Energy System Instrumentation and Data Acquisition for Flight Testing of a Long-Endurance, Solar-Powered Unmanned Aircraft

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The growing application space of Unmanned Aerial Vehicles (UAVs) is creating the need for aircraft capable of autonomous, long-distance, and long-endurance flights. The two main challenges are the limited power capacity of UAVs, as well as the adaptation to real-time detected stimuli, changing the course of the mission. The UIUC-TUM Solar Flyer addresses the aforementioned challenges by balancing power consumption and solar power generation, and therefore enabling on-board data processing for real-time mission adaptation. This paper describes the energy system instrumentation and data acquisition integrated into the aircraft, enabling long-endurance flight testing to be performed. The paper presents an overview of the aircraft and avionics, details regarding energy system instrumentation, and then flight test results from a 1 hour flight performed under near ideal conditions in the Fall of 2020.

Nomenclature

AGL	=	above ground level
BEMT	=	blade element momentum theory
COTS	=	commercial-off-the-shelf
ESC	=	electronic speed controller
GaAs	=	gallium arsenide
GNSS	=	global navigation satellite system
IMU	=	inertial measurement unit
MPPT	=	maximum power point tracker
PWM	=	pulse width modulation
RPM	=	rotations per minute
UAV	=	unmanned aerial vehicle
ϕ, θ, ψ	=	roll, pitch and heading angles

I. Introduction

In recent years, we have seen an uptrend in the popularity of UAVs driven by the desire to apply these aircraft to areas such as precision farming, infrastructure and environment monitoring, surveillance, surveying and mapping, search and rescue missions, weather forecasting, and more. Since the inception of unmanned aircraft, a key design driver and limiter has been the limited on-board energy storage, as it significantly constrains flight time and ultimately usability. Notably, the majority of the aforementioned applications require continuous collection and processing of visual data. 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.[1–5] Given the finite energy resources found on board an aircraft (battery or fuel), traditional designs greatly limit aircraft endurance since significant power is required for propulsion, actuation, and the continuous transmission of visual data.

All the mentioned application scenarios would benefit by carrying a high-performance, embedded computer system to minimize the need for data transmission. The aircraft should be able to carry a high-performance embedded computer

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system that could perform all required computations online and only downlink final results, saving a significant amount of energy. Performing on-line, on-board computation also allows the aircraft's autopilot to adapt its mission to external stimuli in real-time, broadening the application space of UAVs. A major technical hurdle to overcome is that of drastically reducing the overall power consumption of these UAVs so that they can be powered by solar arrays, therefore extending flight time. When powered by solar arrays, a careful reduction in battery size can decrease the aircraft's weight. reducing propulsion power even further. An additional advantage of long-endurance flight is the increase in aircraft availability and the decrease of takeoffs and landings that constitute the riskiest portions of flight. Currently, all long endurance solar-powered aircraft have incorporated custom airframe designs and many custom components (e.g. single-application propellers and gearboxes, maximum peak power-point trackers, etc.)[6,7] However, to truly enable the above applications, the solar-powered aircraft needs to be assembled from only commercial-off-the-shelf (COTS) components and that it can sustain continuous flight. Using only COTS components reduces aircraft cost, thereby increasing accessibility to the community.

Assuming the ambitious goals of on-board computing, long-endurance flight capabilities, and COTS-only components are achieved, the resulting unmanned aircraft will be more readily available to various communities such as research, industry, and emergency response, among others. For this purpose, a computationally-intensive, long-endurance solar-powered unmanned aircraft called the UIUC-TUM Solar Flyer[8] was developed, which is shown in Fig. 1. The aircraft was built from a majority of COTS components using a mixture of trade studies and power simulations in order to enable a variety of all-daylight hour missions while minimizing aircraft size. The 4.0 m (157 in) wingspan UIUC-TUM Solar Flyer aircraft weighs approximately 3.3 kg (7.2 lb) and will soon have the continuous daylight ability to acquire and process high resolution imagery. The aircraft is instrumented with an autopilot and high-fidelity data acquisition system and is powered by a 64 W gallium arsenide (GaAs) solar array. Its configuration, wing platform area, and expected lift-to-drag ratio were also considered, along with motor and propeller data. This paper describes recent long-endurance flight testing performed with the UIUC-TUM Solar Flyer.

This paper first provides an overview of the UIUC-TUM Solar Flyer including aircraft and sub-system descriptions, and specifications. Next, the paper describes the energy system instrumentation integrated into the aircraft as it evolved during flight testing. Flight testing results from an approximately 1 hour flight performed under near ideal conditions are presented and discussed. Conclusions from these flight tests are then discussed. The paper ends with a statement of future work and application.

Figure 1: The flight-ready UIUC-TUM Solar Flyer aircraft.

