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Development, Integration, and Initial Ground & Flight Testing of an Unmanned Aircraft for Dynamically-Scaled Flight Testing Research: Great Planes Avistar 30cc

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This paper presents ongoing efforts to develop the Great Planes Avistar 30cc into a dynamically-scaled research aircraft in order to enable dynamically-scaled flight testing research. Specifically, planned research will compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. Two commercial-off-the-shelf (COTS) geometrically similar aircraft will be used: the Avistar Elite, which has been extensively characterized in previous work, and the approximately 50% larger, Avistar 30cc. Therefore, aircraft development and avionics integration was performed, yielding a baseline, instrumented Avistar 30cc research aircraft. Afterwards, the Avistar 30cc underwent initial ground and flight testing. The results presented mark an important milestone in the development of the Avistar 30cc as a dynamically-scaled-up version of the Avistar Elite aircraft using the methodologies described in the literature.

I. Introduction

In the past several years, there has been a major increase in the popularity of unmanned aerial vehicles (UAVs) for military, commercial, and civilian applications. Part of this uptrend in UAV use includes increase in the research related to them. There have been UAVs used to study aerodynamic qualities,[1,2] especially in high angle-of- attack conditions.[3–5] Others have been used as testbeds to develop new control algorithms.[6–11] Additionally, some unmanned aircraft are used as low-cost stand-ins for experiments that are too risky or costly to perform on their full scale counterparts.[12–17] Yet other times, unmanned aircraft are developed to explore new aircraft configurations[18–21] or flight control hardware and software.[22–26]

Though a large number of studies have been conducted using free-flying scaled models, there is very little flight test data publicly available that can be used to develop scaling projects. Scaling laws are typically used to design and validate dynamically scaled models, whereas a emphasis is placed on matching predicted results using data obtained from flight testing.[27,28] Results from wind tunnel tests are typically validated using a calibration model,[29–34] which is typically not conducted for flight tests as it is not practically feasible due to limited time and resources. Though validating every dynamically scaled model is not feasible, the flight test procedures, development, and results can still be refined using a validated database as is typical for wind tunnel results.

Therefore, future research is planned to compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. The research will utilize two commercial-off-the-shelf (COTS) geometrically similar aircraft, the Avistar Elite, which has been extensively characterized in previous work,[35–38] and the approximately 50% larger, Avistar 30cc — the topic of this paper and is shown in Fig. 1. As the Avistar Elite already has extensive flight and ground testing datasets, this research effort aims to modify the larger Avistar 30cc into a dynamically-scaled-up version of the baseline Avistar Elite aircraft, using the methodologies described within literature and with results within the error margins of other scaling efforts such as NASA AirSTAR.[12,13] The planned research effort will specifically target longitudinal flight test maneuvers, as these longitudinal motions are typically not coupled to lateral motions simplifying the process.

Recent efforts have defined the scaling process, aircraft testbeds, instrumentation, and development and testing plans, forming the basis for this research.[39] Thus, this paper will present the ongoing efforts to develop the Great Planes

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Figure 1: The flight-ready, 90.5 in (2.3 m) wingspan Great Planes Avistar 30cc.

Avistar 30cc into the dynamically-scaled, 50% larger, Avistar aircraft. The results presented in this paper as well as the planned dynamically-scaled flight testing research will be available as part of the Unmanned Aerial Vehicle Database[40] (UAVDB)[a].

Specifically, the paper is structured as follows: Section A provides a description of the planned dynamic scaling research including a comparison of the Avistar aircraft. Then, Section III presents the current development and integration of the Avistar 30cc. Afterwards, Section IV presents the initial ground and flight testing performed to date. The paper concludes in Section V with a summary and statement of future work.

II. Planned Dynamically-Scaled Flight Testing Research

Research is planned to compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. The research will utilize two commercial-off-the-shelf (COTS) geometrically similar aircraft: the Avistar Elite, which has been extensively characterized in previous work, and the approximately 50% larger, Avistar 30cc. This research effort aims to modify the larger Avistar 30cc into a dynamically-scaled-up version of the baseline Avistar Elite aircraft, using the methodologies described within the literature and with results within the error margins of previous dynamic-scaling efforts. The planned research effort will specifically target longitudinal flight test maneuvers, as these longitudinal motions are typically not coupled to lateral motions, simplifying the process.

