PROJECT ARES II: HIGH-ALTITUDE BATTERY-POWERED AIRCRAFT

CALIFORNIA STATE UNIVERSITY NORTHRIDGE

A high-altitude, battery-powered, propeller-driven aircraft has been designed and is being built by undergraduate students at California State University, Northridge. The aircraft will fly at an altitude of 104,000 ft at Mach 0.2 (190 ft/sec) and will be instrumented to record flight performance data, including low Reynolds number propeller and airfoil information.

This project will demonstrate the feasibility of electric-powered flight in a low-density, low-temperature Earth environment that models the atmosphere of Mars. Data collected will be used to design a Mars aircraft to investigate the surface of Mars prior to manned missions.

The instrumented payload and the mission profile for the high-altitude Earth flight were determined. Detailed aerodynamic and structural analyses were performed. Control, tracking, and data recording subsystems were developed. Materials were obtained and fabrication begun.

The aircraft has a 32-ft wing span, a wing area of 105 sq ft, is 17.5 ft long, has a 12-in payload bay, and weighs 42 lb. It is composed primarily of lightweight materials, including Mylar, and composite materials, including graphite/epoxy and aramid core honeycomb sandwich.

Low-altitude flight testing to check guidance and control systems and to calibrate data-gathering instruments will take place this summer, followed shortly by the 104,000-ft flight.

INTRODUCTION

The Universities Space Research Association (USRA), in association with NASA, has sponsored a three-year undergraduate design project in the Mechanical Engineering Department at California State University, Northridge (CSUN). The overall project objective is to design a heavier-than-air craft to fly in the lower martian atmosphere, investigating geological and atmospheric features as a prelude to a manned Mars mission.

The first year's design team (ARES I) investigated the martian mission and made recommendations for mission profile, payload, aircraft configuration, and delivery of the craft to Mars. Now, in the second year of the project, a new student team (ARES II) has designed an aircraft to be built and flown on Earth. This prototype, currently being fabricated at CSUN, will demonstrate the feasibility of the Marscraft by flying on Earth.

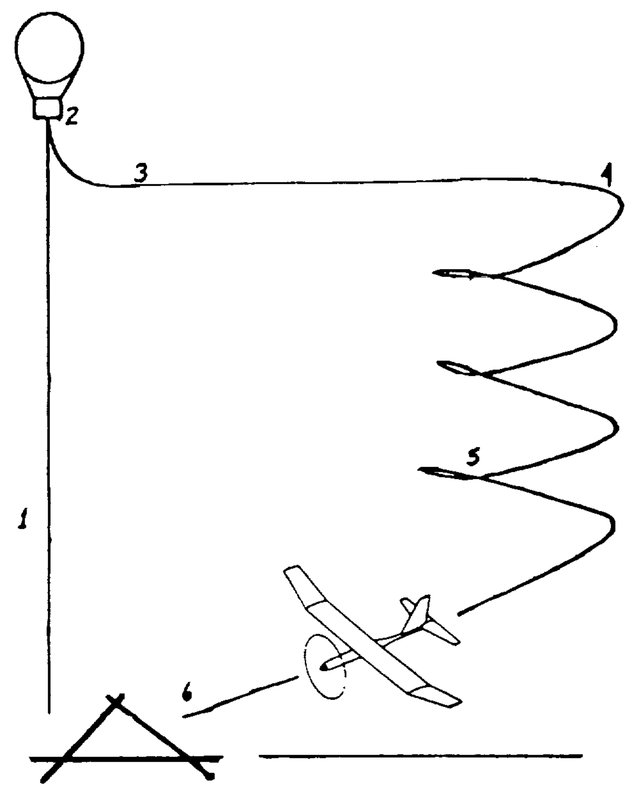
The aircraft will fly at 104,000 ft at Mach 0.2, a flight regime closely resembling the martian mission in the following important parameters: atmospheric density and temperature, Reynolds numbers, and lift coefficient. A successful Earth flight will demonstrate the feasibility of the Mars mission and craft.

For a meaningful demonstration, the Earth prototype will carry an instrument payload to measure and record aircraft performance data. This data will be useful in verifying the design concepts and analytical model developed by the student team and providing a baseline for design of the actual Marscraft, as well as providing valuable low-Reynolds-number propeller and airfoil information.

The high-altitude flight is planned for this summer (1991) at Edwards Air Force Base.

