sensor data acquisition (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
Magnetometer	PNI Corp MicroMag 3
Analog-to-digital converters	4x Gravitech 12 bit - 8 Channel ADC
Potentiometers	6x BI Technologies 6127
Tachometer	1x Sparkfun ProMicro
Power	
Regulators	3x Castle Creations CCBEC
Batteries	1x Thunder Power ProLite 2S 450 mAh (avionics) 2x Thunder Power ProLite 3S 1350 mAh (telemetry and video)
Telemetry transceiver	Digi 9X Tend 900-MHz card
Data Storage	8GB microSD card

B. Ground Facilities

The ground facilities of the SDAC-UAS are made up of a ground interface and a graphical user interface (GUI). The ground interface is a portable computer setup that has a bi-directional data link with the instrumented aircraft. The GUI, which runs on the computer, displays sensor and state data and is used to transmit commands to the SDAC. The ground facilities are designed to provide the human pilot with a quick view of the state of the aircraft and the ability to start or stop on-board data logging.

1. Ground Interface

The ground interface is a portable computer setup that has a bi-directional data link to communicate with the instrumented aircraft; the ground interface can be seen in Figure 5. The portable computer setup used for the SDAC-UAS implementation consists of two pieces: a mini-ITX tower and a tripod monitor rig with the bi-directional data link; the specifications of all components used to aseemble the portable computer setup can be found in Table 9. The ground interface is set up at the flying site by simply opening and expanding the tripod legs, threading the monitor-data link stand onto the tripod, connecting the video and USB cables from the tripod rig to the tower, and finally plugging the power cables into a powered strip or outlet. The ground interface was built with power efficient components, including a processor with integrated graphics, a solid state hard drive, a high-efficiency power supply, and an LED lit monitor, in order to minimize the power requirements at the flying site. The total power required for the ground interface is less than 200 W, allowing it to easily be powered by a car battery inverter. In addition, the tower uses all solid state components, which makes it insensitive to movement or vibrations.

Figure 5. A photograph of the sensor data acquisition system unmanned aerial system (SDAC-UAS) ground interface during flight.

Table 9. **Tested portable computer setup component specifications**

Mini-ITX Tower	
Processor	Intel Core i7-4790S
Memory	PNY XLR8 8GB (2 x 4GB)
Hard Drive	Samsung 840 EVO 250GB SSD
Motherboard	ASUS H97I-PLUS
Power Supply	SeaSonic S12G-450
Case	Rosewill Legacy U2-B
Tripod Monitor Rig	
Tripod	Manfrotto 3221
Monitor	Dell P2314H 23" HD Monitor with LED backlight
Telemetry transceiver	Digi 9X Tend 900-MHz card with RS-232/485/422 interface
Serial-to-USB adapter	Tripp Lite USA-19HS

The tripod rig was constructed as following. An adapter plate was machined to the size of the monitor stand base with a 3/8"-16 threaded hole placed vertically beneath the center of gravity of the monitor. The threaded hole matches the tripod and allows the plate to be easily threaded to and un-threaded from the tripod. The adapter plate was fastened to the base of the monitor stand. The monitor was then attached to the stand using the standard mounting procedure. Afterward, the telemetry radio, which is the same model used on the aircraft, was connected to an RS-232/485/422 interface, then fastened to the back of the stand with the antenna pointing upwards. The telemetry radio was connected to a serial-to-USB converter which was also attached to the monitor stand. A trackball mouse, used to interface with the computer, was adhered to top of the monitor stand base. A trackball mouse was used as there is too limited of a working area to use a regular mouse. Proper cable connection and routing was then performed. For the purpose of testing, a stand alone keyboard was used to debug problems, however, is not required for normal operation of the ground interface.

2. Graphical User Interface

A custom graphical user interface (GUI) was implemented on the ground station interface to display sensor and state data and transmit commands to the aircraft instrumentation. The GUI was designed to provide the human pilot with a quick view of the state of the aircraft. The interface has five sub-displays that show: the physical state of the aircraft, the control inputs, the location of the aircraft; a primary flight display; and a raw input data feed. Along with the displays, the GUI has input buttons to start and stop onboard logging and make adjustments to the sub-displays. The GUI was implemented such that all the aircraft specific data is input into a configuration file, thereby not requiring any modifications to the code to go from aircraft to aircraft. The graphical user interface, which was implemented in a 16:9 ratio to be displayed on today's high resolution monitors, can be seen in Figure 6.

The top left GUI sub-display shows the physical state of the aircraft. The sub-display shows position of all the control surfaces, two control surfaces on each of the wings (right and left), one control surface on each of the stabilizers (right and left), and one control surface on the vertical stabilizer. The aircraft displayed has a T-tail in order to make viewing of all the control surfaces easier. The control surfaces movement displayed are driven by potentiometer measurements and may be scaled as desired. Control surfaces displayed may also be disabled or may be assigned the same values of other control surfaces; e.g., the case of an aircraft with only ailerons and no flaps, the interior wing control surfaces may either be held at center or moved to the same position as the exterior wing control surfaces. The aircraft displayed also provides the pilot a visual cue if a control surface jams during flight; the GUI monitors the measured deflection and compares it to the control input expected deflection, and if the two values do not match within a set error range, the control surface will be highlighted by a flashing red box, which is accompanied by an audible alarm.

