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The Gannet Solar–VTOL: An Amphibious Migratory UAV for Long–Term Autonomous Missions

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** Consider for Best Student Paper Award*

***Abstract*— Vertical Take-Off and Landing (VTOL) Unmanned Aerial Vehicles (UAVs) provide a versatile platform well-suited to applications requiring the efficiency of fixed-wing flight with the maneuverability of a multicopter. Prior work has introduced the concept of using solar energy harvesting using photovoltaic cells embedded in the wings of the vehicle to perform self-recharge in the field when landed and at rest. This work demonstrates a further extension of this concept by optimizing the VTOL aircraft for maximum input-to-output power ratio, such that continuous flight is possible for the majority of a typical day with good sunlight. By also adding amphibious design elements, a transoceanic flight cycle is proposed. The candidate aircraft design is shown with estimated and actual behavioral and performance data for hovering and forward flight. Artwork for design elements such as the tiltrotor nacelle design and interchangeable avionics pod are shown.**

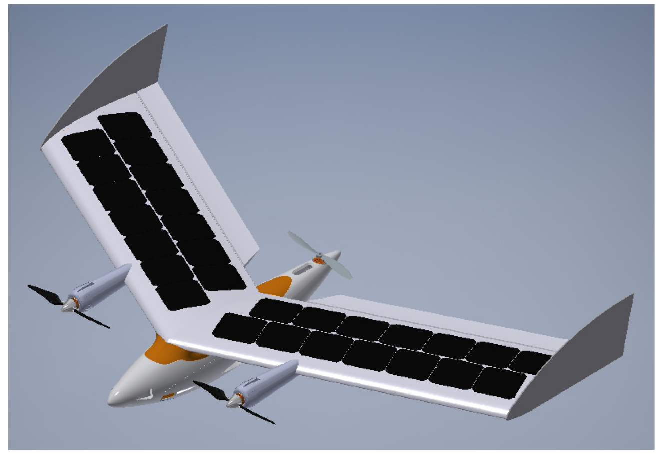

Fig. 1. The Gannet Solar-VTOL, a Tricopter-TiltRotor hybrid aircraft equipped with onboard solar energy harvesting for migratory (recurrent-mission) behavior demonstration.

I. INTRODUCTION

Hybrid Vertical Take-Off and Landing (VTOL) aircraft are nowadays established as the mid-ground solution between flight agility and long-range endurance, they still remain limited by their amount of onboard integrated energy budget. Also, Micro Aerial Vehicles (MAVs) have dominated numerous important application domains such as search and rescue, industrial operations, and exploration of unknown environments [1–8]. However, the paradigm of MAVs having to return to some sort of recharging infrastructure (a human-servicer or a "Drone-in-a-Box" system) has dominated the industry, and unless the aircraft is a lighter-than-air (blimp or dirigible) or a perpetual-flight system (solar flying wing), it would seem that this energy requirement is immutable, if we consider VTOL mission profiles that are executed in succession (recurrent-missions).

As mentioned, an effort to try and break away from the imperative for landing has given birth to the sub-field of perpetual-flight solar-powered fixed-wing aircraft, typically defined as High-Altitude Long-Endurance (HALE). Manned examples include the Solar Impulse, and unmanned examples include the Airbus® Zephyr™ [9] and the ETH AtlantikSolar [10–12]. These remain aloft indefinitely by having a positive energy budget during daytime flight, which allows storing excess energy in batteries such that the aircraft can continue through the night. This however poses severe payload restrictions and flight profile requirements. Such aircraft must fly at rather low airspeeds and at high wing aspect-ratios, and they have been used as flying sensor platforms, but are highly sensitive to the season, cloud cover and prevailing winds, while due to their nature they require complex logistics for launch and landing.