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[a] UAVDB is published online at www.uavdb.org and includes other aircraft such as the smaller Great Planes Avistar Elite 7.5cc[37] and a 26%-scale Cub Crafters CC11-100 Sport Cub S2[41]

A. Dynamic Scaling Methodology

A dynamically-scaled model is a free-flying scaled aircraft model that is capable of simulating the relative motions of a larger full-scale aircraft.[42] This means that in a proportional period of time, the scaled model would react in a similar manner to external stimulus, such as control input and loads. Scaling is accomplished by matching simulatude parameters such as those described in Table 1. These parameters are derived from the law of square-cubes, which correlates the linear scaling of an aircraft geometry to a cubic scaling of the mass properties. In addition to scaling the mass properties of an aircraft, aerodynamic scaling is also applied to to model as the decreasing the geometry of the aircraft will change the Reynolds number (Re) of the model, which will effect flight test results within non-linear operating regimes such as stall. Aerodynamic scaling is typically accounted for by modifying the geometry of the wing planform of the dynamically scaled model, such that the airfoil lift curve slope, maximum lift coefficient, and moment curves match the full-scale aircraft in its operating regime. As the model is scaled down, the flight test maneuvers are time scaled by a factor of $1/\sqrt{n}$, meaning that model will perform a maneuver in less time than the full-scale aircraft. These models are typically used in the development of aircraft configurations and test flight controllers as they are a safer and more cost effective alternative to developing manned aircraft.

An example of a dynamically-scaled model is the NASA AirSTAR which is a 5.5% scale model of a general transport model (GTM) aircraft that wa used to research the motions of commercial transport aircraft flying outside of their fight envelopes.[12,13] The NASA AirSTAR was designed using the same scaling laws in Table 1, with the dynamically-scaled model matching the inertias by 3% and weight by 0.1%. Another example of a dynamically scaled model includes the GA-USTAR project which aimed to develop and test a 1/5th scale model of the Cessna 182 to model upset and stall recovery maneuvers for general aviation (GA) aircraft .[16,17,43] The GA-USTAR project was developed using a COTS ”Almost-Ready-to-Fly” (ARF) model aircraft, similar to the Avistar aircraft that are planned for this research effort. As upset and stall requires analysis within the non-linear operating regime of the aircraft, this project made also made use of aerodynamic scaling factors as well by modifying airfoil of the Cessna 182.[44] As the current scope of this project aims to evaluate the longitudinal characteristics of the Avistar aircraft within a linear operating regime, emphasis will be placed on the mass scaling aspect of the project, specially Iyy which is longitudinal/pitch axis of the aircraft.

Table 1: Derived Scale Factors based on Similitude Parameters

Parameter	Symbol	Scaling Factor
Geometric		
Length	l	n
Density	ρ	σ
Inertial		
Mass	m	σn^3
Moment of Inertia	I	σn^5
Kinematic		
Time	t	$\sqrt{n}$
Velocity	V	$\sqrt{n}$
Attitude	α'	1
Control Surface Deflection	δ'	1
Angular Rate	Ω	$1/\sqrt{n}$
Angular Displacement	ϕ'	1
Angular Acceleration	$\dot{\Omega}$	$1/n$
Linear Displacement	s	n
Linear Acceleration	a	1
Oscillatory Frequency	ω	$1/\sqrt{n}$

B. Aircraft Comparison

The Avistar series of aircraft is comprised of the Great Planes Avistar Elite[45] and the approximately 50% larger, Great Planes Avistar 30cc.[46] The Avistar aircraft were chosen for the planned dynamically-scaled flight testing research as the smaller of the vehicles, the Avistar Elite has been extensively characterized in previous work, including flight testing,[37,38] ground measurement, and modeling and simulation efforts.

The Avistar Elite is a commercial-off-the-shelf (COTS) model aircraft designed for radio control flight training. Specifically, the aircraft has a fixed high-wing configuration and is primarily constructed from wood and plastic film covering. Given the aircraft's ease of construction and operation, robustness, re-configurablity, and procurement availability, it has made an excellent UAV research testbed;[47–51] and was also available for this research. The larger Avistar 30cc is also a commercial-off-the-shelf (COTS) model aircraft and is described as a ”giant-scale” sport trainer, which enables the freshly minted pilot (who has graduated from the Avistar Elite) to move onto a larger aircraft. The Avistar 30cc shares the same airfoil and aircraft configuration as the Avistar Elite. Figs. 2 and 3 present the top and side views of the Avistar Elite and Avistar 30cc, which show relatively similar aircraft proportions.