MISSION PROFILE

To achieve the stated objectives, the mission profile detailed in Fig. 1 was developed. A balloon will take the aircraft to 110,000 ft and release it. After 3 min of programmed level flight and maneuvers within a 25 by 8 mile test area at Edwards AFB, the aircraft will descend and land under manual control.



Phase	Description
1-2	Balloon launch and ascent. Release aircraft nosedown at 110,000 ft.
2-3	Pullout to level flight at 104,000 ft. Maximum 3-*g* load occurs at point 3.
3-4	Preprogrammed level flight and maneuvers for 3 minutes.
4-5	Descend. Wind gusts below 50,000 ft can be dangerous.
5-6	Land under manual control.

Fig. 1. Mission profile.

Prior to the high-altitude flight, low-altitude test flights will be made to test guidance and control systems and to calibrate data gathering instruments.

AERODYNAMIC DESIGN

The basic requirement was to design an aircraft for electrically powered flight at 104,000 ft (a low-Reynolds-number regime). The selected airfoil, the RG15-PT, is suitable for low Reynolds numbers. It has a low design coefficient, small variations in L/D as a function of Reynolds number, and is fabricable due to its simple shape. The expected Reynolds number at altitude is 60,000. See Fig. 2 for additional airfoil details.

Since the Mars craft will very likely be solar powered, the Earth prototype was planned as a solar vehicle too; but due to cost, availability, and low energy density, solar cells were waived in favor of nickel-cadmium batteries for this design. Nevertheless, several key aerodynamic design decisions were made based on the presence of solar cells, as will be discussed.

A trade study was performed based on small payloads, available motor horsepower, wing loading vs. velocity, and, finally, wing loading vs. aspect ratio. An optimum aspect ratio of 10 was determined. A carpet plot incorporating these variables resulted in the simultaneous optimization of wingspan (32 ft), velocity (190 ft/s), and weight (42 lb). Subtracting the known weights of the propulsion and avionics systems from this weight resulted in the target structural weight fraction, to be discussed later.

The wing area was as large as possible to allow for the greatest number of solar cells. Ailerons were eliminated for the same reason. To simplify fabrication, the wing has a 20-ft-span constant chord center section with 6-ft tapered outboard sections. To improve stability, the outboard sections have a taper ratio of 7.5, all in the leading edge, to give a sweep effect, and a 13° dihedral, giving the equivalent of a 5° total wing dihedral.

The tail was designed in conventional configuration, although an inverted V-tail could still be built. The conventional tail is preferred for landing, since the aircraft will not have landing gear. Symmetric airfoil sections were selected for both vertical and horizontal tail sections. Ailerons were not used; instead, a large rudder and elevator were designed to control pitch, roll, and yaw.

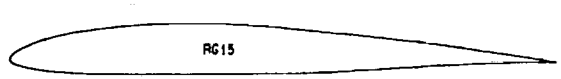
The fuselage was designed in a one-piece "guppy" shape, tapering from a payload bay to a tail boom. This configuration simplified structural analysis, eliminated stress concentrations associated with a separate boom attachment, and simplified fabrication. The wetted area was reduced by rounding the square cross-section, and drag was reduced by giving the payload bay a slightly sculptured profile.

The propulsion system includes an 7-ft propeller, driven by a 1.6-hp electric motor through a belt-driven gear reducer, powered by nickel-cadmium batteries (see Fig. 3.) With a smaller payload, or reduced structural weight, the same system can be powered by K7 solar cells. All the cells can be placed in the wing beneath the clear Mylar skin.

A summary of final aircraft specifications is provided in Fig. 4.

STRUCTURAL DESIGN

Large structural elements were divided into finite segments, allowing the analysis of a tapered geometry with nonlinear distribution of loads, moments, and properties. All loads were multiplied by a load factor and safety margin, and the resulting moments used to determine stresses, deflection, and rotation



