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Continued Development and Flight Testing of a Long-Endurance Solar-Powered Unmanned Aircraft: UIUC-TUM Solar Flyer

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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. This paper describes the continuous development of the UIUC-TUM Solar Flyer, which is equipped with low-power, high-performance computing capabilities. The Solar Flyer addresses the aforementioned challenges by balancing power consumption and solar power generation, and by performing on-board data processing, to enable real-time mission adaptation. The Solar Flyer was developed from commercial-of-the-shelf components, making it affordable for a wide variety of applications. Current efforts have built on previous work in terms of airframe, avionics, and flight software. Significant effort has been allocated to the re-design of the propulsion and energy systems as well as the re-organization of the aircraft system layout. The avionics and the open-source uavAP flight software were integrated into the aircraft, which was recently flight tested in a variety of conditions, confirming aircraft power consumption and production values.

Nomenclature

CG	=	center of gravity
DOF	=	degree of freedom
ESC	=	electronic speed controller
GNSS	=	global navigation satellite system
IMU	=	inertial measurement unit
IR	=	infrared
PWM	=	pulse width modulation
RC	=	radio control

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I. Introduction

In recent years, there has been 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. Notably, the majority of the aforementioned applications require continuous collection and processing of data, especially visual data. Conceptually, there are three main approaches for handling the collected data. The first approach is to process the data offline and off-board. The data is collected and stored on the UAV, in order to be downloaded and analyzed after the mission.[1–5] This approach is very cost effective, since data storage is inexpensive. However, the mission cannot be adapted based on real-time stimuli, making it infeasible for long-endurance missions. The second approach is to process the data online but off-board. This approach takes advantage of high-bandwidth communication to stream video data to a ground station, where the data is analyzed in real-time to remotely adjust mission plan and objectives.[6–8] The benefit is that the UAV can react to stimuli, an important requirement for many mission objectives. However, the high-bandwidth communication is costly and dependent on infrastructure or high power transmission capabilities, rendering it problematic for many mission profiles especially long-distance, long-endurance missions.

In the third approach, which is used for this project, the data is processed online as well as on-board. For this approach the continuous progress in low-power, high-performance computing platforms is exploited. The data is collected and processed on-board in order to adjust planning and control for mission optimization. Low-bandwidth communication can optionally be used to monitor the general state of the UAV as well as to update non-real-time objectives. This approach is ideal for long-endurance autonomous missions as it offers closed-loop control without requiring unreliable and costly communication. So far it has only be used in high-cost, classified aircraft[9] or for low-complexity objectives such as ”follow me” mode.[10,11]

Besides the approaches for data processing, a key design driver and limiter has been energy storage, as limited on-board capacity significantly constrains flight time and ultimately usability. Given the finite energy resources found on-board of an aircraft (battery or fuel), traditional designs greatly limit aircraft endurance since significant power is required for propulsion, actuation, and potentially the continuous transmission of data. A major technical hurdle to overcome is drastically reducing the overall power consumption of these UAVs so that they can be powered by solar arrays, extending flight time. There have been many existing aircraft that use solar panels and are able to sustain continuous flight, however, they lack the ability to perform significant on-board computation beyond automating flight.[12–18]

To address the aforementioned problems, a computationally-intensive, long-endurance solar-powered unmanned aircraft called the UIUC-TUM Solar Flyer is in development. The Solar Flyer, depicted in Fig. 1, carries a high-performance embedded computer system that will ultimately perform all required computations online and only downlink final results, saving a significant amount of energy. Additionally, a careful layout of batteries carried and the inclusion of solar arrays have allowed the aircraft to fly for extended periods of time. In order to truly enable the above applications, the goal is to develop a solar-powered aircraft that was assembled from only commercial-off-the-shelf (COTS) components. Currently, all long endurance solar-powered aircraft have incorporated custom airframe designs and many custom components (e.g. single-application propellers and gearboxes).[12,13] Using only COTS components reduces aircraft cost, thereby increasing accessibility to the community. Furthermore, an aircraft that can sustain continuous, overnight flight decreases the need for takeoffs and landings that constitute the riskiest portions of flight. With all of these ambitious goals achieved, the resulting unmanned aircraft will be more readily available to various communities such as research, industry, and emergency response, among others.

This paper describes the continued development and flight testing done to date of the UIUC-TUM Solar Flyer.[19] The aircraft, built from a majority of COTS components, was designed using a mixture of trade studies and power

Figure 1. The UIUC-TUM Solar Flyer aircraft shown with solar arrays.

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 (7.33 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, which will integrate a quad-core central processing unit (CPU) and a graphics processing unit (GPU) for mission computation. It is powered by a 64 W gallium arsenide (GaAs) solar array from Alta Devices.[20] Its configuration, wing platform area, and expected lift-to-drag ratio were also considered, along with motor and propeller data.