Table 2 presents the physical specifications for the Avistar Elite and the Avistar 30cc and scale factors for each measurement. As can be seen in the table, the scale factors for the geometric measurements of the wing are between 1.45 and 1.50 while those for the horizontal stabilizer are between 1.34 and 1.48. Comparing the Avistar Elite and Avistar 30cc aircraft, they have nearly identical wing aspect ratios at 5.8 and 5.7, respectively; while their horizontal stabilizer aspect ratios are similar but not at close as 3.6 and 3.3, respectively. In general, the wings of the Avistar 30cc are scaled mostly proportionally to the Avistar Elite; however, the horizontal tail is relatively smaller and closer to the wing on the Avistar 30cc than on the Avistar Elite.

Figure 2: Top and side views of the Great Planes Avistar Elite [taken from Great Planes[45]].

Figure 3: Top and side views of the Great Planes Avistar 30cc [taken from Great Planes[46]].

Table 2: Avistar Elite and Avistar 30cc physical specifications and scaling factors.

	Avistar Elite	**Avistar 30cc**	**Scaling Factor (n)**
Geometric			
Wing Chord	10.7 in (272 mm)	16.0 in (406 mm)	1.50
Wing Span	62.5 in (1590 mm)	90.5 in (2300 mm)	1.45
Wing Area	672 in^2 (43.3 dm^2)	1448 in^2 (93.4 dm^2)	1.46
Wing Aspect Ratio	5.8	5.7	–
Wing Airfoil	Avistar	Avistar	–
H. Stab Mean Chord	6.3 in (160 mm)	9.2 in (234 mm)	1.46
H. Stab Span	22.9 in (582 mm)	30.7 in (780 mm)	1.34
H. Stab Area	144 in^2 (9.3 dm^2)	282 in^2 (18.3 dm^2)	1.40
H. Stab Aspect Ratio	3.6	3.3	–
H. Stab Airfoil	Flat Plate, 8.6 mm Thick	Flat Plate, 12.4 mm Thick	1.44
Distance from Wing LE to H. Stab LE	30.7 in (780 mm)	41.3 in (1048 mm)	1.34
Aircraft Length	55.0 in (1395 mm)	77.25 in (1962 mm)	1.41
Inertial			
MFG Weight	6.5-7.0 lb (2.95-3.17 kg)	16.5-17.5 lb (7.48-7.94 kg)	1.36
Final Weight	8.70 lb (3.95 kg) *Instrumented, As-Built*	29.36 lb (13.33 kg) *Dynamically-Scaled, Desired*	1.50 *Desired*

The flight-ready, fully-instrumented Avistar Elite weighs 8.70 lb (3.945 kg) as-built, which is 1.70 lb (0.77 kg) or 24% greater than the upper end of the manufacturer weight range, due to the instrumentation and necessary modifications. As the target scale factor between the two aircraft is approximately 1.5, the 8.70 lb Avistar Elite yields that the Avistar 30cc should weigh 29.36 lb (13.33 kg). Given that the upper end of manufacturer weight range for the Avistar 30cc is 17.5 lb (7.94 kg), to achieve the 1.50 scale factor for weight/mass, there is 11.86 lb (5.38 kg) available for instrumentation and ballast. Note that the ballast will be used to both achieve the desired weight and the dynamically-scaled moment of inertia.

Further details regarding the Avistar Elite and the Avistar 30cc airframe components, control systems, and propulsion systems, as well as a comparison between the aircraft, can be found in the related literature.[39]

III. Aircraft Development and Integration

A. Airframe Construction

The Great Planes Avistar 30cc was a commercially available model aircraft that is the 50% scaled up version of the Great Planes Avistar Elite (7.5cc). Unfortunately, the Avistar 30cc was discontinued in 2018, making it very difficult to purchase a new kit. Fortunately, a used hobbyist-owned Avistar 30cc was located and then purchased; the aircraft had already been constructed and flown in a taildragger (conventional landing gear) configuration, without flaps, and with an electric propulsion system. The airframe was mainly constructed following manufacturer recommendations with several hardware deviations. The aircraft, its wings, and the internal configuration as purchased are shown in Fig. 4.

In order to convert the used Avistar 30cc into a research aircraft, several modifications were performed. First, the landing gear was modified to a tricycle configuration; the tricycle configuration is one of the manufacturer options, so the change was simply performed by requisitioning and changing landing gear components. Next, the flaps were enabled and servos and linkages were installed. In order to increase aircraft safety, the control surface linkages were strengthened. Additionally, the previous electronics gear was removed, and a redundant flight control power regulator was installed. The existing electric propulsion system, i.e., motor, propeller, and electronic speed controller (ESC),

Figure 4: The as-purchased, used Great Planes Avistar 30cc in a taildragger (conventional landing gear) configuration, without flaps, and with an electric propulsion system.