Nevertheless, if the imperative to stay airborne during the night is dismissed, the energy self-sufficiency problem only becomes a matter of preserving battery charge overnight (or during periods of poor illumination), such that a mission can be attempted whenever the battery becomes fully recharged. This is the method used by the Mars Ingenuity Helicopter [13]. This ability to harvest energy "in the wild" allows for true energy self-sufficient unattended operations, but to enjoy this to maximum effect with an Earth-operating MAV, the helicopter form factor is a poor fit in terms of solar array estate. What matches well to this concept of operations, is a fixed-wing VTOL aircraft, which has the wing area to promote efficient forward-flight while also hosting a generous wing-mounted solar array, and also has the vertical maneuverability to launch and land from a confined area. The next frontier in increasing the capabilities of small aerial robotics lies in this- the ability to operate anytime and anywhere at any range using the solar-VTOL migratory recurrent mission cycle.

Our prior work has detailed the minimum demonstration of the Solar-VTOL migratory recurrent mission [14–16], using the MiniHawk-VTOL [17–20] equipped with a power management system which harvests solar energy and

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preserves battery charge. But while the MiniHawk-VTOL has energy self-sufficiency, it is not designed to maximize the performance and payload for the Solar-VTOL paradigm. Furthermore, it lacks a waterproof avionics compartment or other means to accommodate waterborne operations. This paper introduces the successor to the MiniHawk-VTOL: The Gannet Solar-VTOL prototype, shown in Figure 1, which is designed specifically for amphibious migratory long-term autonomous missions.

This paper is organized as follows: Section II addresses similar and previous work. Section III presents the high-level vehicle design process and performance estimations. Section IV presents experimental results with the currently developed vehicle. Finally, Section V summarizes the work presented.

II. RELATED WORK

The migratory recurrent mission profile exists in the intersection between the HALE, Solar-recharging VTOL and Amphibious sub-fields in aerial robotics. Airbus® Zephyr™ [9] and ETH AtlantikSolar Project [10–12] are mentioned above as examples of the HALE sub-field, providing insight into the design of an efficient fixed-wing solar platform. An example of a solar-recharging seaplane is demonstrated by The University of Michigan Flying-Fish [21] in 2010, and more recently a fully-aquatic amphibious UAV is demonstrated by [22], providing details on constructing a sealed electronics capsule for an amphibious UAV. Solar-recharging VTOLs are demonstrated by The University of Minnesota [23, 24] and alluded to in the design for a tiltrotor by [25]. The only known true peer to the Gannet in terms of attempting to perform an amphibious migratory Solar-VTOL mission is the Sherbrooke University SUWAVE [26, 27], as shown in 2017 and 2020.

III. SYSTEM DESIGN

The Gannet was selected for and designed to provide the best VTOL payload ability for the least power required while also maximizing the solar collection potential of the vehicle and also remaining relatively simple to build. The envisioned full demonstrator will be capable of performing long–range transoceanic autonomous flight using amphibious features in the design that protect critical avionics and systems. The following sections discuss the design procedure and the implementation elements.

A. Design Process and Performance Estimation

1) Flight Performance: The Gannet was selected by an iterative design process, in which multiple aircraft candidates were developed in simulation, using the XLFR5 Low-Reynolds simulation suite, and analysed for performance. These notional aircraft were prescribed variations in sizing and scale across various planform types such as Plank Flying Wing, Swept Delta Wing, and Conventional Sailplane, among others. All candidates were required to host the same standardized and persistent payload: An essential equipment set comprised of an autopilot, GPS, Power Management System, telemetry and control systems, and battery.

Each candidate had airfoil selections constrained based on the requirement of the planform, such as the case of the Plank Flying Wing and Swept Delta Wing requiring reflex in the airfoil to reduce pitching moment. Stability and trim were equalized across all cases, with each candidate compared in stable level flight. Trim was forced by changing the simulated center of mass or longitudinal control surface deflection to induce a desired pitching moment, such that the static pitch equilibrium occurred at roughly the same angle of attack across all candidates.

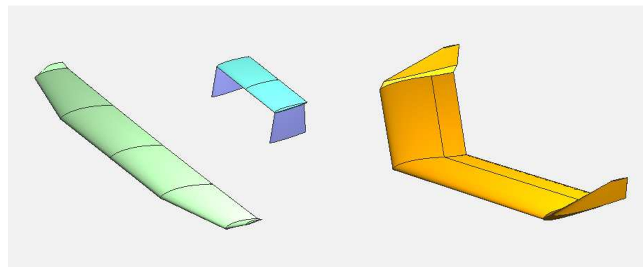

Fig. 2. Final Candidates in XFLR5: Laysan (green and blue, left) and Gannet (orange, right).