II. Aircraft Overview

The UIUC-TUM Solar Flyer was developed to enable continuous, all-day acquisition and processing of high resolution visible and infrared imagery while minimizing resources. In order to keep the aircraft relatively inexpensive, both in labor and cost, the aircraft has been developed using a majority of commercial-off-the-shelf components, which therefore highly limits the number of viable options. The airframe chosen for development was selected through trade studies [9] that considered airframe availability and payload requirements as well as potential energy collection — more detail regarding airframe selection and integration can be found in related literature.[8–10] In similar recent related work, a propulsion system optimization tool was developed and validated[11] and then applied to the UIUC-TUM Solar Flyer.[12]

A. Aircraft Description

The UIUC-TUM Solar Flyer airframe was constructed from a F5 Models Pulsar 4.0E Pro remote control aircraft sailplane kit.[13] The fuselage is composed of a kevlar pod and a carbon fiber tail boom. All of the flight surfaces are built from balsa wood that is reinforced with carbon fiber and a kevlar-carbon fiber laminate. The wings are composed out of 3 sections: center with flaps and outer right and left with aileron. The airframe was built per the manufacturer instructions with slight modifications to ease future computational device and solar array integration.

As mentioned above, the Solar Flyer propulsion system components were selected using a propulsion system optimization tool, which was applied to a typical field coverage mission the aircraft would perform. The tool used the propeller performance data for 40 Aero-Naut CAM carbon folding propellers and motor parameters for 28 motors from Hacker Motor GmbH,[14] Model Motors s. r. o.,[15] and Neutronics,[16] which were mass and size compatible to the aircraft. 1120 combinations were computed and ranked by the efficiency. After considering thrust requirements for upset scenarios and thermal management, the Model Motors AXi 480/1380 and Aero-Naut CAM 12x8 were chosen as this combination provided a 15% increase in propulsion efficiency than the baseline combination and ample aircraft safety. Finally, in order to control and power the motor, a Castle Creations Phoenix Edge Lite 50A electronic speed controller (ESC) was chosen as it provided sufficient current capability and the required interfaces and sensing.

The aircraft energy storage systems were developed to collect, store, and distribute energy on-board as required. Gallium arsenide (GaAs) solar arrays from Alta Devices, which are estimated to be 25–26% efficient, are used on the aircraft in conjunction with a maximum power point tracking (MPPT) charge controller and a 3S 8P, 10.8V 28Ah Samsung 35E 18650 lithium-ion battery that acts as an energy buffer. The aircraft carries 64 W of solar cells mounted onto the upper surface of the wings; areas such as the leading edge and the control surfaces do not have solar cells mounted on them due to overhead weight and wiring associated as well as the decreased solar power production potential. The batteries are distributed within the fuselage, while maintaining center of gravity location. A side view of the fuselage layout is shown in Fig. 2

The UIUC-TUM Solar Flyer avionics are based around a commercially available flight control and data acquisition system, the Al Volo FC+DAQ,[17,18] and uses the open-source uavAP autopilot[19,20] and uavGS ground station interface.[21,22] The system integrates a 9-DOF inertial measurement unit (IMU) and 10 Hz Global Navigation Satellite System (GNSS) and operates at 100 Hz. The main avionics unit as well as the airspeed probe and sensor, GNSS antenna, ESC data interface, 900 MHz radio module, and control multiplexer are laid out within the center wing panel; a top view of the instrumentation layout within the wing is shown in Fig. 3. Further detail regarding the UIUC-TUM Solar Flyer avionics development, and layout can be found in related literature.[10,23]

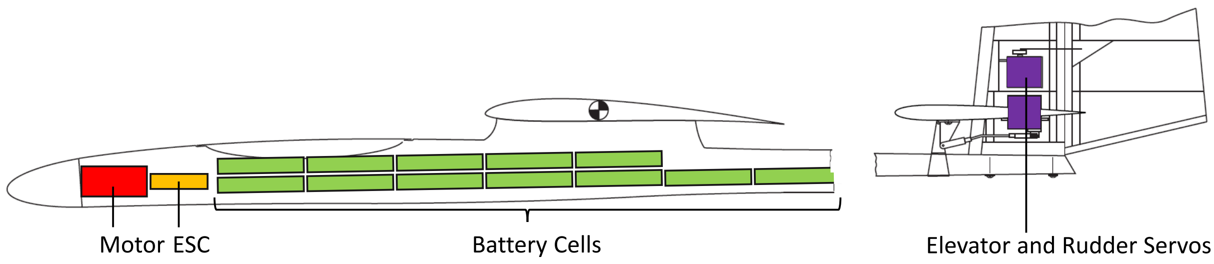


Figure 2: Side view of the UIUC-TUM Solar Flyer fuselage, showing the layout of the motor, the ESC, the battery cells, and the elevator and rudder servos.