This paper first describes the previously performed development, followed by a presentation of recent airframe development, including a re-organized layout of the aircraft and a re-design of the propulsion and energy systems, as well as updated aircraft specifications. After that, the paper provides details of the current instrumentation and flight software installed on the aircraft. After presenting flight testing results, a summary and a statement of future work is provided.

II. Previous Development

Previous development[21] of the UIUC-TUM Solar Flyer started with requirement definitions, an initial feasibility study, and an aircraft selection trade study. This was followed by separate development of the base aircraft, the computing platform, and the solar energy system.

A. Requirements and Studies

Development of the UIUC-TUM Solar Flyer began by defining the requirements for the aircraft, including that it must be able to self-sustain in all daylight hours and be able to cope with rapid power changes. It is required that the aircraft must also be able to sustain a mission sensor payload. Over time, the goal of sustaining flight in all daylight hours was extended to the goal of continuous flight, including overnight periods. The sensor payload requirement was refined for several possible application, which are discussed later in this paper.

A preliminary feasibility study was then conducted with assumptions for aircraft size, propulsion and solar array efficiency, and payload power requirements. This preliminary study showed that the aircraft concept was viable for the mid-sized (3-4 m wingspan) class of unmanned aircraft. Finally, a trade study was conducted to select the COTS airframe that the Solar Flyer would be developed from.

B. Previous Aircraft Development

Figure 2. The F5 Models Pulsar 4.0E Pro used as the UIUC Solar Flyer airframe.

A baseline, instrumented aircraft was developed based on the results of the trade study, using a majority of commercial-off-the-shelf components; the completed baseline aircraft is shown in Fig. 2. The Solar Flyer airframe was constructed from a F5 Models Pulsar 4.0E Pro remote control aircraft sailplane kit.[22] 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.

The propulsion system chosen for the aircraft was at the lower range of the manufacture recommendation range as high thrust to weight ratios are not required for the final aircraft. Specifically, a Model Motors AXi Cyclone 46/760 motor and Aeronaut CAM Folding 13x6.5 propeller were used in combination with a Castle Creations Phoenix Edge Lite 50A electronic speed controller and a Thunder Power ProLiteX 25c 3-cell, 11.1V 2800 mAh lithium polymer battery. This propulsion system combination provided enough excess power to thrust out of dangerous flight conditions, e.g. poorly angled hand-launch takeoffs and upset conditions, which are typical scenarios during initial operations of newly developed UAVs.

In order to keep with the objectives of using a COTS system, a commercially available flight control and data acquisition system, the Al Volo FC+DAQ, was used. The specific system model used in the Solar Flyer operated at 100 Hz and had an internal Kalman-filtered inertial measurement unit (IMU) with an integrated 10 Hz Global Navigation Satellite System (GNSS). The system was stripped of its enclosure for this application and hard mounted into the aircraft in the fuselage at a 90 deg angle. Sensors were installed throughout the aircraft, including an airspeed probe and sensor and an ESC interface, along with a 900 MHz radio module and a control multiplexer. Specifications of the original instrumentation can be gathered from previous literature.[21] The flight control and data acquisition system was configured to run the open source uavAP autopilot, which is described in Section IV.

C. Previous Sub-System Development

Effort was focused on the development of the computing platform and the solar energy system. An Nvidia Tegra TX1 was tested in performing visual data processing tasks. The goal was to enable the processing of video streams from visible-light and infrared cameras. Eventually, it was determined that given the speed of the aircraft and the corresponding amount of data captured, the Tegra TX1 would provide superfluous processing capability. Instead, it was decided to integrate an ARM-based quad core CPU module with a GPU into the flight control system.

The solar energy system was developed in parallel. Given their low weight and high efficiency, single junction gallium arsenide (GaAs) solar array from Alta Devices[20] were chosen for use on the Solar Flyer. A pan-tilt testing apparatus was developed that could mount and aim a subset of the solar cells into any sun-facing orientation. The testing rig integrated an IMU and GPS such that the direction of the cells with respect to the sun could be estimated accurately. A MPPT solar charge controller, small 3-cell lithium polymer battery (similar to the battery present on the aircraft), and load were also integrated into the test rig.

III. Airframe Development

Continued development of the UIUC-TUM Solar Flyer included the re-design of the propulsion and energy systems and the re-organized layout of the aircraft.

A. Propulsion System

Considerable effort has been allocated towards propulsion system optimization as the choice of components, specifically the motor and propeller, have been shown to significantly affect propulsion system efficiency.[23] Hundreds of options are available for each of the components with generally non-scientific advice for choosing the proper combinations. Thus, a mission-based propulsion system optimizer was developed[24] that selects components, i.e. motors and propellers, from databases with experimentally-validated analytical models, BEMT results and wind tunnel data, to yield the combinations with the greatest efficiency for a given expected multi-segment flight path.