LOW DESIGN COEFFICIENT C(L)= 0.63

SMALL L/D VARIANCE FOR DIFFERENT REYNOLDS NUMBERS

8.9% THICKNESS

SIMPLE SHAPE FOR EASE OF FABRICATION

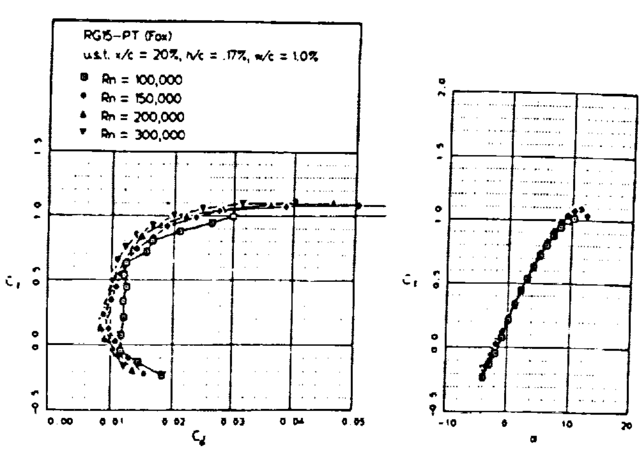
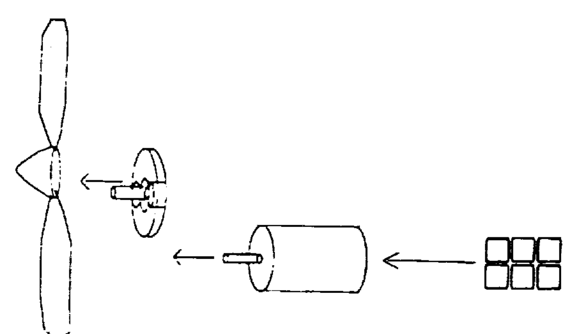


Fig. 2. Airfoil data.



PROPELLER	GEARING	MOTOR	BATTERIES
1150 RPM	8:1 RATIO	1.6 HP	LiSoCl
3.4 LB THRUST	BELT DRIVE	1.25 LB	10 cells
7.0 FT DIAMETER	ALUMINUM	D.C. BRUSHED	15 AH
87% EFFICIENT	2 LB	2IN X 2.75 IN	

Fig. 3. Propulsion schematic.

PERFORMANCE

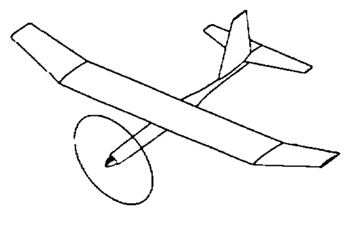
Altitude	104,000	ft
Vel (cruise) Mach	0.02	
Vel (cruise)	190	ft/sec
Vel (climb)	180	ft/sec
Vel (stall)	172	ft/sec
Load Factor	3	G
Safety Factor	1.2	

WING

No sweep		
Wing Area	105	ft^2
Aspect Ratio	10	
Taper Ratio	0.5	
b	32.3	ft
C (root)	3.5	ft
C (tip)	2.2	ft
C Bar	3.34	ft
Y Bar	7.18	ft

DESIGN PARAMETERS

Wing Loading	0.4	lb/ft^2
Weight	42.0	lb
Hp/wt	0.038	
Wt/Hp	26.18	



VERTICAL TAIL

A	1.6	
Taper ratio	0.4	
S	11.89	ft^2
b	4.36	ft
C (root)	3.89	ft
C (tip)	1.56	ft

HORIZONTAL TAIL

A	6	
Taper ratio	0.4	
S	18	ft^2
b	10.39	ft
C (root)	2.47	ft
C (tip)	0.99	ft

Fig. 4. Aircraft specifications.

of structural assemblies. The geometry, material, or configuration of each assembly was modified until the computed stresses, deflections, and rotations met acceptable limits, and were then refined to reduce weight.

Table 1 indicates the target weight summary. Note that the structure comprises 42% of the total aircraft weight, and the wing alone weighs 0.1 lb/sq ft. Recent advanced aircraft data (e.g., the Gossamer *Penguin*) suggest that these targets are achievable.

A maximum load factor of 3 *g* was determined from an aerodynamic analysis of the launch. Four-g loads due to gusts may be encountered at 50,000 ft (during descent), determined from velocity-load diagrams. Nevertheless, it was decided to use a design load factor of 3 *g*, to help reduce weight, and fly on a low-gust day. Similarly, a safety factor of 1.2 was selected, even though 1.5 is typical in aircraft applications.