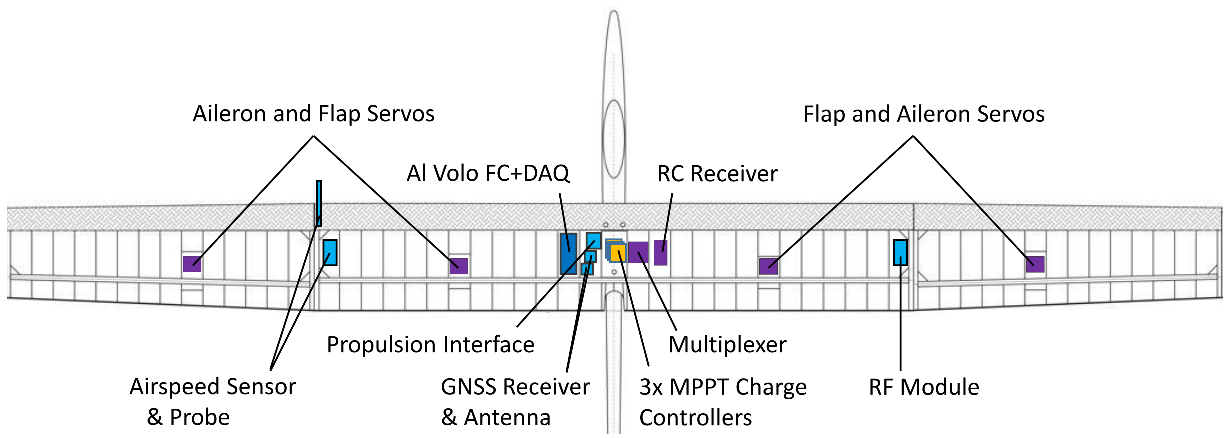


Figure 3: Top view of the UIUC-TUM Solar Flyer center and mid-outer wing sections, showing the layout of avionics components, MPPTs, and the aileron and flap servos.

B. Specifications

The physical and system component specifications of the UIUC-TUM Solar Flyer are provided below in Tables 1-4.

Table 1: Physical aircraft specifications of the UIUC-TUM Solar Flyer.

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	
Empty Mass/Weight	2.0 kg (4.4 lb)
Battery Mass/Weight	1.3 kg (2.8 lb)
Gross Mass/Weight	3.3 kg (7.2 lb)
Wing Loading	39.1 gr/dm^2 (12.8 oz/ft^2)

Table 2: Specifications of the UIUC-TUM Solar Flyer airframe, flight control, and propulsion systems.

Airframe	F5 Models Pulsar 4.0E
Flight Controls	
Receiver	Futaba R6208SB
Servos	(6) S3173SVi
Propulsion	
Motor	Model Motors AXi Cyclone 46/760
ESC	Castle Creations Phoenix Edge Lite 50
Propeller	Aeronaut CAM Folding 13x6.5

Table 3: Specifications of the UIUC-TUM Solar Flyer solar and energy storage systems.

Solar	
Photo Voltaic Cells	64W of Alta Devices Single Junction GaAS cells in 20S, 16P
Blocking & Bypass Diodes	80x Diodes Inc. 12A SBR
Charge Controller	Analog Devices MPPTs in 3P
Current Tracking	Allegro Hall-Effect Current Sensor
Energy Storage	
Battery	10.8V 28Ah Samsung 35E 18650 in 3S 8P

Table 4: Specifications of the UIUC-TUM Solar Flyer avionics.

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 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

III. Energy System Instrumentation

Flight testing of the UIUC-TUM Solar Flyer began in 2018 and followed a risk-mitigation approach to slowly build up the aircraft from essentially a model sailplane to a highly-complex and autonomous long-endurance, solar-powered unmanned aircraft. As presented above, the initial Al Volo FC+DAQ instrumentation installed on the aircraft included a 100 Hz, 9-DOF inertial measurement unit (IMU), 10 Hz Global Navigation Satellite System (GNSS), airspeed probe and sensor, and an ESC data interface. The ESC data interface provided motor voltage, current, and rotation rate, and commanded throttle. The motor voltage and current were measured between the ESC and motor and allowed motor power to be computed.

During the first solar-powered flights in the fall of 2019, it became apparent that further energy systems instrumentation was desired in order to better monitor and log solar energy capture and propulsion power consumption. As the Al Volo FC+DAQ flight control and data acquisition system had 32 integrated 0 to 5V analog inputs available, as well as

5V power rail, adding additional sensors was possible. Sensors could therefore be placed about the aircraft to measure power power input from the 3 maximum power point tracking (MPPT) charge controllers as well as at the battery. The power sensing components added to the aircraft were primarily hall-effect current sensors and voltage-dividing circuits.