There exists a highly-accurate motor model that can be used in this optimization, based on readily available motor parameters. However, this is not the case for propeller data, specifically for folding propellers, which are required for the Solar Flyer class of aircraft (i.e. sailplane). Based on examination of existing long endurance aircraft, Aero-Naut CAM carbon propellers,[25] were identified as good candidates as these propellers are well known in the UAV industry to offer superior performance while being ubiquitous.[7,26–28] Little performance data exist for the Aero-Naut CAM carbon propellers (or other folding propellers). Propeller performance testing for a range of diameters and pitches of Aero-Naut CAM carbon propellers is currently scheduled in the UIUC low turbulence wind tunnel in the Spring of 2020.[29]

Therefore, intermediary propulsion system optimization was performed using similar shaped, fixed-blade propellers and an expected mission profile, yielding the choice of the Model Motors AXi Cyclone 550/720 motor. The mounting system for the motor allows for a range of motors from the same manufacturer to be substituted in. The existing Aeronaut CAM Folding 13x6.5 propeller continues to be used until the performance testing is done. Additionally, it should be noted that a Castle Creations Phoenix Edge Lite 50A electronic speed controller, identical to the ESC that was previously used, was slightly modified to decrease its size and weight. Photos of the original and current motor and ESC are shown in Fig. 3.

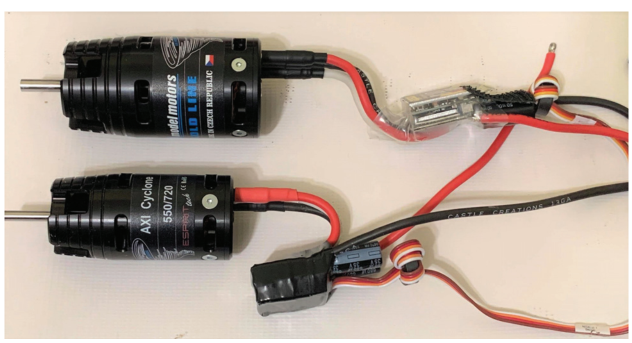


Figure 3. The original (top) and current (bottom) motor and ESC combinations that were/are used on UIUC-TUM Solar Flyer aircraft.

B. Energy Systems

The UIUC-TUM Solar Flyer energy systems were developed to collect energy from solar radiation, store it on-board the aircraft, and provide it when required. Specifically the energy system is made up of a 64 W solar array connected to 3 independent maximum power point tracking (MPPT) charge controllers, which charge a 302 Wh lithium ion battery. The battery provides a buffered energy source for on-board systems including the propulsion, flight control, and avionic systems as well as to the payload. Specifications of the energy systems are given in Table 1.

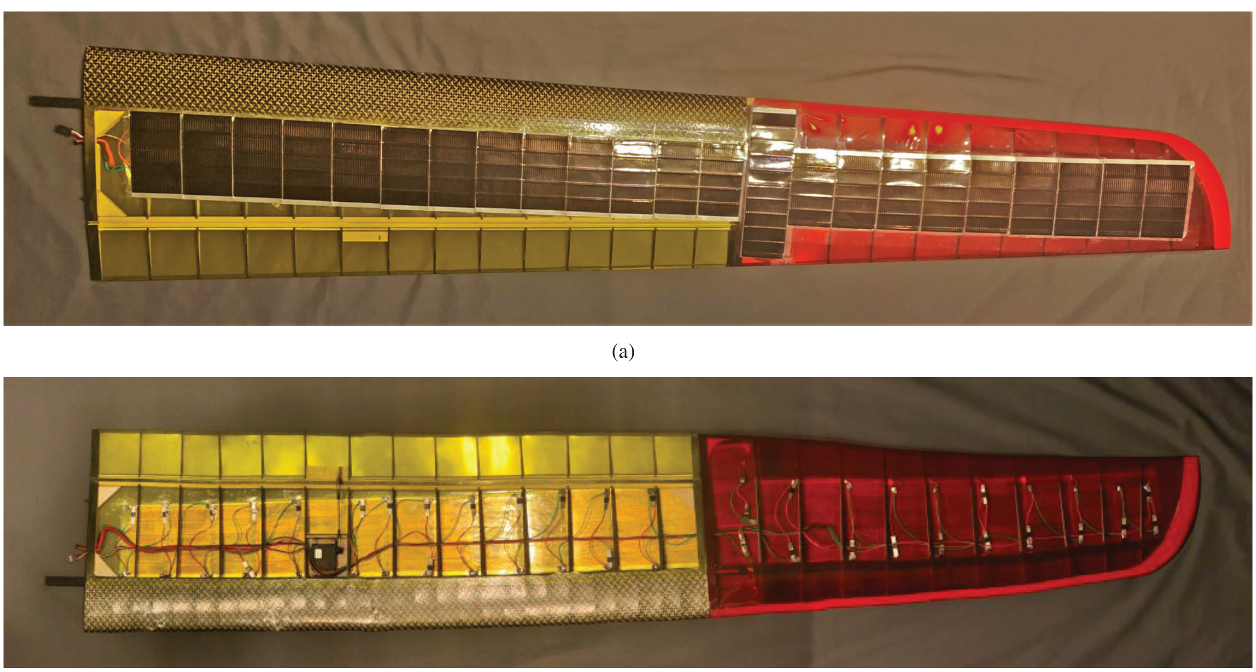
Table 1. UIUC-TUM Solar Flyer energy systems component specifications.