(a)

(b)

Figure 5: The as-purchased, used Great Planes Avistar 30cc aircraft construction details: the wing panels constructed with aileron control surfaces, servos, and linkage, but without flaps (shown from the bottom); and a the rear of fuselage, under wing mounting location containing the elevator and rudder servos, and miscellaneous gear.

was removed and replaced with components selected during the planning stage. Table 3 provides a complete list of all airframe components installed in the Avistar 30cc after modifications were performed.

To mitigate risk to the soon-to-be-installed flight test avionics, the aircraft was thoroughly inspected and then test flown several times, in an un-instrumented state. A dozen checkout flights were performed, both to verify the structural condition of the aircraft as well as to provide the test pilot time to familiarize themselves with the aircraft. Specifically, they practiced takeoff, landing, slow-speed, and upset behavior with various levels of flaps (0, half, and full). Fig. 6 shows the aircraft with full flaps, flying at a high angle-of-attack.

Table 3: The final Avistar 30cc 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	Aileron (2), elevator, rudder, throttle, and flaps (2)
Transmitter	Futaba T14MZ
Receiver	Futaba R6014HS
Servos	(7) Hitec HS-5645MG
Regulator	SmartFly SportReg
Receiver Battery	(2) Thunder ProLite RX 2S 7.4V 900 mAh
Propulsion	
Motor	Hacker A60-5S V4 28-pole Outrunner
ESC	Castle Creation Phoenix Edge HV 120
Propeller	APC 20x10E
Motor Flight Pack	Thunder Power ProLiteX 25c 8S 29.6 V 6.8 Ah lithium polymer battery
Motor Power Switch	Emcotec SPS 60/120

Figure 6: The un-instrumented Avistar 30cc being flown with full-flaps at slow speeds with a high angle-of-attack.

B. Avionics Integration

The Avistar 30cc was instrumented with an Al Volo FC+DAQ[52] flight control and data acquisition system, which is able to collect high-frequency, high-fidelity data from a large number of sensors.[53] The system operates at 400 Hz and integrates a 9 degree-of-freedom (9-DOF) XSens MTi-G-700[54] IMU with a GPS receiver. The pilot commands are also logged by measuring the pulse width modulation (PWM) signals generated by the receiver for each servo channel. The propulsion system information is logged by the FDAQ through an interface with the Castle Creations Edge 120 HV electronic speed controller (ESC); additionally, an integrated 100 A Hall-effect current sensor was added between the ESC and the battery to monitor current input.[55] Using the sensors, the system is able to log and transmit: 3D linear and angular accelerations, velocities, and position along with GPS location; pitot-static probe airspeed; 3D magnetic field strength and heading; control surface deflections; and propulsion system voltage, motor and ESC current, RPM, and power. Specifications for the avionics installed in the Avistar 30cc are given in Table 4, a diagram showing the layout is provided in Fig. 7, and a photo of the pitot-static probe installed is shown in Fig. 8. The avionics integrated into the Avistar 30cc are almost identical to those installed in the Avistar Elite.

Table 4: Instrumentation specifications.

Data acquisition system	Al Volo FDAQ 400 Hz system
RF Module	Digi International 900 MHz XBee Pro S3B Module
RC Multiplexer	Acroname RxMux
Sensors	
Inertial measurement unit	XSens MTi-G-700 AHRS with GPS
Airspeed sensor	Al Volo Pitot Static Airspeed Sensor
Motor/ESC sensor	Al Volo Castle ESC Interface
Motor current sensor	Allegro MicroSystems ACS758LCB-100B
Power	
Regulator	Built into FC+DAQ
Battery	Thunder Power ProLiteX 3S 1350 mAh