A system-level energy diagram of the aircraft in its current state is provided in Fig. 4. In the diagram, the shapes with black outlines signify energy generating (shaded yellow), modulating (shaded green), storing (shaded brown), and consuming (shaded blue) components with black power lines connecting between them. It should be noted that in actuality, the power bus is simply a rail connecting the components with a safety disconnect for the battery. The red cylinders signify the inline power sensors added to the aircraft during the flight test campaign while the blue dashed outlines signify existing power measurement sensors that are integrated in the core devices, i.e. the flight control and data acquisition system and the ESC. An inline power sensor was not added between the battery and the bus for safety / fail-safe reasons due to risk of in-flight disconnection. Specific power measurement of the actuators and radios was not implemented for risk-mitigation and fault-tree reasons.

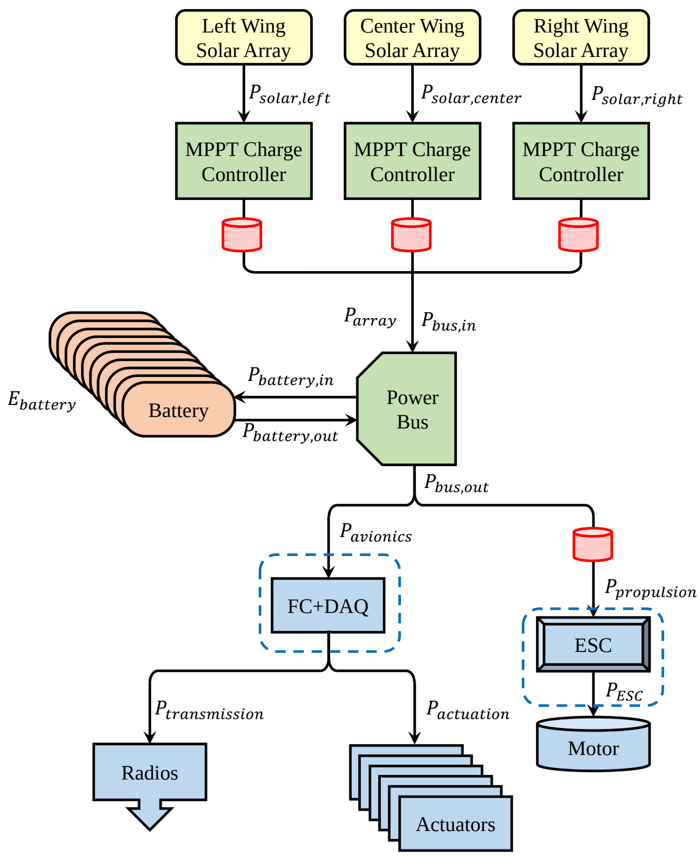


Figure 4: The system-level diagram of energy generating (shaded yellow), modulating (shaded green), storing (shaded brown), and consuming (shaded blue) components within the UIUC-TUM Solar Flyer with power sensing capabilities (outlined red and blue).

IV. Flight Test Result and Discussion

During the 2020 flight season, the UIUC-TUM Solar Flyer performed several long-endurance, solar-powered flights. Of them, the longest flight performed was an 8 hour flight in August 2020 under non-ideal (cloudy and windy) weather conditions.[24] For the purposes of examining on-board power generation and consumption, a 1 hour flight performed under ideal conditions is presented.

The approximately 1 hour flight was performed on Oct 8, 2020 with the UIUC-TUM Solar Flyer taking off at 11:43 AM and landing at 12:40 PM local time. During that time the sun shifted from 42 deg elevation, and 158 deg azimuth to 45 deg elevation and 177 deg azimuth. A nearby national weather station reported that winds were calm to 3 mph (1.3 m/s) from a variable direction and that it was sunny with fair skies (less than 40% clouds). Locally at the field, the flight crew observed sunny skies with the winds of 3-5 mph (1.3-2.2 m/s) from the SSW (190-210 deg), which was aligned with the runway, from right to left (in the perspective of the flight crew).

The trajectory of the flight is shown in Fig. 5. The figure is laid out from the perspective of above the flight crew area, looking towards the flight testing area and the aircraft flight path. The takeoff was performed from the runway using a dolly, from left to right and was followed by an ascent into a clockwise race track flight pattern. Specifically, the aircraft was commanded to perform a race track pattern of 650×150 m at an altitude of 100 m AGL; and maintain an airspeed of 11 m/s. The aircraft performed 26 laps of the flight pattern with some deviations that are addressed below. This was followed by a descent to landing. The landing was performed from left to right, on a grass strip parallel to the runway.