Eventually, the candidate pool was down-selected to only two planforms: a Sailplane-like candidate defined as the “Laysan”, and a Swept Delta Wing identified as the “Gannet”. Both simulated models are shown in Figure 2. The power required for level flight was calculated for each candidate, with extra drag assigned based on wing area. Figure 3 shows the Pitching Moment, Lift-Drag Relationships and Power Required for the Laysan and Gannet candidates. Observe that the Laysan has the lowest absolute power requirement, but that both aircraft are similar in best range and wind penetration (similar L/D). Note that both of these candidates are immune to the imperative of having to stay aloft through the night, and thus, both can utilize a reduced-aspect-ratio wing which allows for a higher cruising speed, which allows for a greater wind penetration ability when compared to HALE aircraft in the same size class.

2) Solar Power Performance: For each of these two remaining candidates, the wing size and shape were adjusted to support an array of 28 Maxeon C60 solar cells. This cell count was arrived at as a compromise between aircraft size and power input-to-output ratio as informed by the previous aerodynamic power requirement estimations. With the wing area and expected solar contribution fixed, and the estimated flight power requirements, estimated cruise speed, and aircraft mass known, it was possible to perform a numerical simulation of the aircraft behavior in a migratory mission. The typical output of our migratory mission simulation tool is shown in Figure 4 and Figure 5, with the former showing the ideal performance for flight at the equator at the spring equinox with no clouds, and the later providing a more realistic simulation for typical conditions at 35° North Latitude with realistic cloud cover.

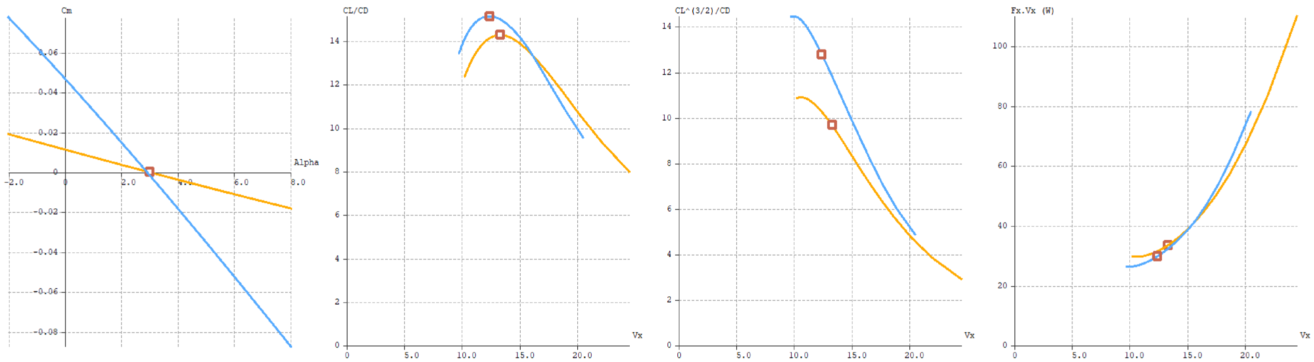

Fig. 3. Aerodynamic performance comparison between the Gannet (orange) and Laysan (blue).

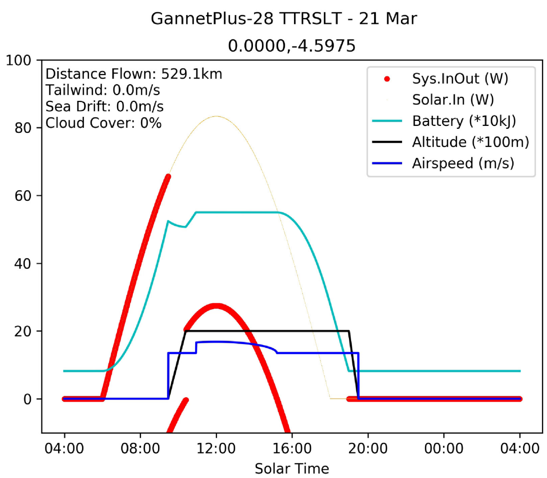

Fig. 4. Energy Plot for the Gannet in ideal conditions at the equator during the Spring Equinox.