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
Battery	10.8V 28Ah Samsung 35E 18650 in 3S 8P

1. Solar Collection

As mentioned in Section II, development of the solar power collection system yielded the choice of gallium arsenide (GaAs) solar arrays from Alta Devices, which hold the world record for solar efficiency and power density. The 64 W array mounted on the aircraft is made up of 16 sub-sets of four 1 W sub-arrays connected in series. The 1 W sub-arrays are themselves each made up of 5 cells in series. Thus, there are effectively 16 parallel sets of 20 cells in series. These parallel sets have approximately 16 V in potential. There are 24 W of arrays on each outer wing panel and 16 W of arrays on the center wing panel, with the possibility of increasing the center wing array by 8 W. The arrays, with exception of 2 sets on the outer wing panels, are all mounted right behind the quarter chord line to decrease the aerodynamic effects they pose on the aircraft. Specifically, the arrays are attached to the plastic film covering of the aircraft using an adhesive; this technique demonstrated to be both light-weight and robust. The electrodes of the 1 W sub-arrays are placed through the plastic film allowing electrical connections to be made within the wing box. Photos of the top and bottom surfaces of the right outer wing panel can be seen in Fig. 4. The electrical wiring includes the bypass diodes in parallel to each of the 1 W sub-arrays and blocking diodes in series with each of the 20-cell sub-sets, as can be seen in the example diagram in Fig. 5.

The solar arrays on each wing section are connected to individual maximum power point tracking (MPPT) charge controllers. These MPPT charge controllers were miniaturized for this application from an existing development board



(a)

(b)

Figure 4. Photos of the right outer wing of the UIUC-TUM Solar Flyer, showing: (a) solar array layout and (b) wiring.

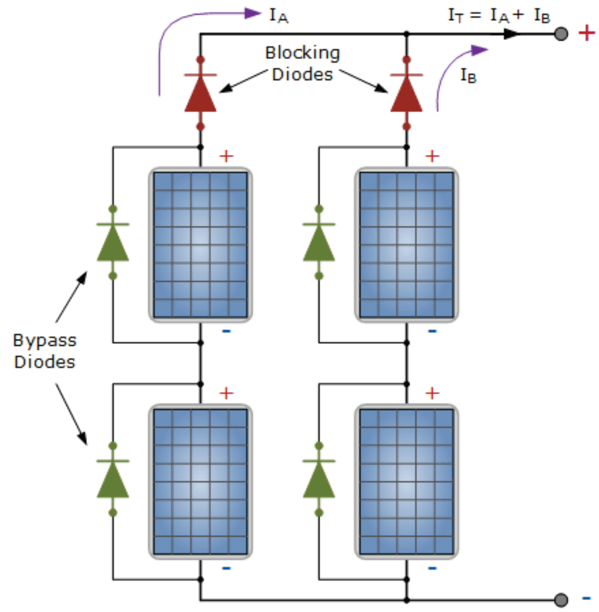


Figure 5. Example wiring diagram for solar cells in series and in parallel (taken from Sunbeam Systems[30]).

design available on the market. The charge controller component values are set to charge the 3-cell lithium-ion batteries that are used on the aircraft. The output of the 3 MPPT charge controllers are connected in parallel to each other before being connected to a hall effect current sensor, which is connected to the aircraft battery; this sensor allows the estimation of the solar power being input into the energy system.

2. *Energy Storage*

Energy is stored on the UIUC-TUM Solar Flyer using a 10.8V 28Ah lithium-ion battery, which also acts as an energy buffer. The battery is made up of 24 3.5Ah Samsung 35E 18650 lithium ion battery cells assembled in a 3 series, 8 parallel (3S 8P) configuration. These cells were chosen following a trade study of available battery cells, specifically looking at battery volume and mass densities; see Fig. 6. The number of cells in parallel follows the energy requirement for sustaining overnight flight between the months of April and August in central Illinois (where the aircraft is flight testing), months where the aircraft would presumably be used for agricultural inspection, e.g. plant disease detection. Power consumption estimates are based on initial flight testing of the aircraft in previous work.

The cells are laid out from the nose, behind the motor and ESC, to approximately 1/3 way down the tail boom. The physical layout is 4 cell square configuration in the main fuselage pod, for the first 16 cells, followed by a single cell in the tail boom, for the last 8 cells. There are interconnect cables between sets of 3S sub-packs, allowing the battery to be separated to either single parallel (1P) or double parallel (2P) configurations for ground charging and assessment of cell capacity. Balance connectors are soldered to each of these sub-packs.