The race track path flown is equivalent in flight maneuvering to an area coverage mission with 500 m long straights that are 150 m apart, with required 180 deg, 75 m radius turn-arounds at the ends of the straights. As mentioned, 26 laps were performed during the 53 min of maneuvering, yielding an effective coverage area of 1.95 km^2 (481 acre). Therefore, the race track maneuvering demonstrated equates to an area coverage of 2.2 km^2/hr (545 acre/hr).

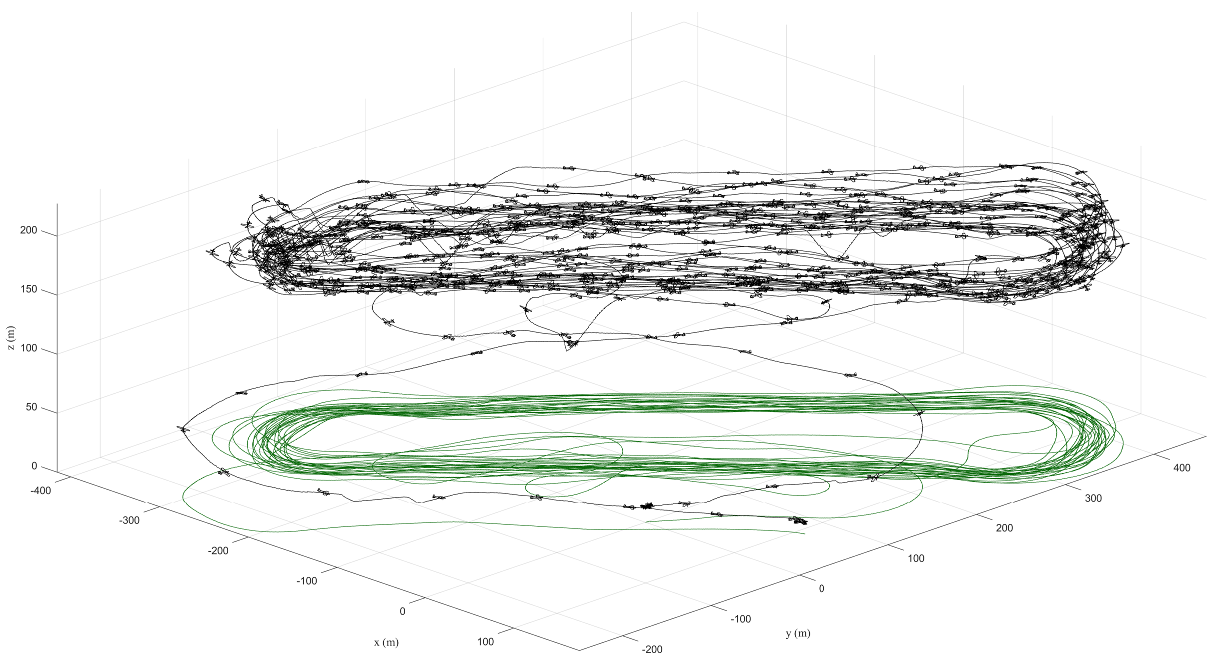


Figure 5: The trajectory of the UIUC-TUM Solar Flyer performing the approximately 1 hour flight under ideal conditions (note that the aircraft is plotted every 5 sec).

