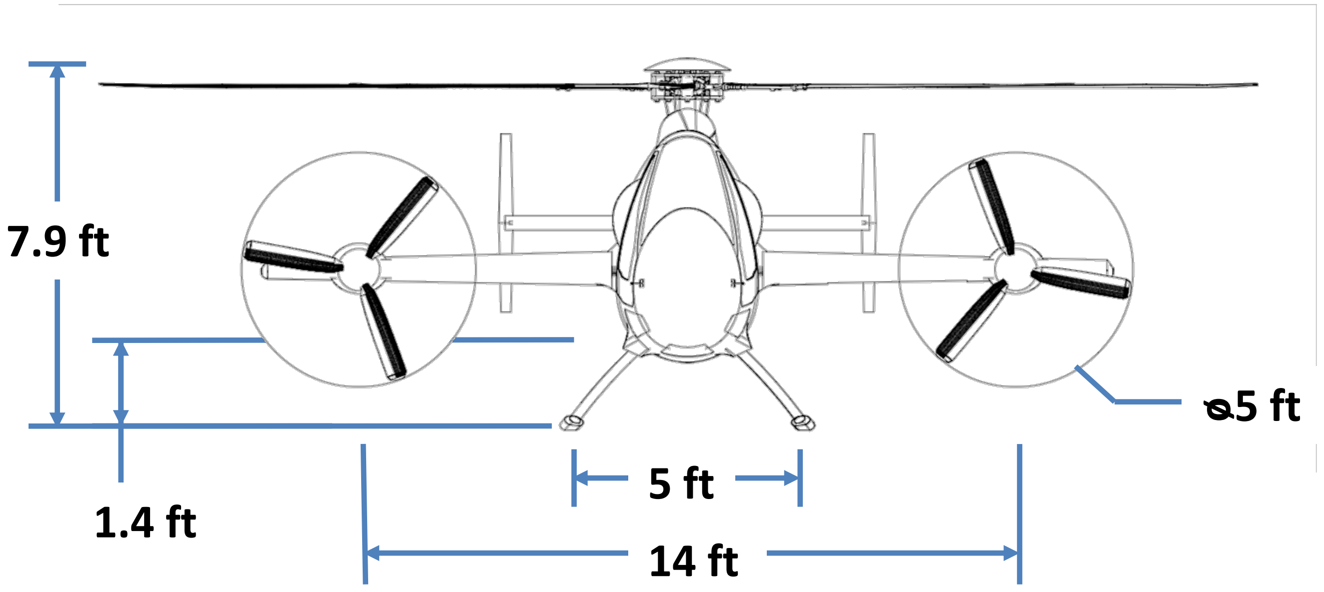
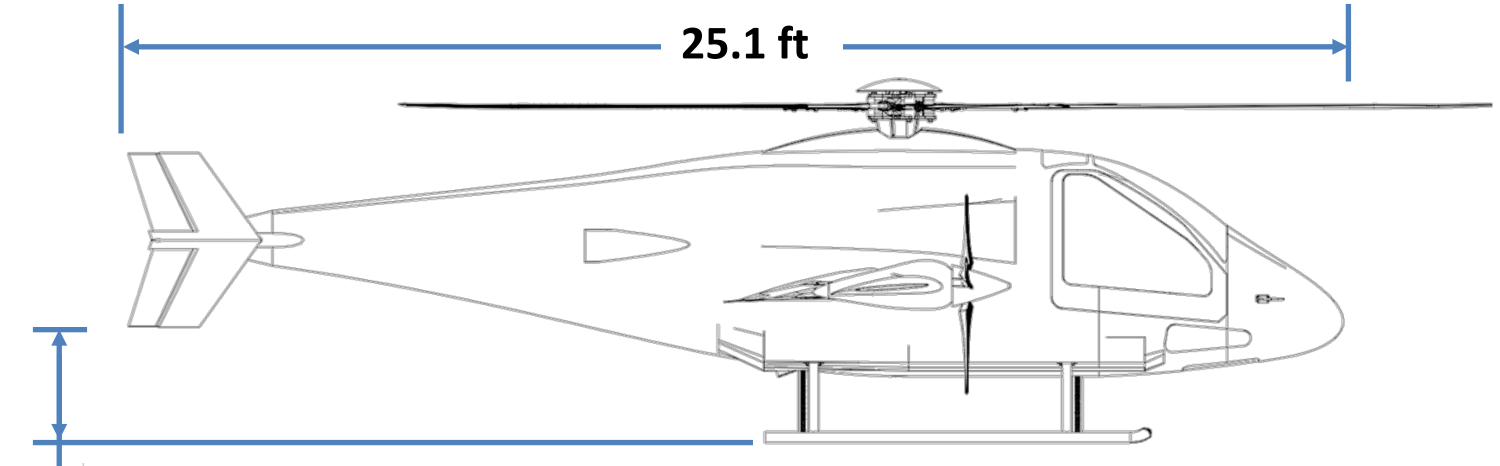