Both the Gannet and Laysan candidates showed similar behavior in these simulations, with the ability to remain aloft continuously during uninterrupted daylight for moderate latitudes.

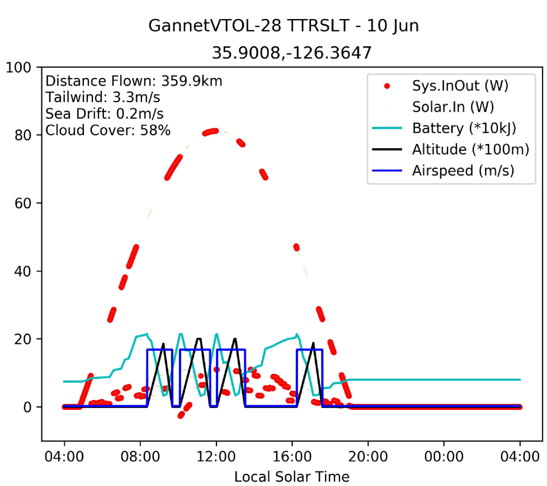

Fig. 5. Energy Plot for the Gannet in typical conditions at 35 deg North Latitude in mid-June.

3) Manufacturability Considerations: While the primary aim was flight efficiency and best behavior in the migratory mission, a secondary object was to arrive at a design that is easy to build, maintain and reproduce. While the Laysan demonstrated slightly better performance for various wing sizes, the Gannet satisfied the desire for a simpler prototype construction process, while attaining roughly the same performance of the sailplane candidate. With the two candidates being fairly matched, the decision was made to move forward with the Gannet concept. Table I lists the finalized design parameters for the Gannet.

TABLE I
GANNET SOLAR-VTOL DESIGN CHARACTERISTICS

Category	Parameter	Value	Units
Planform	Root Airfoil	MH45	
	Tip Airfoil	MH45	
	Root Chord	450	mm
	Tip Chord	450	mm
	Wing Span	1800	mm
	Wing Area (projected)	83	dm^2
	Aspect Ratio	4	
	C/4 Sweep	25	deg
	Dihedral	0	deg
	Washout Angle	2.5	deg
Rotors	Forward Diameter	255	mm
	Tilt Range	115	deg
	Rear Diameter	330	mm
	Rear Thrust Angle	2	deg
	Bounding Circle Diameter	775	mm
Est. Performance	Solar Power Prod. (max)	98	W
	Cruise Power Required	80	W
	Hover Power Required	800	W
	Battery Cap. (w/ reserve)	62	Wh
	Total Mass	3.6	kg
	Additional Payload	0.8	kg
	Cruise Velocity	13.5	m/s
	Endurance (no solar)	32	min
	Range (no solar)	26.4	km

B. Design Elements and Implementation

This section shows the implementation details and unique elements of the Gannet.

1) Wings and Flight Control Surfaces: The wings were cut from a low-density foam using the hotwire method. Channels were routed in the wing for inlaid carbon fiber spars, with joints lashed and bonded with polyaramid tow soaked in epoxy. Slots for ribs were cut, with rib material either being corrugated plastic sheeting or basswood, depending on the level of strength required. The wing is built as stiff as possible to ensure the integrity of the Maxeon C60 solar cell array, arranged in a 7x2 grid on each wing as shown in Figure 6 (i). The Gaussian curvature for the upper surface of the wings is zero for all points in the region covered by the solar array, such that the cells wrap evenly and with no distortion or creasing.

The elevon flight control surfaces and winglets are composed of corrugated plastic sheeting. The winglets provide sufficient directional stability while the elevons provide pitch and roll authority.