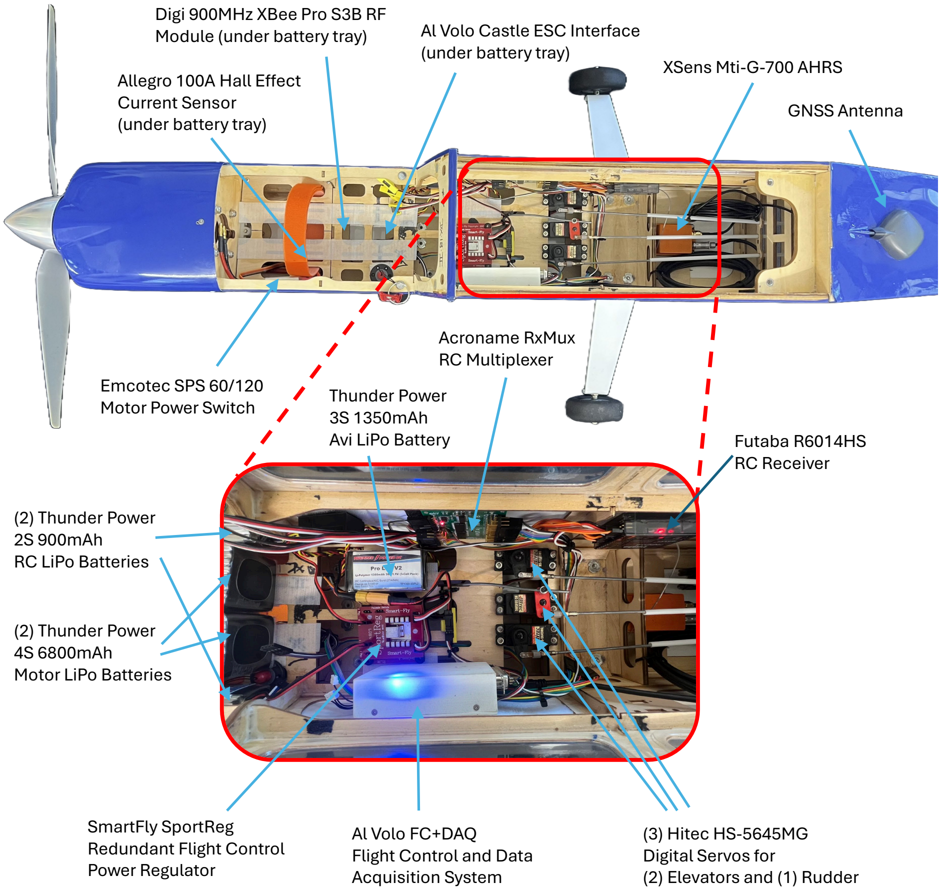


Figure 7: The avionics, RC, and propulsion system layout inside the instrumented Avistar 30cc.

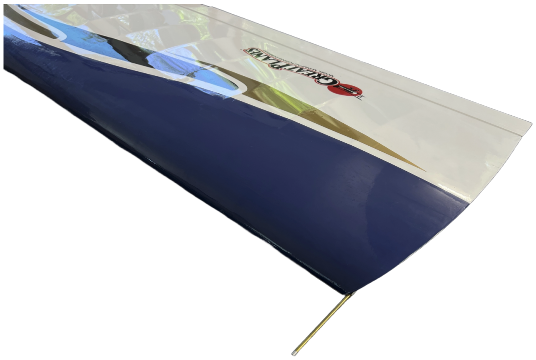


Figure 8: The pitot-static probe installed on the left wing of the Avistar 30cc.

IV. Initial Testing Results

Ground and flight testing has been ongoing with the Avistar 30cc after the avionics were installed. The current instrumented configuration is assumed to be final. As the aircraft has not yet been dynamically-scaled, it is referred to as the baseline, instrumented configuration of the aircraft.

A. Ground Testing

Ground testing efforts to date have included physical measurements of the aircraft, parametrization of the flight control surface deflections to the commanded servo signals (PWM), and propeller performance testing. Moment of inertia testing is planned using a previously-developed testing apparatus.[56]