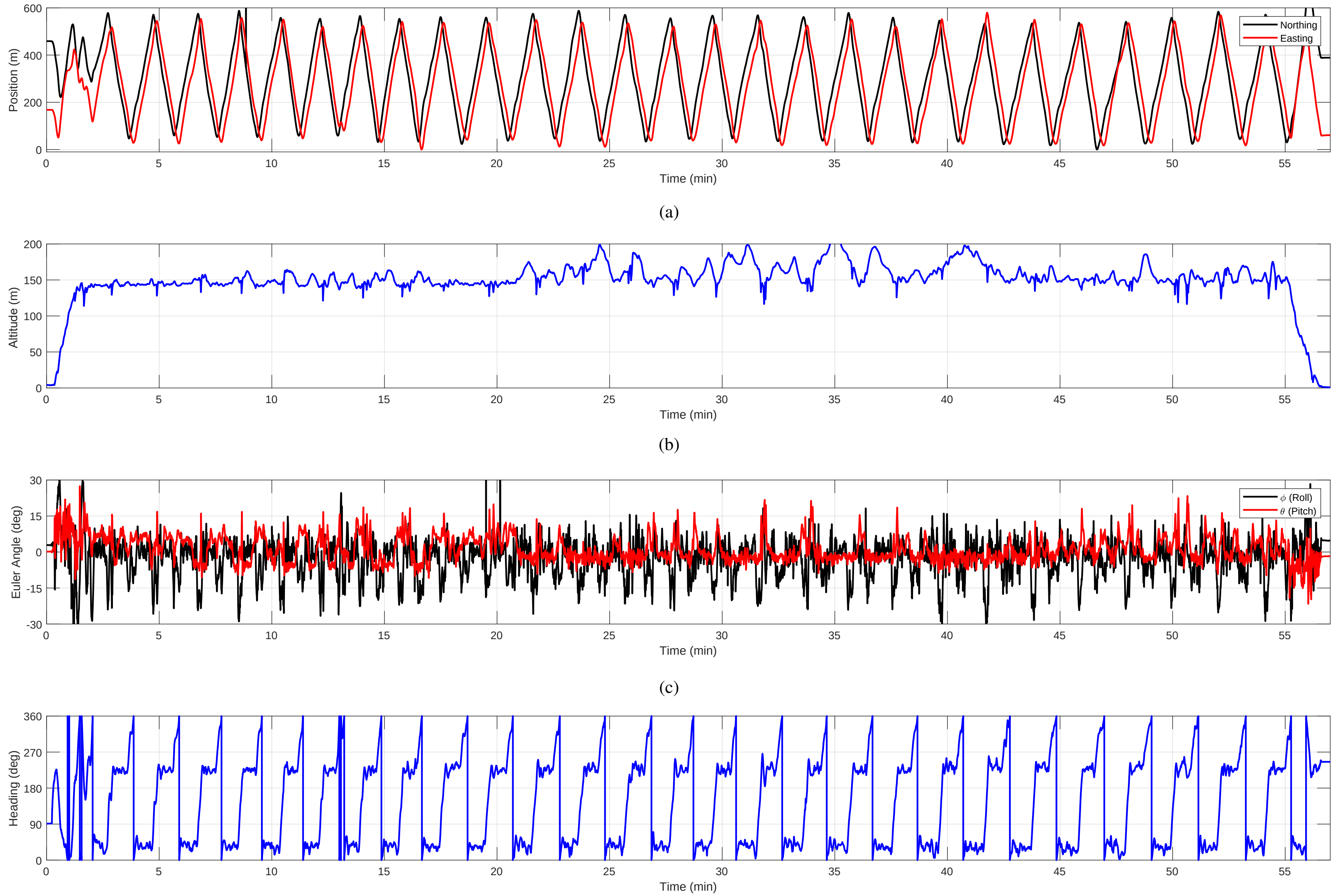
The state data time history is presented in Fig. 6. The aircraft position, Northing and Easting, and the altitude are presented in (a) and (b), respectively; note that due to the flight site geography, the runway altitude is lower than the ground level of the maneuvering area yielding an altitude difference of greater than 100 m. The Euler angle pitch and roll are presented in (c) and heading is presented in (d). The aircraft air and ground speeds are presented in (e); the ground speed is measured by the GNSS while the airspeed is computed by a wind-tunnel calibrated pitot-probe airspeed sensor. The ESC and motor propulsion power, measured between the battery and ESC and between the ESC and motor, respectively, is presented in (f). The propeller rotation rate, measured by the ESC, is presented in RPM in (g). The battery voltage is presented in (h). The MPPT currents presented in (i). And the solar power generated by the solar arrays is presented in (j).

The position and Euler angle data shows 26 race track laps being performed, each approximately 2 min long. There are an increasing amount of mostly positive vertical excursions from the commanded altitude during the middle part of the flight. The airspeed data shows an attempt to maintain the 11 m/s commanded airspeed with increased airspeeds correlating to the times when the positive vertical excursions occurred. There are also a repeated offsets between air and ground speed, which result from wind; the magnitude is either positive or negative based on whether the aircraft is flying upwind or downwind.

The aircraft propulsion power heavily oscillates during the entire flight for both the motor and ESC. There is a decrease in the on-power times used during the middle of the flight when positive vertical excursions occurred; these are also the same times when the airspeed exceeded the commanded 11 m/s. It is assumed that the uncommanded positive altitude deviations are the result of thermals. During this time, the ESC throttles the motor off with the propeller wind milling. Meanwhile, the negative altitude deviations seem to be the result of an interplay between the autopilot attempting to pitch the aircraft downward to maintain altitude and often, the thermals weakening. As a result, the ESC is commanded to throttle-up the motor to create thrust and increase airspeed, which corresponds to propulsion power consumption.