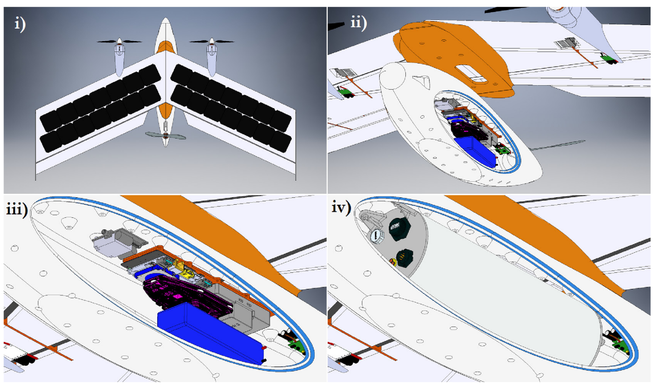

Fig. 6. Aircraft design specifics.

2) Fuselage Pod and Waterproof Compartment: The avionics fuselage pod is produced using a FDM rapid prototyping process. The avionics bay internally can support a volume of over 10 Liters, with M3 mounting stanchions placed at 50mm intervals. The sides of the avionics bay are accessible by the removal of a left and right lid with a cantilever retention lever mechanism securing each lid. The entire fuselage is designed to be interchangeable allowing for future revisions or alternate implementations. Figure 6 shows the interchangeable attachment scheme (ii). Also illustrated is the "Dry" (iii) and "Wet" avionics configuration, where the Wet variation (iv) contains all water-sensitive avionics inside a Water-Tight-Cylinder, with thermal and electrical connections exposed to the interior of the avionics bay for further connection.

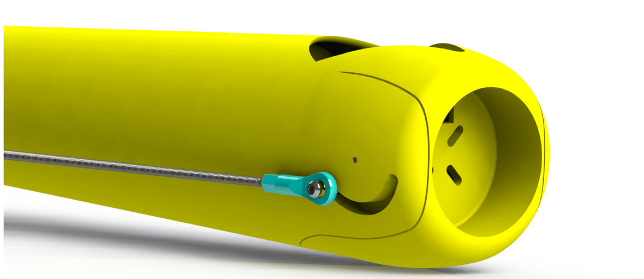

Fig. 7. Nacelle view, showing the motor mount locked in forward flight.

3) Essential Electronics: The key enabling feature of the Gannet Solar-VTOL migratory mission behavior is the custom Power Management System, composed of a Maximum-Power-Point-Tracker with a combined Battery Management System, Load Switch, and other peripherals. This device enables deep hibernation of the vehicle. This is a novel and unique device that goes beyond the similar and related projects touched on in Section II. When the Gannet is resting in a terrestrial or oceanic environment, the majority of the avionics and power systems are switched off, as the vast majority of these devices are not designed with low quiescent power in mind. By disabling the idle current draw from these components, the aircraft enters a state of hibernation while energy harvesting or waiting until proper solar illumination. Without this device, the battery will discharge overnight due to the idle load. The Power Management System also acts as a mission timer and radio management system, with the ability to separately power and send and receive commands from a satellite or cellular communication transceiver. The Power Management System is detailed in [15, 16].

4) Nacelles: The function of the nacelle is to facilitate the transition between hover and forward flight. It is therefore critical that the structure of the nacelle be able to support the mass of the vehicle with the addition of drag while ascending in vertical flight. Therefore, it is necessary to either limit the ascent velocity of the vehicle to minimize drag or ensure the nacelle structure is designed with a factor of safety many times greater than the mass of the vehicle to prevent structural failure. Additive manufacturing via fused deposition modeling is utilized to produce the nacelles, due to the high strength-to-weight ratio of Acrylic Styrene Acrylonitrile Filament and the ultraviolet radiation-resistant nature of the material. The primary focus of the nacelle design is to allow for hover-to-forward flight transition while the secondary focus was reducing flow separation. The reduction in flow separation is accomplished by using a teardrop profile for the overall design.

The servos in this application provide substantially more torque than required to reduce servo wear as well as to ensure if dirt or debris obstructs the tilt mechanism, the nacelles will

Fig. 8. Gannet assembled experimental prototype: Current iteration is mechatronically complete and flight-proven.