The physical state of the aircraft sub-display also shows the rotation rate of the motor. The current implementation of the GUI is set up to allow up to four motor rotation rates to be shown, however it should be mentioned that the current version of the SDAC could in theory allow for up to 124 motor pulse based rotation rates units to be used simultaneously. Finally, the sub-display also shows voltage level of up to six batteries, visually using a bar and numerically below; the colors of the voltage level bars change from green to yellow to red depending on the battery voltage and the assigned transition points. Once a battery hits a red voltage transition point, an audible alarm will sound to alert the pilot. The

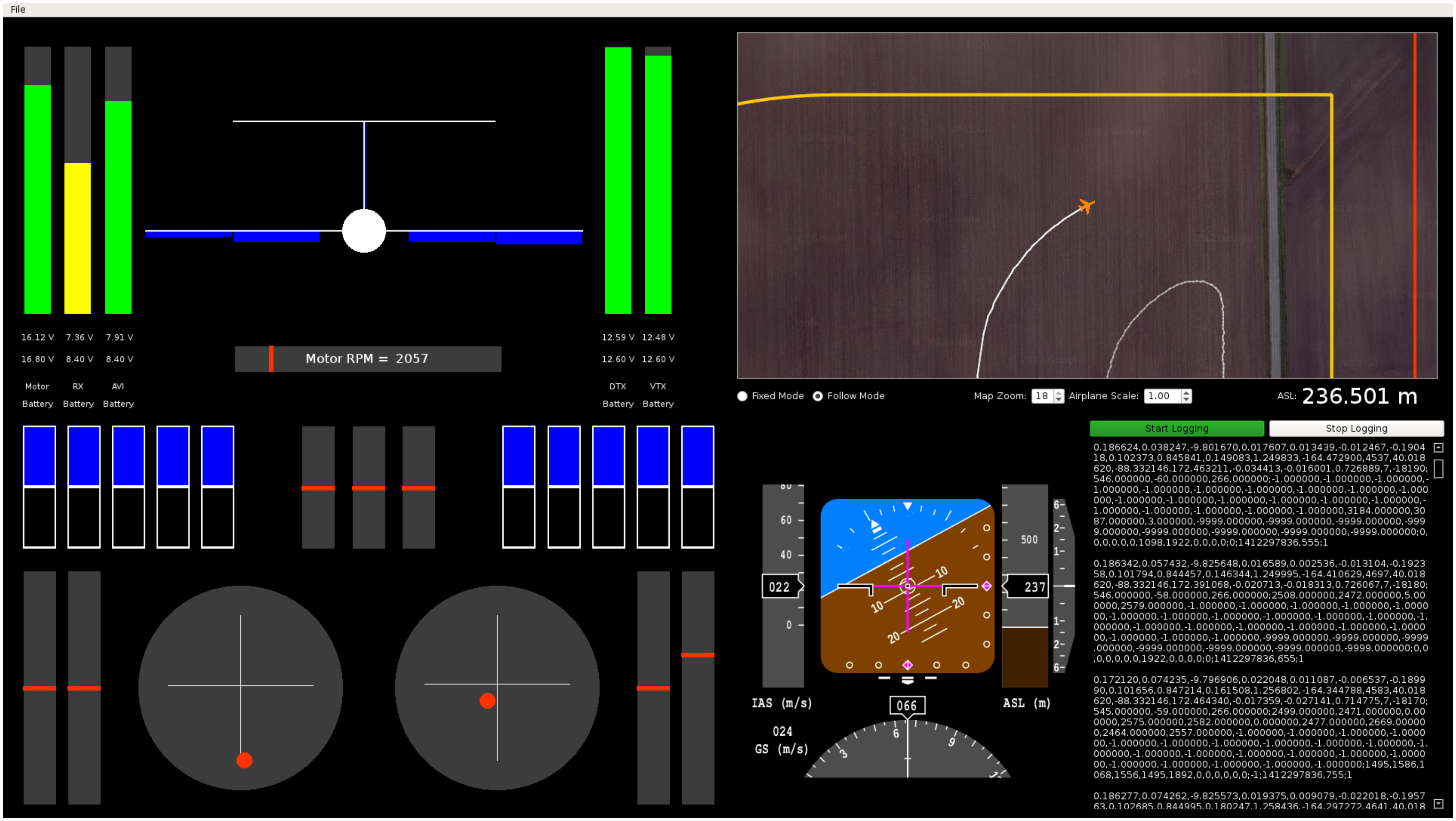

Figure 6. A screenshot of the GUI during flight.

number of how many batteries are measured could also be expanded depending on how many of the SDAC ADC channels are used for voltage measurement.