A 3S 1P, 10.8V 3.5Ah prototype battery was assembled for initial testing; a photo of this battery is presented in Fig. 7. This battery represents 1/8 the capacity of the battery on the aircraft. The solar array testing rig, presented in Section II.C from previous work, and an MPPT charge controller were used to verify the solar charging performance of the battery as well as the functionality of the MPPT charge controller. Additionally, a battery charger-discharger was used to further test this prototype battery at various charging and discharging rates per the battery cell specifications.

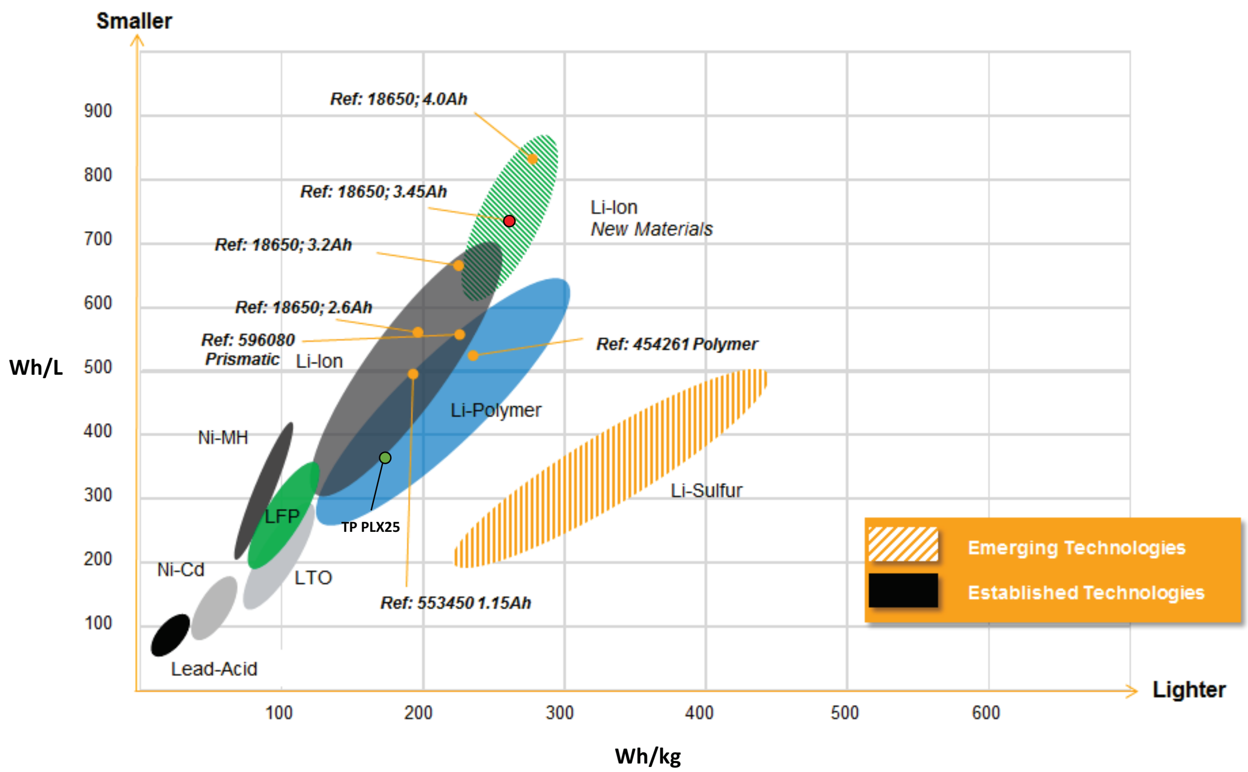


Figure 6. Battery technology volume and mass densities with previous battery cell/chemistry in green and current battery cell/chemistry in red (adapted from NASA).

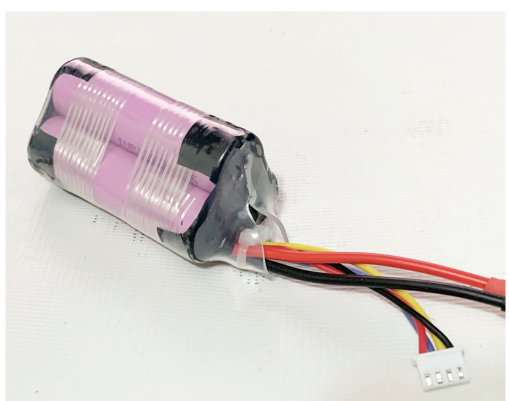


Figure 7. The 3S 1P, 10.8V 3.5Ah prototype battery assembled from Samsung 35E 18650 lithium ion battery cells.

C. Aircraft Layout

In order to accommodate for the significant increase in battery volume, the layout of the aircraft components had to be changed, to remain with the aircraft structure and to keep everything within its geometry (i.e. out of the freestream). Since the fuselage could thus only accommodate the motor, ESC, and battery cells, the avionics and flight control systems would need to shift into the wing. This presented both a wiring and a component miniaturization challenge to maintain everything within the wing volume. A further discussion of the avionics layout is provided in the following section. A diagram of the fuselage layout is provided in Fig. 8.