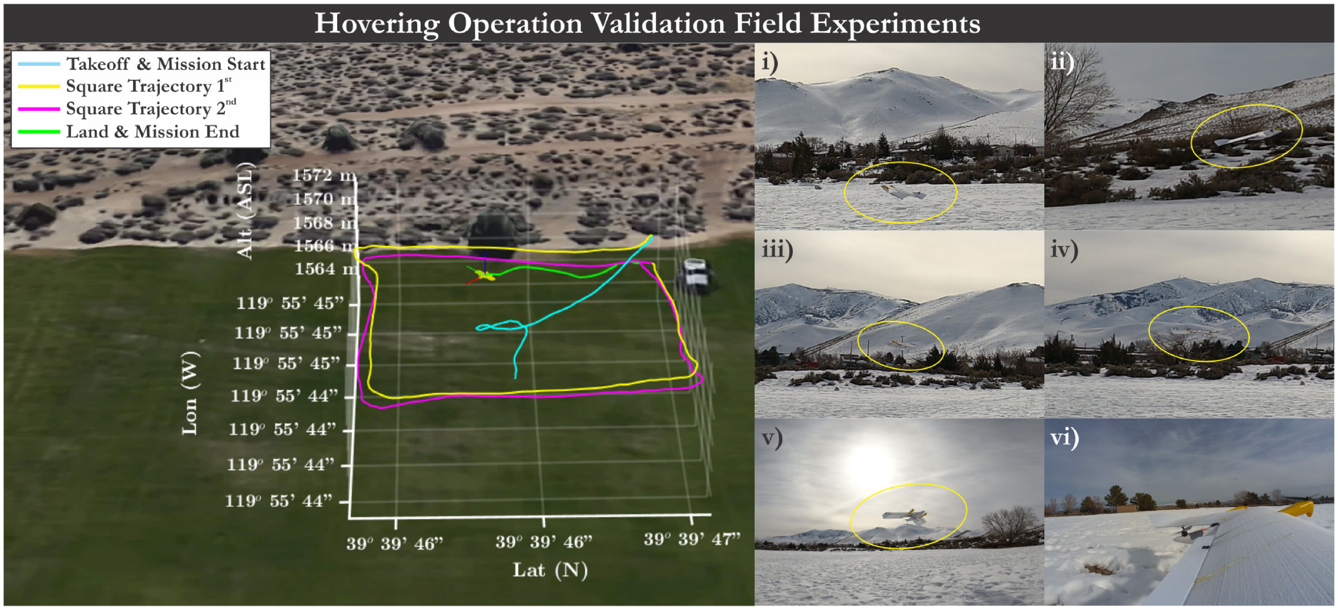

Fig. 9. Experimental Validation of the vehicle in VTOL low-altitude hovering.

still function. To provide a robust linkage between the tilt mechanism and the servo, a stainless steel shaft connects the servo horn to the tilt mechanism via ball joints secured with machine screws. To reduce mechanical wear on the system and maximize power transfer, the servo is placed in line with the tilt mechanism on the nacelle.

The tilt mechanism of the nacelle is composed of two pieces: the motor mount, and the nacelle body. The nacelle body remains statically attached to the wing of the Gannet while the motor mount houses the motor and rotates to enable the transition between hover and forward flight. The motor is mounted at the point of rotation to minimize the torque required to rotate the motor mount. The body of the nacelle contains a rounded slot in order to limit the rotation of the motor mount. The machine screw passes through this slot into the motor mount. With the machine screw in place, this effectively limits the motor mount to 115 degrees of rotation. At the rearmost position, the motor mount is physically locked into forward flight as seen in Figure 7.

Finally, Figure 8 depicts the most recent iteration of the flying Gannet prototype that adheres by the previously elaborated design specifications.

IV. EXPERIMENTAL STUDY

We experimentally validated the Gannet's flightworthiness in its two main flight modes, VTOL hovering as well as Fixed-Wing flight. Figure 9 illustrates the first case, which corresponds to tracking a low-altitude square trajectory of $20m$ edge-size. The first column shows the georeferenced location, selected due to its remoteness and relatively safe conditions for low-altitude hovering field experiments. The differently colored line segments indicate the initial Takeoff and hovering to the square trajectory's first waypoint, the yellow and magenta-colored lines correspond to two iterations of executing the aforementioned path, and the green one stands for the final VTOL Landing. The right column presents zoomed-in video instances of the Gannet flying from VTOL Takeoff (i), to the square's four corners ($ii-v$), as well as a wing-mounted camera instance of the moment before the final VTOL Landing touchdown.