1. Physical Measurement

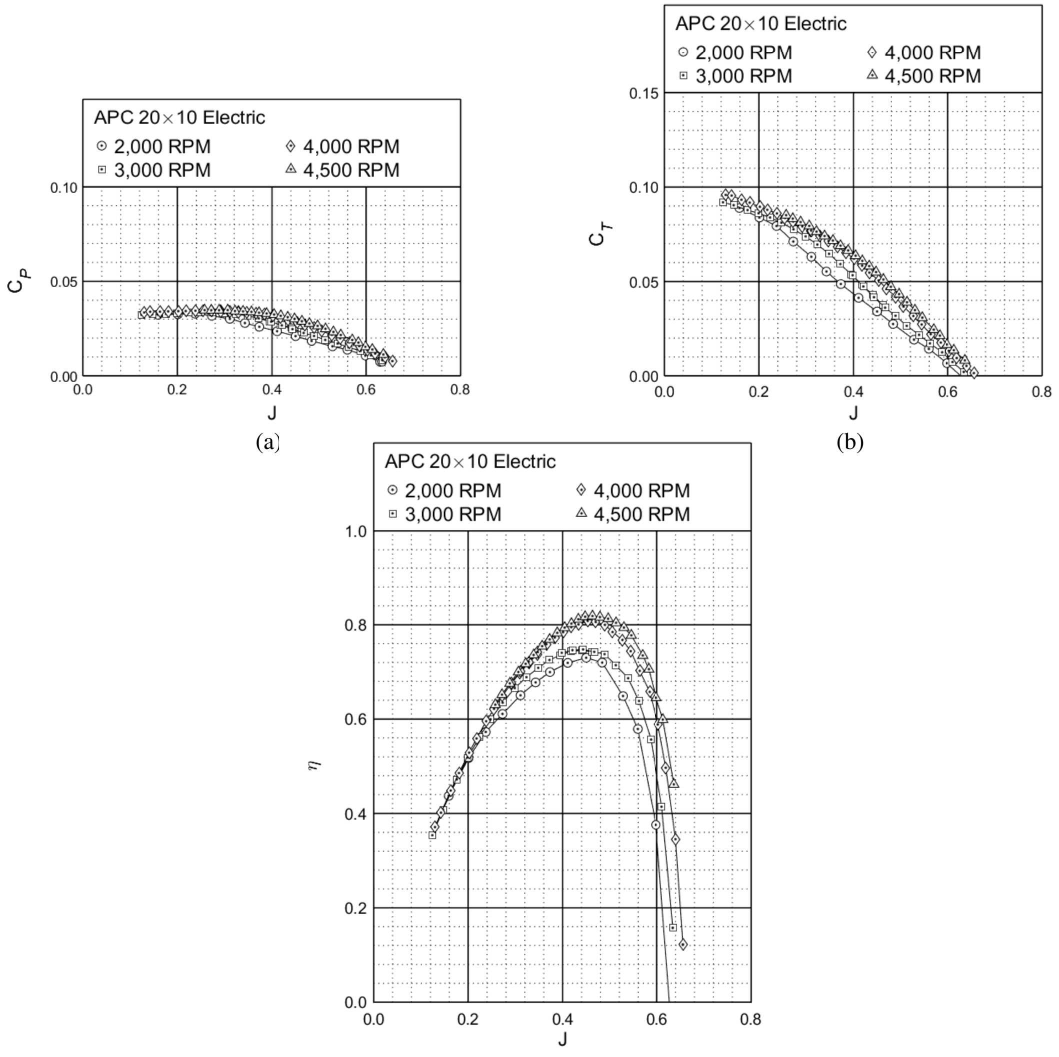
Physical measurements of the baseline, instrumented Avistar 30cc were performed. Geometric measurements collected were presented Table 2 in Section II.B. The airframe component masses and test pilot-preferred, center of gravity location were measured, and are presented in Table 5.

Table 5: Baseline aircraft physical specifications.

Weight/Mass Properties	
Fuselage	10.37 lb (4.707 kg)
Right Wing	1.99 lb (0.905 kg)
Left Wing	2.10 lb (0.951 kg)
Wing Tube	0.30 lb (0.138 kg)
(2) RC LiPo Batteries	0.23 lb (0.103 kg)
Avionics LiPo Battery	0.22 lb (0.099 kg)
(2) Motor LiPo Batteries	2.71 lb (1.232 kg)
Gross Aircraft Weight	17.93 lb (8.135 kg)
Flight Properties	
Wing Loading	28.5 $\mathrm{oz/ft^2}$ (87.1 $\mathrm{gr/dm^2}$)
Center of Gravity Behind LE	5.125 in (130.2 mm)

2. *Propeller Performance Testing*

Performance testing of the APC 20×10E propeller used on the Avistar 30cc was performed in December 2021 in the UIUC low-turbulence subsonic wind tunnel.[57] Fig. 9 and 10 present dynamic and static performance results.



(a)

(b)

(c)

Figure 9: Performance of the APC 20×10 Thin Electric propeller: (a) thrust coefficient, (b) power coefficient, (c) efficiency.

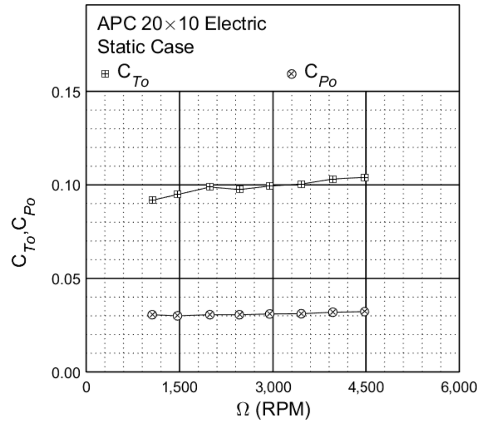


Figure 10: Static performance of the APC 20×10 Thin Electric propeller: thrust and power coefficient.