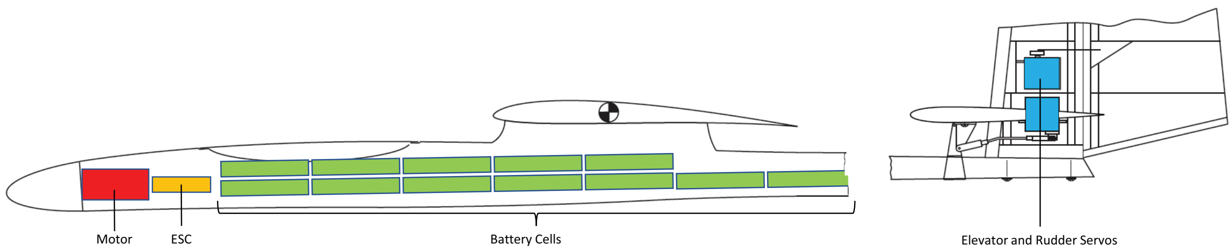


Figure 8. A diagram of the internal layout of the fuselage including the motor, ESC, battery cells, and servos.

D. Aircraft Specifications

The specification of the current UIUC-TUM Solar Flyer are provided below in the following tables. Table 2 provides the physical specifications of the aircraft; note that the inertial properties include the instrumentation components described in the following section. Table 3 provides specifications of the aircraft components.

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

Table 3. UIUC-TUM Solar Flyer 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 System	
Motor	Model Motors AXi Cyclone 550/720
ESC	Castle Creations Phoenix Edge Lite 50
Propeller	Aeronaut CAM Folding 13x6.5

IV. Avionics Development and Flight Software

A. Avionics

Following the movement of the avionics from the fuselage into the wing, the component and wiring required miniaturization. The COTS flight control and data acquisition system, the Al Volo FC+DAQ, was moved from the fuselage into a wing cell, left of center, with a smaller 10 Hz GNSS receiver module and antenna being placed in the adjacent cell; the propulsion system interface board was also placed in the same wing cell as the GNSS receiver. It should be noted that the FC+DAQ was manufacture modified to enable the integration of a quad-core central processing unit (CPU) and a graphics processing unit (GPU) for mission computation. Additionally, it was hard mounted into the wing in order to fully transfer motion from the airframe to the integrated 9-DOF inertial measurement unit (IMU). To the right side of center, the flight control multiplexer was placed in a wing cell with the radio control receiver being placed in the adjecent cell. Servo control PWM wiring ran between the FC+DAQ PWM output pins and radio control receiver to the multiplexer input pins, respectively. PWM wiring ran from the multiplexer output pins each of the servos throughout the wing and into the fuselage; uni-directional connectors were soldered into the PWM wiring between the central wing panel and the fuselage and outer wing panels, respectively. Finally, the airspeed probe and sensor and 900 MHz radio module remained in their locations in the left and right ends of the center wing panel, respectively. Updated specifications of the instrumentation are given in Table 4.

Table 4. UIUC-TUM Solar Flyer instrumentation specifications.

Autopilot-DAQ system	Al Volo FC+DAQ 100 Hz flight control and data acquisition system
Mission system	Al Volo ARM-based quad-core CPU with GPU module
RF Module	Digi International 900 MHz XBee Pro S3B Module
Multiplexer	7-channel PWM multiplexer with redundant input
Sensors	
Inertial	100 Hz AHRS
Positioning	10 Hz uBlox GNSS
Airspeed sensor	Al Volo Pitot Airspeed Sensor with pressure and temperature
Motor sensor	Al Volo Castle ESC Interface

B. Flight Software

In order to have autonomous long-endurance solar flight, an autopilot with a broad variety of functionality is needed. Besides a planning and control stack, communication with a ground station for commanding and monitoring is crucial during initial testing. Control and communication enable descriptive data collection, which is important to measure aircraft efficiency and to tune parameters for power optimal flight. This section describes the functions of our open-source uavAP autopilot[a] that are essential for this project. Further details of the uavAP autopilot can be found in Theile et al.[31] The described software was tested and evaluated using our uavEE emulation environment[b].[32]

1. Planning and Control

For general control, uavAP implements a standard control stack. For this project the control stack consists of a mission planner reading waypoints from a configuration file. These waypoints are sent to a global planner, which connects them using 3D cubic splines. A local planner determines how to approach and follow the trajectory given the aircraft's position and attitude. The resulting attitude and velocity commands are passed to a PID controller cascade, in which the actuation outputs are computed.

To control the servos of the sailplane, the actuation outputs have to be converted into Pulse-Width Modulation (PWM) values for individual channels. During the conversion the camber and throws values, i.e. the center and maximum deflection values, have to be considered. For this project camber and throws can be tuned and adapted on the fly, to evaluate flight stability and efficiency.