Figure 10 illustrates the second case, which corresponds to a Fixed-Wing field experiment where the vehicle is hand-launched into the air, and tracks a sequence of six Loitering waypoints at several GPS coordinates and altitudes. It is important to note that due to the Gannet's development early stage, as a safety precaution these are performed in a conservatively geofenced area, as shown in Figure 9, wherein the first set of rows presents georeferenced plots of the vehicle's trajectory. Parts of the trajectory are differently colored per the legend to aid with visualization, and the overall mission progress from Takeoff to Landing is illustrated as a sequence of seven of these plots. The bottom row presents characteristic video instances of the mission as captured from a wing-mounted camera and a static ground one. More specifically, the Takeoff launch and the Final Descent touchdown during belly Landing can be seen in the first and last frames, while the second frame gives a perspective of the Above Ground Level altitude and the location / environment conditions during the flight, and finally the third frame presents an instance of aggressive banking turns when executing the waypoint loitering sequence of the commanded flight path.

V. CONCLUSIONS

This paper proposed and demonstrated the design and early testing of an all-environment amphibious Solar Electric VTOL UAV. Novel features include a modular avionics fuselage for quick interchange with various wing sets, a waterproof compartment for amphibious operation, and solar cell area allocations. Preliminary flight data is shown, demonstrating progress toward achieving long–range transoceanic autonomous flight.

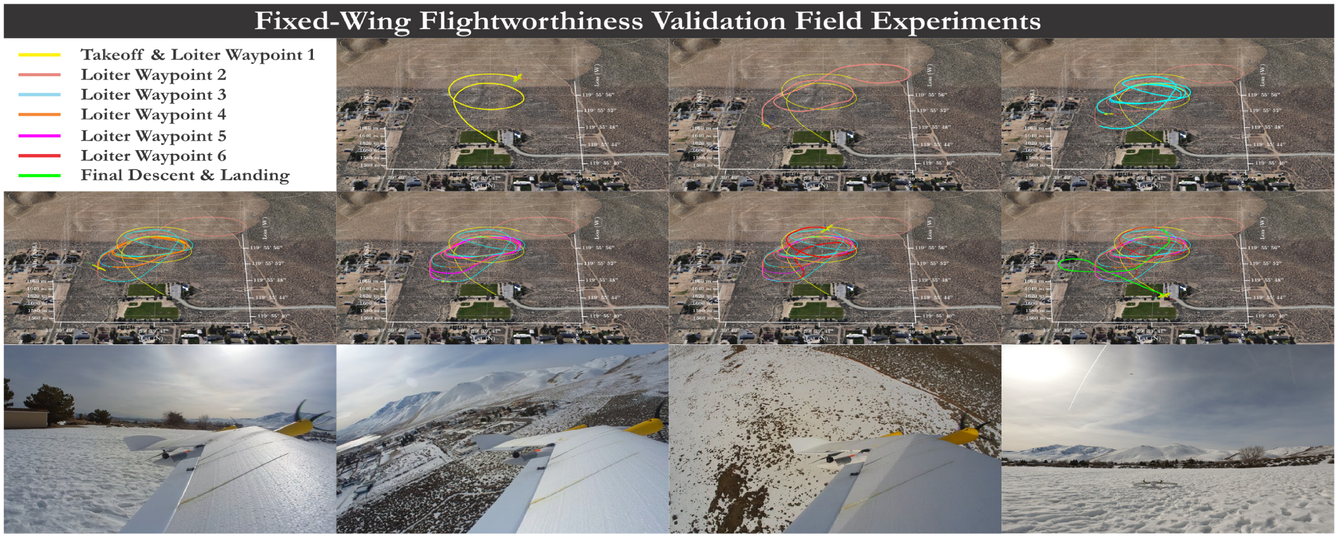

Fig. 10. Experimental Validation of the vehicle in Fixed-Wing flight.

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