B. Flight Testing

Preliminary flight testing was performed with the baseline, instrumented Avistar 30cc. A typical flight with the Avistar 30cc spans approximately 15 to 20 minutes, and flight data is collected starting before takeoff and stopping after landing. To test the aircraft's flight data collection capability, a short, 80 sec flight was manually performed with a takeoff, one race-track pattern, and then a landing. The flight conditions were 80 F (26.7 C), 81% humidity, 29.15 inHg pressure, and no wind observed. Data was captured at 400 Hz across all sensors described in Section III.B. The trajectory of the flight is shown in Fig. 11 and the time history can be seen in Fig. 12.

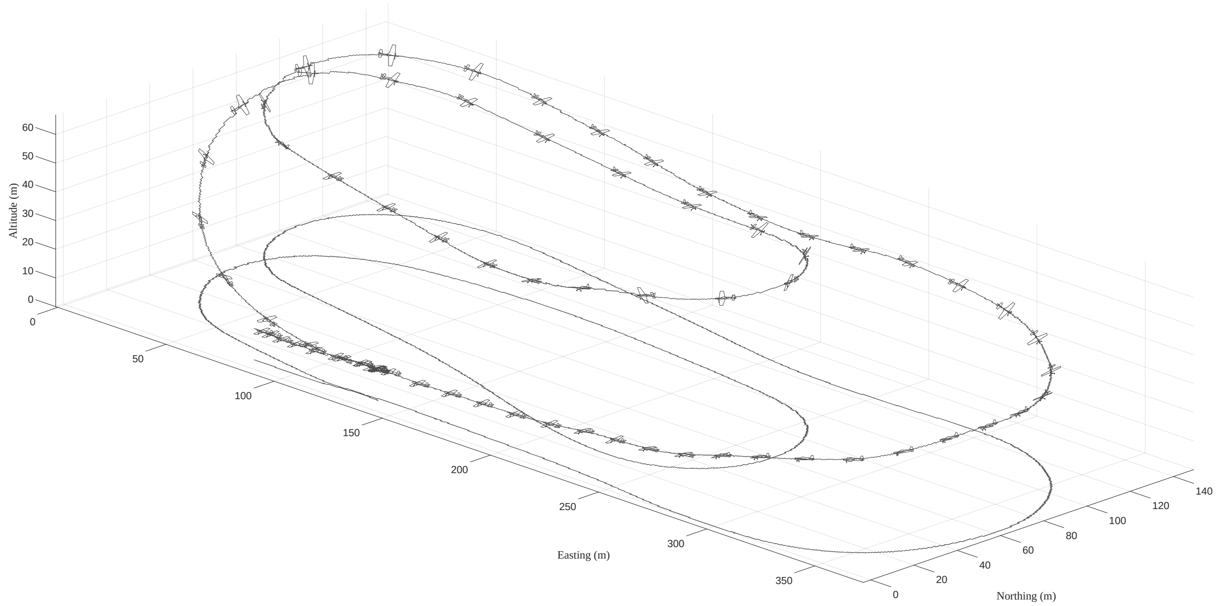


Figure 11: Trajectory plot of the Avistar 30cc short flight (the aircraft is drawn once every 1 sec).

The trajectory and time history plots show mostly ideal flight data collection with 2 issues. The first issue is that the given the flight occurred in no wind conditions, it is expected that the airspeed would mostly match the ground speed. However, the time history plot shows that the airspeed is consistently lower than the ground speed, independent of the aircraft direction (if there was wind). This observation leads to the theory that the pitot-static airspeed probe is too close to the wing and is thus within the wing's flow field, yielding the lower measured speed. This theory is supported by the fact that the probe installed on the Avistar 30cc is identical to that used on the Avistar Elite and is therefore relatively closer to the leading edge, given the aircraft's larger size. Therefore, for future flight testing, the pitot-static probe will either be extended out or be replaced with a longer probe that places the measurement ports outside the wing's flow field.

The second data collection issue is the lower current values measured by the Hall effect sensors compared to those measured by the ESC. As the Hall effect sensor is placed between the battery and the ESC, it is expected to have the same or greater current measurements than the ESC due to potential losses. Therefore, this issue could likely be rectified with additional calibration of the Hall effect current sensor. Integrating a filter to decrease the sensor noise would also be beneficial.