The bottom left GUI sub-display shows the control inputs sent to the aicraft, specifically showing the position of the RC transmitter joysticks, switches, and sliders. There are two 2-axis joysticks, ten switches, and seven sliders. The positions of each of the control inputs to the aircraft are shown in the absolute, meaning that any curve modifications applied between the physical motion of the control sticks on the transmitter to the output of the transmitter are disregarded, only the control inputs received by the aircraft actuators are shown.

The top right GUI sub-display shows the location of the aircaft using the aircraft GPS measurements. The sub-display provides an overhead map with the view either fixed with the home point at center, so called ”Fixed Mode”, or following the aircraft with the aircraft at the center, so called ”Follow Mode.” The map zoom, given in map tile units, may be changed along with the size of the aircraft icon. The map shown in the sub-display is also set up such that colored boundary lines can be drawn on the map to show the pilot a visual indication of when the aircraft is going to fly outside of an intended flight zone. The boundary lines automatically adjust to changes in zoom and map motion, as would occur in ”Follow Mode.” The GUI can also be set up to provide a visual and audible alarm when a boundary line is crossed. Finally, the altitude of the aircraft is displayed at the bottom right of the sub-display.

The bottom middle GUI sub-display provides a primary flight display (PFD). The PFD implemented[26] provides a pitch ladder, a bank angle indicator, an indicated airspeed indicator, a ground speed readout, an altitude above sea level indicator, and a heading indicator. All the values displayed in the PFD are given in metric units.

Lastly, the bottom right GUI sub-display provides the raw input data feed. The sub-display shows the full data messages being transmitted by the SDAC and received by the ground interface. These messages are useful in order to diagnose system failures; e.g., if the the raw input data feed no longer updates, the pilot knows there is a problem with data transmission. The messages are also used in order to set up the aircraft configuration file. The messages provide the digital values for each of the sensor outputs, which are used to set the minimum, middle, and maximum values for each display parameter in the configuration files.

Like most modern graphical applications, the GUI uses an event-driven programming model. This means that there is a main event loop that queues and processes all events that are triggered by the program. The main event loop processes events by running the callback functions of any objects that have registered as listeners. This event-driven programming model has a useful optimization of detecting the rapid fire of a single event and running the appropriate handlers once. In an effort to take advantage of modern multi-core processors, a thread is dedicated to reading and processing data received from the SDAC through the wireless link. This thread is separate from the main event loop. It reads data from the serial connection as a string and then parses the data from the string. After parsing, the data is placed in a buffer. Finally, the thread triggers an event and provides listeners with a reference to the buffer. When the GUI is initialized, the main window is registered as a listener for data sample read events. When its event handler is triggered, the main window copies the data to the proper sub-displays. After copying, a user interface repaint event is triggered. This process continues for the lifetime of the program. By separating the serial input and output from the main event-loop, the user interface remains responsive while the input thread blocks waiting for the next data sample. Dedicated graphics processing units are increasingly common in modern computers. Knowing this fact, the widgets composing the GUI were made to use OpenGL so that rendering can be accelerated by dedicated hardware when it is present.

The GUI requires that the host system have the Qt (open source) libraries[27] installed, which are cross platform. The GUI has rather minimal system requirements and thus should be able to run smoothly on any computer with a recent processor and hardware accelerated graphics support. In the current implementation, the GUI ran on an Intel Core i7-4790S using just the processor integrated graphics for rendering acceleration. The GUI only utilized 2% of the processor resources and therefore did not stress the system.

IV. Summary and Future Work

This paper describes the implementation of a sensor data acquisition unmanned aerial system (SDAC-UAS) for flight state monitoring and aerodynamic data collection research on small to mid-sized unmanned aerial vehicles (UAVs). The SDAC-UAS was developed to provide the ground-based human (safety) pilot an easily discernible display of sensor and state data for aircraft monitoring along with providing him the ability to remotely start and stop on-board logging. The system is composed of three elements: an unmanned aerial vehicle, the sensor data acquisition system (SDAC), and ground interface. The SDAC acts as the sensor data distribution hub that combines at 100 Hz a large variety of sensor streams into a unified high-fidelity state data stream that is simultaneously: recorded for post-flight analysis, transmitted to provide telemetry, and forwarded to a separate processing unit. The ground interface is a portable computer setup that runs a custom graphical user interface (GUI), which displays the sensor and state data and is used to transmit commands to the SDAC. The entire SDAC-UAS was completely fabricated from commercial-off-the-shelf (COTS) components, which reduced cost and implementation time; and it is designed such that it can be used with almost any small to mid-sized UAVs.

Future work to improve the current implementation of the SDAC-UAS will include the miniaturization of the ground interface, from the tripod rig and tower to a light weight, battery-powered tablet. The tablet would be placed onto the RC transmitter and would eliminate the need for most of the wiring along with the mouse. Beyond making improvements to SDAC-UAS ground interface, most of the components in the onboard instrumentation will also be miniaturized by transitioning from through-hole components and perfboards to surface-mount components and custom printed circuit boards. The change would decrease the amount of manual wiring and therefore ease assembly along with reducing the system weight.

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Figure 7. A photograph of the test implementation of the SDAC-UAS in use.

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