TABLE 1. Weight Summary

Item	Weight (lb)
Structure	
Wing	10.5
Fuselage	12.0
Tail	3.0
Propulsion	
Propeller	4.4
Motor	1.6
Gear reducer	2.0
Batteries	2.5
Payload	6.0
Total	42.0

TABLE 2. Final Material Selection

Item	Material
Ribs	Composite sandwich: 1/4" aramid honeycomb core with 7 mil, 1-ply graphite/epoxy (g/e) facings
Torsion box	g/e sandwich, all four sides
Leading and trailing edges	7 mil, 1-ply g/e
Skin	0.5 mil Mylar, adhered and heat shrunk
Fuselage	7 mil, 1-ply g/e, with local stiffening

For simplification of the wing analysis, it was assumed that the torsion box alone would carry all loads. Normal spanwise stresses at every box segment were determined using advanced beam theory. The maximum stress in a given segment was then compared to the local buckling stress, determined from thin-plate buckling theory. Predicted failure stress was kept at least 20% higher than the maximum stress, wing tip deflection was kept less than 1 in, and tip rotation was less than 2°.

The fuselage was designed similarly to the wing torsion box. A mostly square cross section was adopted to simplify (1) wing and tail attachment, (2) analysis and design, and (3) tooling and fabrication. The tail section was patterned on the wing.

A number of tests were conducted to provide insight into the behavior and characteristics of certain structural component materials and fabrication methods. A rib test fixture was built to determine the lowest-weight rib configuration that could sustain the applied load. A thin-film skin test was performed to evaluate skin deflection under load and to observe the behavior of film and adhesive at low temperatures (-70°F). Lastly, some informal allowable testing was performed to confirm assumptions regarding adhesive and composite strength in tension at low temperatures. The tests were useful in confirming or modifying the selection of materials.

A wide range of materials was considered for all structural elements. Primary selection criteria were availability, cost, density, and ease of tooling and fabrication. Table 2 indicates the final materials selection. Figure 5 shows the final configuration.

AVIONICS

Systems for flight control and tracking, testing, and data recording were designed, tested, and assembled. Flight control will be provided via modified radio-controlled model aircraft hardware. The transmitter station will include an amplifier and directional antenna to boost the control signal to the required range. The aircraft will carry a miniature radio transponder to aid in radar tracking. The control system incorporates a fail-safe feature whereby the aircraft assumes a preprogrammed descent profile in the event of a loss of control signal.

The aircraft will carry sensors to measure and record airspeed, altitude, ambient temperature, motor power consumption, and propeller thrust and speed. This information will be stored for later retrieval by the flight data recorder (FDR). The FDR uses the latest in LSI and surface-mount chip technology to pack what is, in essence, a complete microcomputer onto a few square inches. The FDR will also provide sensor signal conditioning and supply regulated reference voltages.