In addition to trajectory tracking control, custom control targets can be specified. These control targets can override different entities in the control stack. This functionality is crucial for the collection of efficiency, performance, and stability related data. However, this override functionality induces the risk of leaving a designated flight zone. This risk is mitigated using a geo-fencing algorithm, which is using the same override functionality to keep the aircraft inside the designated flight zone.[33] With the override framework, automated data collection is possible. By conditionally concatenating controller overrides, a variety of flight maneuvers can be performed.[34,35] For example, to find the stall speed, a chain of overrides can be used. First the autopilot is instructed to fly level at a constant speed. When it reaches steady-state, the motor is turned off and the pitch controller is instructed to maintain altitude. When a nose drop is detected, meaning the aircraft entered stall, the controls are centered to determine stall characteristics. After a certain time, or below a certain altitude, the autopilot is commanded to recover. Using uavAP, these conditionally concatenated overrides can be described in a simple configuration file and are executed automatically when commanded from the ground station.

2. Communication

For commanding and monitoring, uavAP is capable of communicating with a ground-station. The communication is based on binary string packets that are transmitted using serial-bus radios. The serialization and deserialization of these packets is handeled through the core functionality of uavAP. This simplifies the addition of messages for new functionalities. The graphical user interface used in this project can be seen in Figure 9. In this ground-station layout the aircraft is displayed on a map (top-right), with a primary flight display and detailed sensor data (bottom-right), PID monitoring and tuning (bottom-left), as well as maneuver, mission, and control-settings commands (top-left). Additional communication can be handled in separate windows.

[a]https://github.com/theilem/uavAP
[b]https://github.com/theilem/uavEE

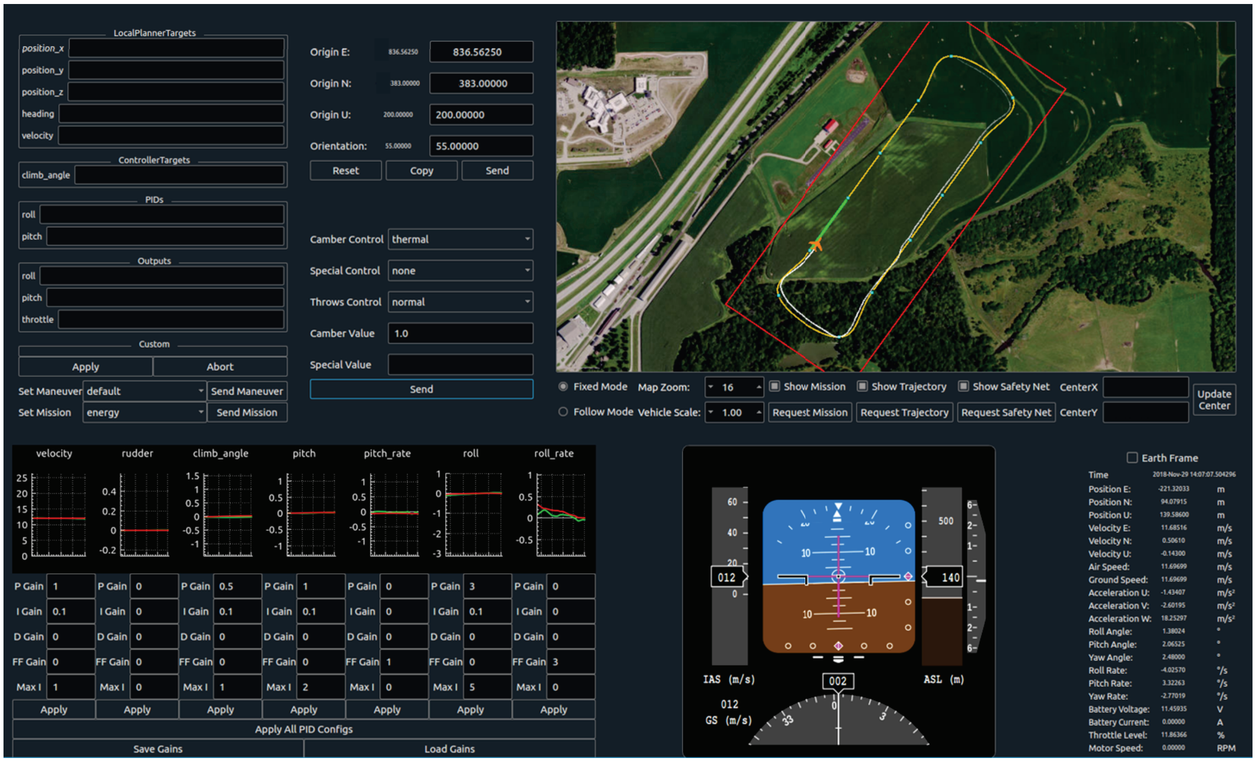


Figure 9. Ground station view of UIUC-TUM Solar Flyer flight test.