Future flight testing will be conducted using a flight test automation tool developed using the Avistar Elite.[58] The automation tool ensures consistent flight test results as the autopilot uses real-time flight test data to orient and control the aircraft. The flight test automation tool is integrated into uavAP,[26] which will run on the Al Volo FC+DAQ flight control and data acquisition system installed in the Avistar 30cc, identically to how it operates on the Avistar Elite. Flight testing planned will include a range of maneuvers outlined in related work.[39]

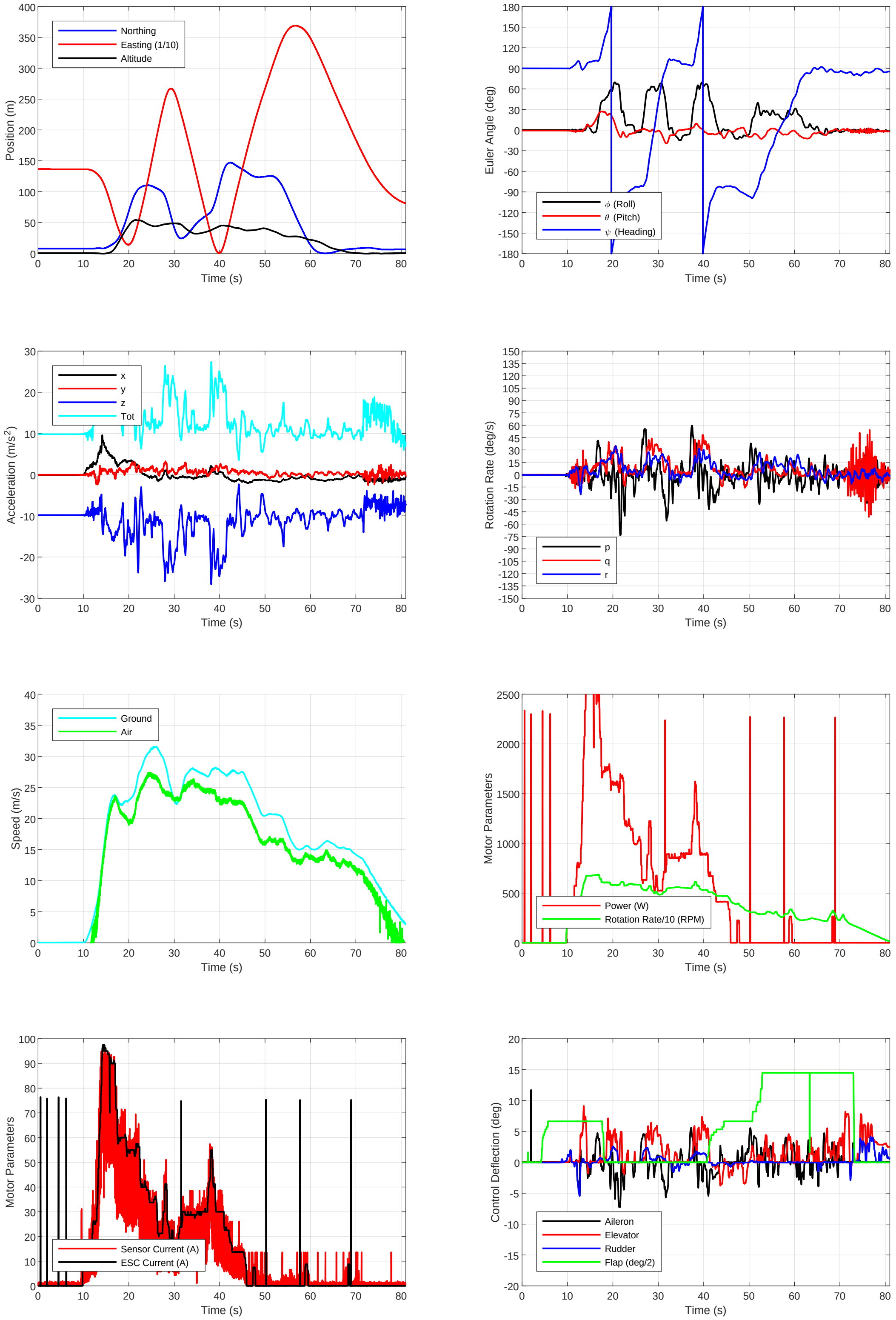


Figure 12: A time history of the Avistar 30cc short flight.

V. Summary and Future Work

This paper presented ongoing efforts to develop the Great Planes Avistar 30cc into a dynamically-scaled research aircraft in order to enable future dynamically-scaled flight testing research. Specifically, planned research will compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. Two commercial-off-the-shelf (COTS) geometrically similar aircraft will be used: the Avistar Elite, which has been extensively characterized in previous work, and the approximately 50% larger, Avistar 30cc. Therefore, aircraft development and avionics integration was performed, yielding a baseline, instrumented Avistar 30cc research aircraft. Then, the Avistar 30cc underwent initial ground and flight testing, leading to further test and characterization efforts.

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