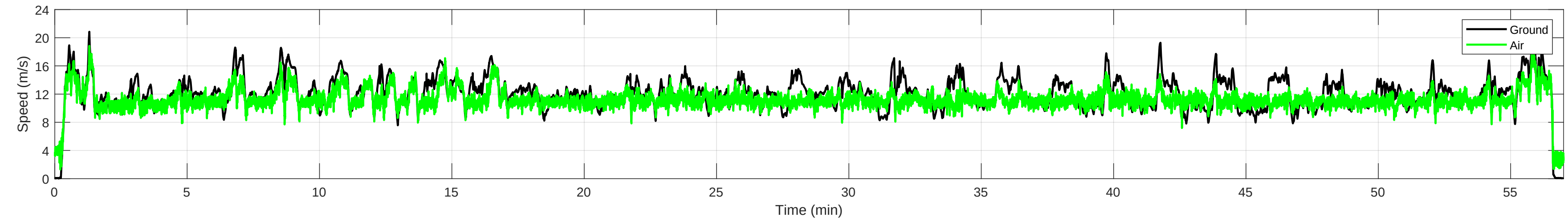
Thus, the throttling-on and throttling-off of the motor is the result of the interplay between the autopilot and ESC controllers and limits. With the earlier thermal assumption, it is assumed that some of the energy used to propel the aircraft and counter drag also comes from thermals through the uncommanded altitude and thus potential energy gains. In order to better estimate propulsion power consumption, 10 min moving averages of the race track laps were calculated, comprising of 5 laps of 60,000 data points each, yielding average power values between 14 and 53 W. Due to large difference in 10 min average values, a true average propulsion power consumption value could not definitively be calculated. As expected, the propeller rotation rate correlates with the propulsion power, i.e., when propulsion power is high, the propeller rotation rate increases to approximately 6,400 RPM, while when propulsion power is near 0, the propeller rotation rate decreases to approximately 2,900 RPM. This is indicative of the ESC throttling the motor on when the airspeed dips below 11 m/s and then off when it is above that airspeed.

During the flight the MPPT currents can be seen to oscillate with aircraft orientation as it flies about the race track trajectory. The left MPPT seems to be better oriented when it faces towards the sun during the right to left straight leg compared to the right MPPT when when it faces towards the sun during the left to right straight leg. The center MPPT has less solar cells in its array, 80 cells as opposed to 120 cells for the left and right MPPTs, and therefore produces less current throughout the flight. Finally, the solar power is observed to vary cyclically between 14 and 55 W, correlating to the aforementioned repeated re-orientation of the aircraft as laps are being performed. Over the entire flight, the average solar power was approximately 35 W. The results show that power consumption was balanced with power generation. This is supported by the fact that, with the exception of an oscillation during takeoff, the battery voltage remains constant at 12.05 V for the entire flight.

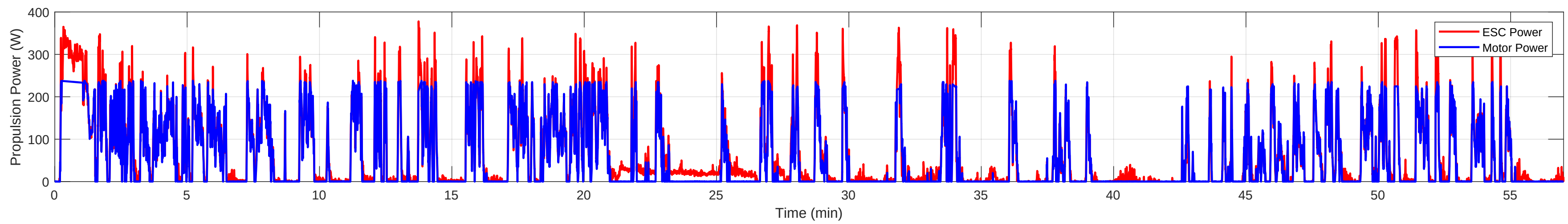


(a) (b) (c) (d)

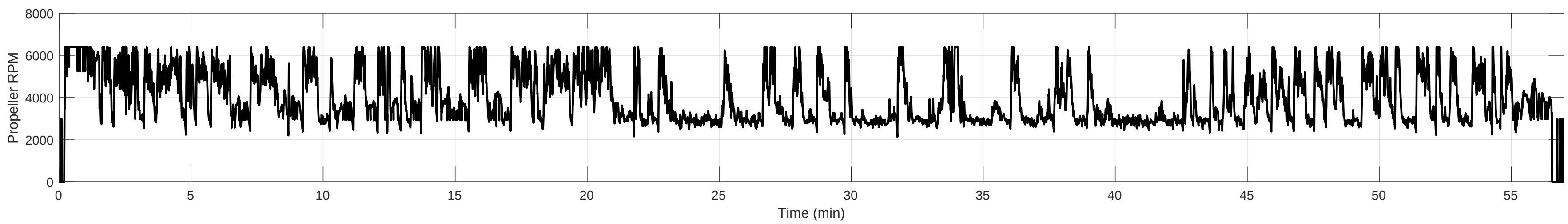
Figure 6: The state data time history of the UIUC-TUM Solar Flyer performing the approximately 1 hour flight under ideal conditions: (a) Northing and Easting position, (b) altitude, (c) pitch and roll, (d) heading.