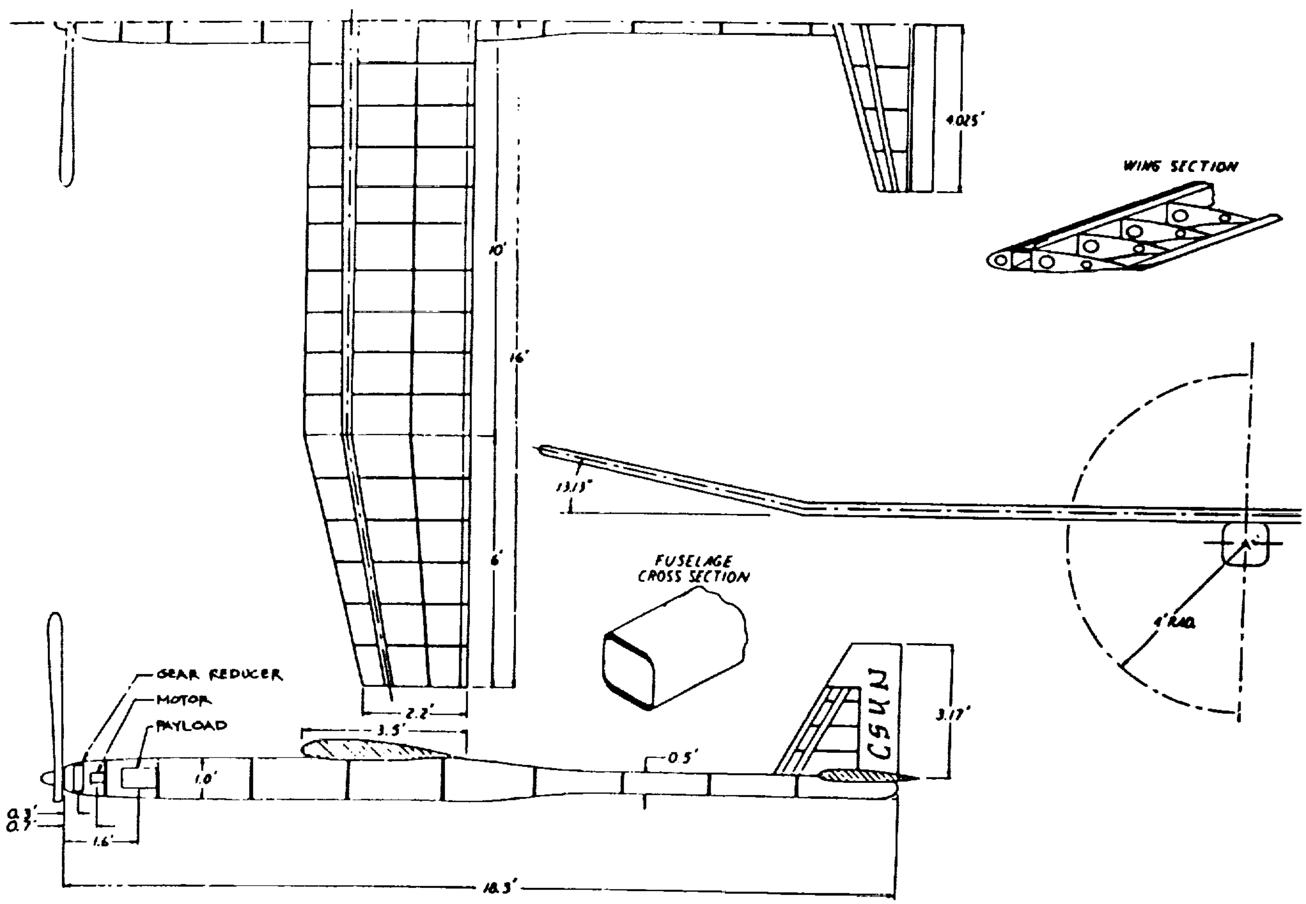


Fig. 5. Configuration drawing.

Additionally, the aircraft will carry a wing pressure port scanner system to record air pressure differentials at 32 different chord-wise wing locations. This data will validate the computational fluid dynamics model.

Because of low ambient temperatures at altitude (-70°F), the instrumentation package will be insulated. The FDR will be able to monitor and regulate the payload bay temperature with the aid of a small film resistance heater. Power for the onboard avionics will be provided by a dedicated carbonmonofluoride lithium battery. The FDR will be furnished independently with a battery backup. Figure 6 illustrates the control, data collection, and flight data recorder schematics.

BUDGET

In a project of this scope, the required instrumentation and materiel support is substantial. Thanks to the generous donations of interested industrial associates, the fabrication phase has proceeded on schedule with a continuing promise of success. Table 3 is a budget of this year's work.

TABLE 3. Budget

Item	Cost, $
Avionics	8,600
Propulsion	3,800
Structure	19,000
Mission Support	5,300
Travel	5,800
Total	42,500

FABRICATION

The aircraft is being constructed entirely by the student team. Individual elements and major subassemblies are being built and tested, and redesigned if necessary, before final construction.

Most of the structural components were made from fiber/epoxy sheets or composite sandwich (an aramid honeycomb core with graphite/epoxy facings). Molds, made of wood or sheet metal, were built, surfaced with putty and enamel paint, then prepared with release agents to accept the wetted cloth. Curing was done in vacuum. A brief discussion of fabrication methods used for the major components follows.

The wing is being built in three sections (a 20-ft center section and two dihedral sections), due to fabrication space limitations and transportation difficulties. The wing torsion box for each section was laid up full length in two L-shaped pieces and assembled with epoxy. Mylar tape was used to attach the ribs to the box, and to face the edges of the ribs for skin attachment. The leading and trailing edge caps were made in 4-ft sections and adhered to the ribs. The Mylar skin, in 50-in wide strips,