V. Flight Testing Results

The UIUC-TUM Solar Flyer underwent flight testing in the Fall of 2019 to measure aircraft power consumption as well as solar power generation. The aircraft was autonomously flown in a repeated level race track maneuver as it would be typical of a field or ground mapping survey. An example trajectory for this maneuver can be found in Fig. 10. The testing was performed in both low wind (near calm) and moderate wind (5-6 m/s), either in-line (up/down) wind or crosswind conditions, with the aircraft attempting to maintain air speed of 10 m/s. From the flight data collected, an average propulsion power consumption of approximately 20 W was measured for low wind conditions. Average power consumption slightly increased for moderate in-line winds, specifically during the turn-arounds, due to the relative crosswinds. However, for moderate crosswind conditions, average power consumption increased to between 30 and 50 W depending on the degree of perpendicularity and wind strength. In order to decrease power consumption in moderate wind conditions, the racetrack could be reoriented using a simple frame transformation built into uavAP; this would greatly reduce the propulsion power consumption.

Since the battery pack has approximately 300 W-hr of energy stored, the aircraft could be flown for 15 hours neglecting avionics and mission power consumption, as well as portioning reserve energy. Given a 5 W allocation for avionics power consumption and a safety reserve, the aircraft is able to fly continuously for approximately 10 hours on battery power alone. With this overnight power consumption and approximate 60 W of available daytime solar power, the battery is expected to cycle between about 100 and 20% charge for a typical summer mission. Note that mission components are not expected to operate during the night, which greatly aids in flight time. Additionally, during the day, approximately half to two-thirds of the solar power collected is used for flight power, avionics, and mission components while the remaining half to one third is used for recharging the battery. To date, the aircraft has been flown 4.5 hours at night time, using less than an estimated half of battery capacity in low-wind conditions. Daytime flight has also confirmed solar power generation.

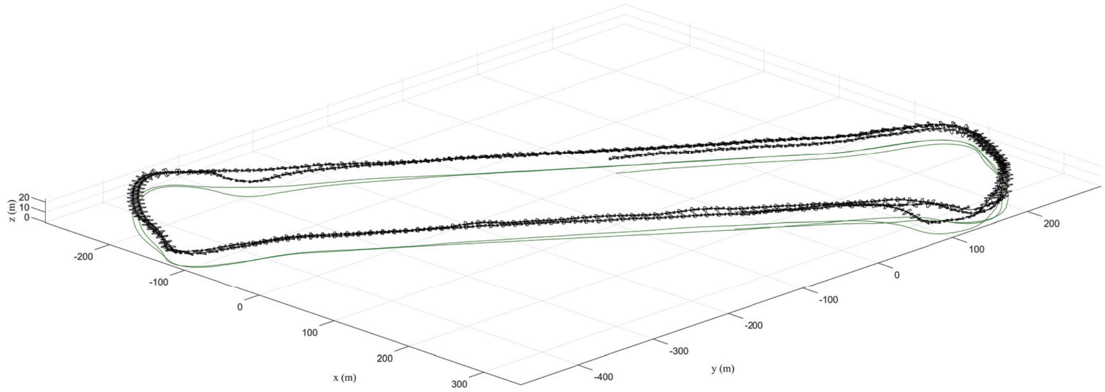


Figure 10. The trajectory of the UIUC-TUM Solar Flyer during a repeated level race track maneuver (note that the aircraft is plotted 6x scale every 0.5 sec).

VI. Summary and Future Work

This paper described the continued development and flight testing of the UIUC-TUM Solar Flyer. Current efforts build on previous work in terms of airframe, avionics, and flight software. Specifically, significant effort has been allocated in the re-design of the propulsion and energy systems as well as the re-organization of the aircraft system layout. The avionics and flight control software were integrated and the whole vehicle was flight tested. To date, flight testing has confirmed aircraft power consumption and production values for a variety of flight conditions.

The planned work for the future is twofold, including improvements of the platform itself, as well as utilizing the platform for demonstration and novel research directions. To improve the platform, refining power sensing for accurate flight path and control optimization, is beneficial. Furthermore, adding and integrating mission components, such as high-resolution cameras will enable future demonstrations of the capabilities of the UIUC-TUM Solar Flyer.

When equipped with mission components, the Solar Flyer will be used to perform different missions, ranging from mapping and surveying to agricultural analysis. When performing these missions, trajectory and control optimization will be essential. Due to the high non-linearities, the optimization will likely be non-convex and thus not analytically solvable. Therefore, we will use advanced optimization techniques, among others, reinforcement learning. The presented eco-system consisting of the flight hardware, uavAP, and uavEE will be valuable in order to evaluate the applicability of reinforcement learning in this context. We will investigate, how utilizing simulation training together with curriculum learning can train a reinforcement learning agent for an actual cyber-physical system.

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