(e)



(f)



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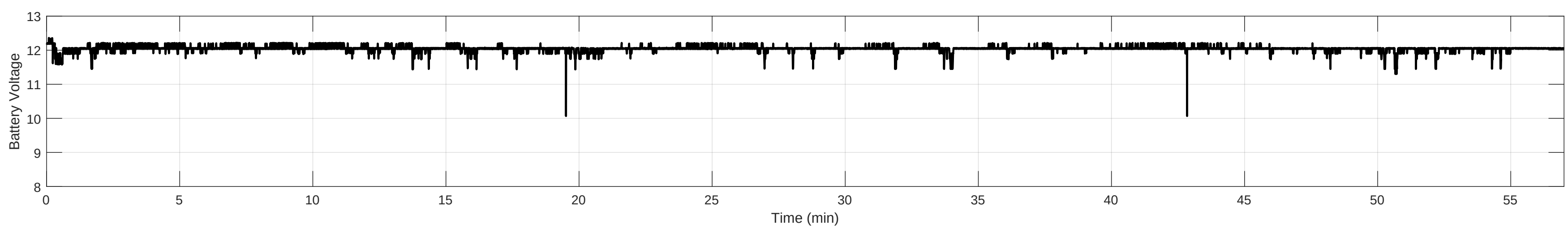
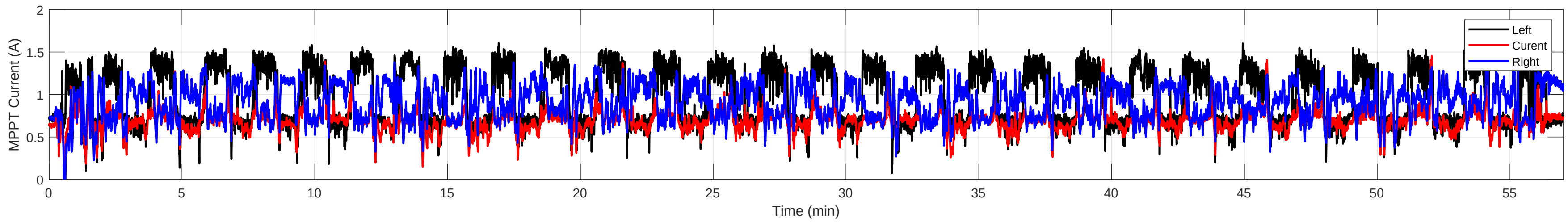
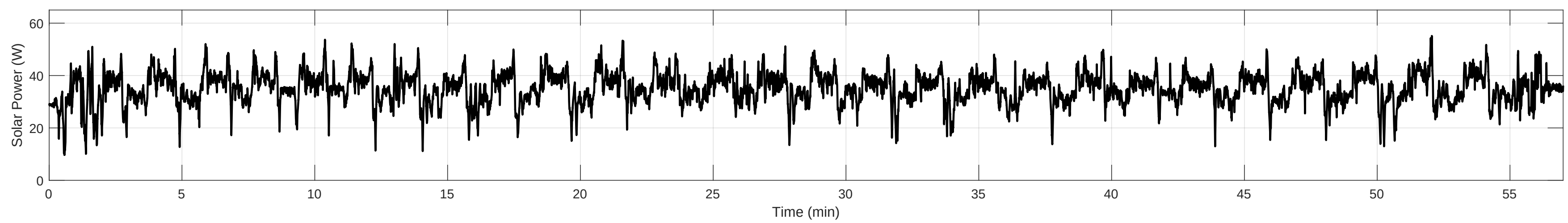


(h)

Figure 5 (continued): The state data time history of the UIUC-TUM Solar Flyer performing the approximately 1 hour flight under ideal conditions: (e) air and ground speed, (f) propulsion power consumption, (g) propeller rotation rate in RPM, (h) battery voltage.



(i)



(j)

Figure 5 (continued): The state data time history of the UIUC-TUM Solar Flyer performing the approximately 1 hour flight under ideal conditions: (i) MPPT current, (j) solar power generated.

V. Summary and Future Work

This paper describes the energy system instrumentation and data acquisition integrated into the UIUC-TUM Solar Flyer, which enabled long-endurance flight testing to be performed. Specifically, an overview of the UIUC-TUM Solar Flyer, including aircraft and sub-system descriptions, and specifications was provide. Then paper described the energy system instrumentation integrated into the aircraft as it evolved during flight testing. Finally, flight testing results from an approximately 1 hour flight performed under near ideal conditions were presented and discussed.

In future work, a long-endurance flight testing is planned in order to demonstrate its power balancing capabilities. Ideally, a full-day flight performed under ideal conditions would provide a demonstration of balancing power consumption and solar power generation with energy storage. The aircraft could also be further improved by integrating soaring sensing capabilities into the avionics software to better detect and harvest energy from thermals.

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