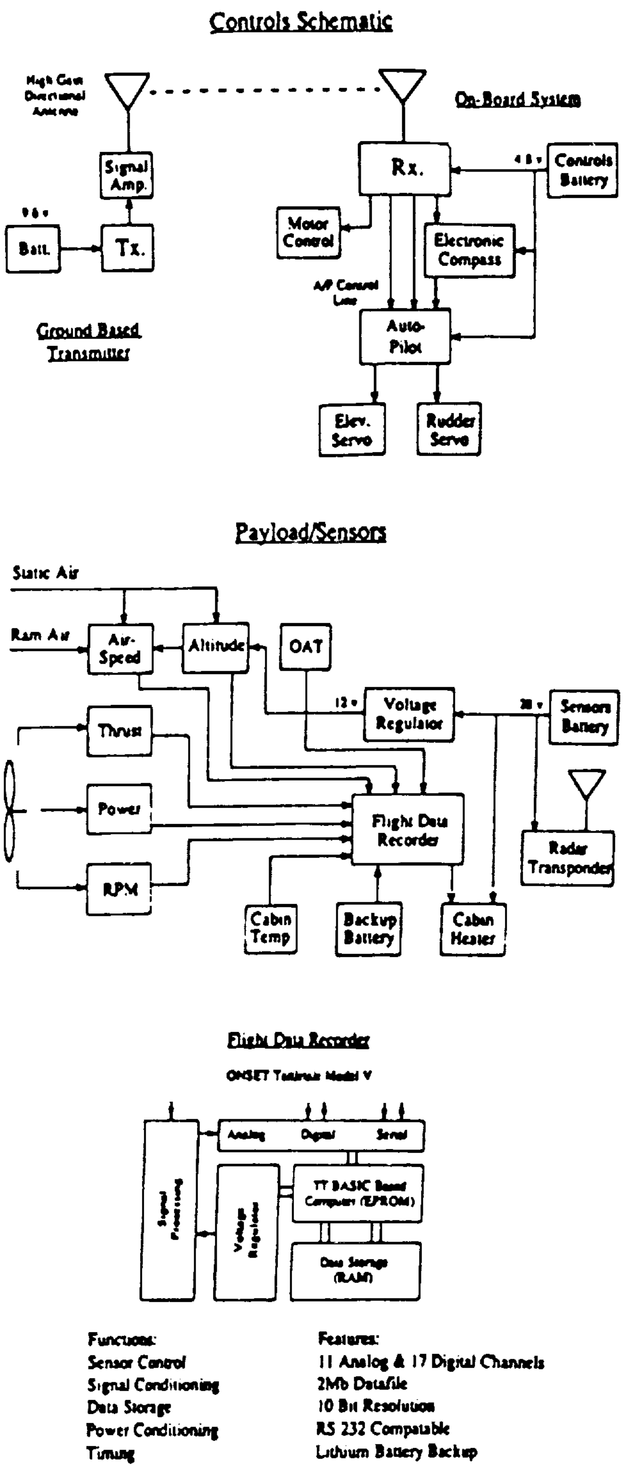


Fig. 6. Avionics schematics.

was adhered chordwise to the wing skeleton and heat shrunk. Connectors were made to join the 6-ft dihedral sections to the center wing section.

The fuselage has a symmetrical cross-section, so the top and bottom halves were made full-length from the same mold. Bulkheads were installed for shape control and for the wing, tail, motor, and payload mounting. The two halves were attached with adhesive tape and epoxy at the seam and around the bulkheads.

Tail assemblies were built similarly to the wing. Aluminum brackets were made to secure the wing and tails to the fuselage and permit disassembly for transport.

CONCLUSION

Through the successful flight of a high-altitude Earth prototype aircraft, CSUN Mechanical Engineering students hope to verify the feasibility of a heavier-than-air craft for the martian atmosphere. Though the prototype is battery-powered, it is reasonable to expect the Marscraft to be solar-powered.

Some of the major design challenges included (1) using low Reynolds number airfoils, (2) electric motor selection and power system development, (3) low Reynolds number propeller design, (4) structural analysis of composite aircraft components, and (5) high-altitude, low-density atmospheric flight performance.

The data collected from various onboard sensors will be used to build a database that can be used to improve the aircraft design for subsequent flights. Next year's Project Ares III will benefit from our experience in aircraft structural design and fabrication, in high-efficiency aerodynamic design (verified by CFD), and in aircraft guidance and control with onboard data acquisition. With this knowledge, future design objectives can include detailed aircraft subsystems such as flaps, slots, landing gear, video cameras, autonomous control systems, and refined aerodynamic and structural designs.

The Ares II design team has responded to a difficult challenge: the design and fabrication of an all-composite, high-attitude, electrically powered aircraft. In the summer of 1991, we will fly this aircraft at an altitude of 104,000 ft. This accomplishment will generate world-wide interest and set CSUN and its students apart for having flown at an altitude never yet achieved by propeller-driven aircraft.

ACKNOWLEDGMENTS

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