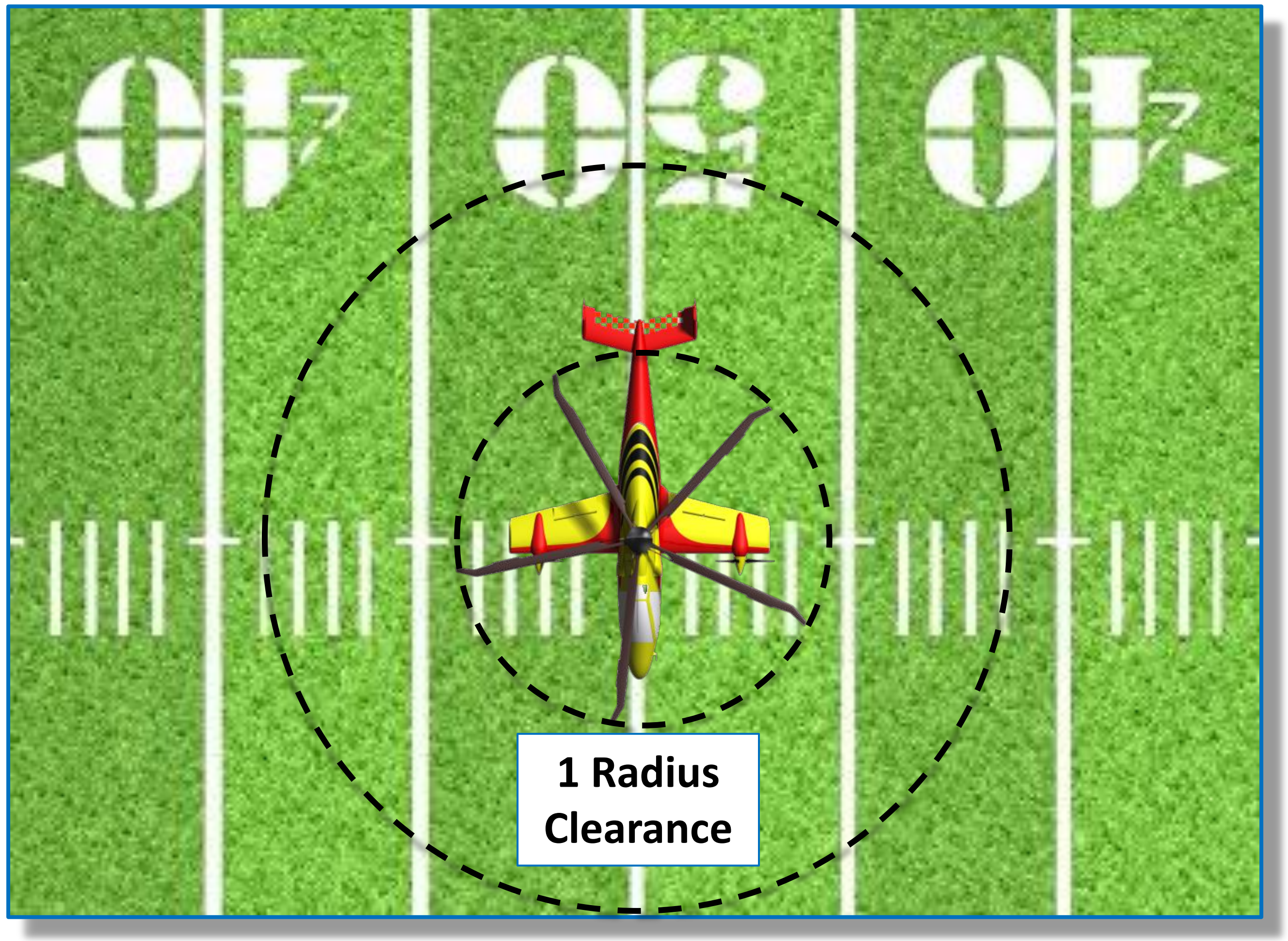
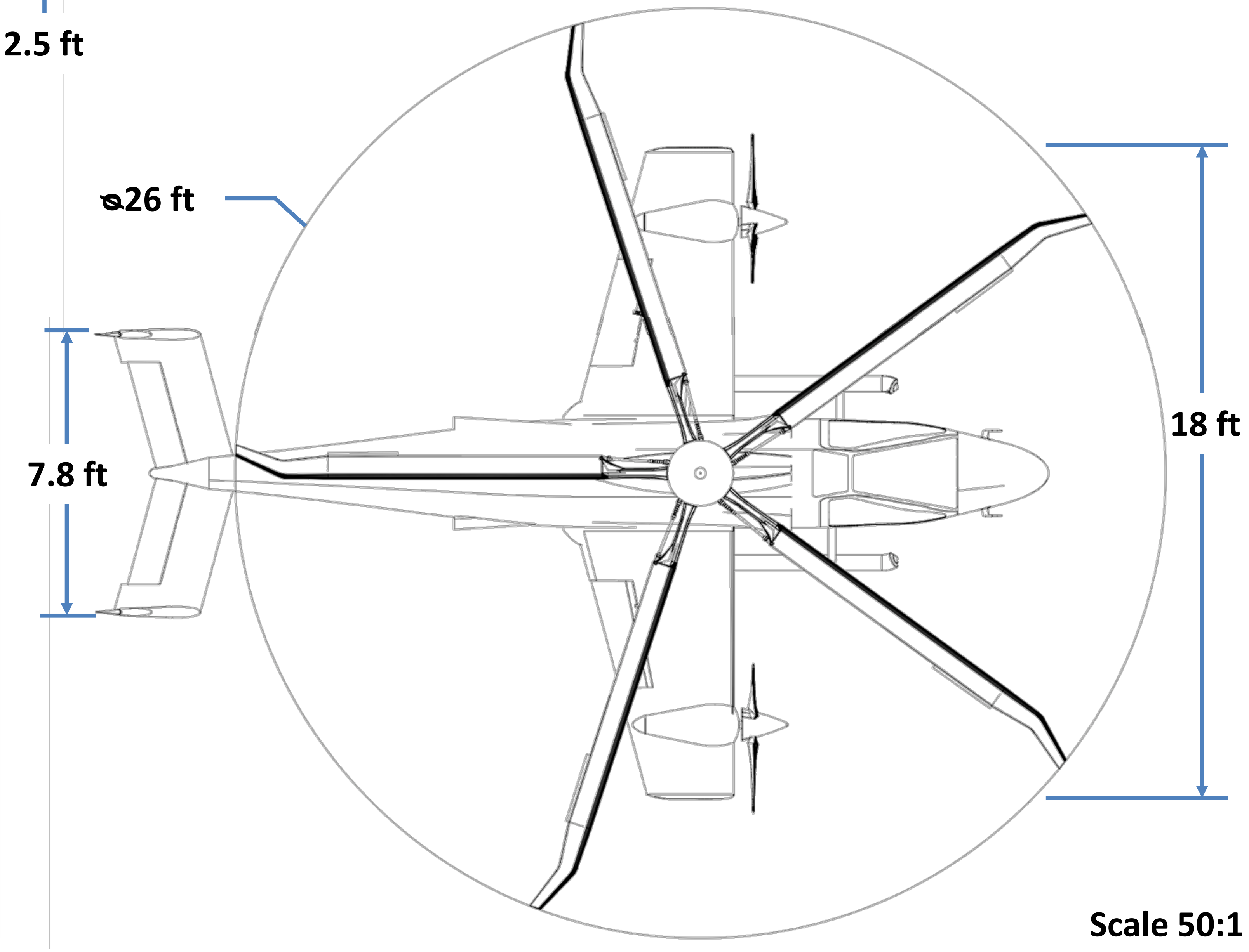
Three View

DART T690









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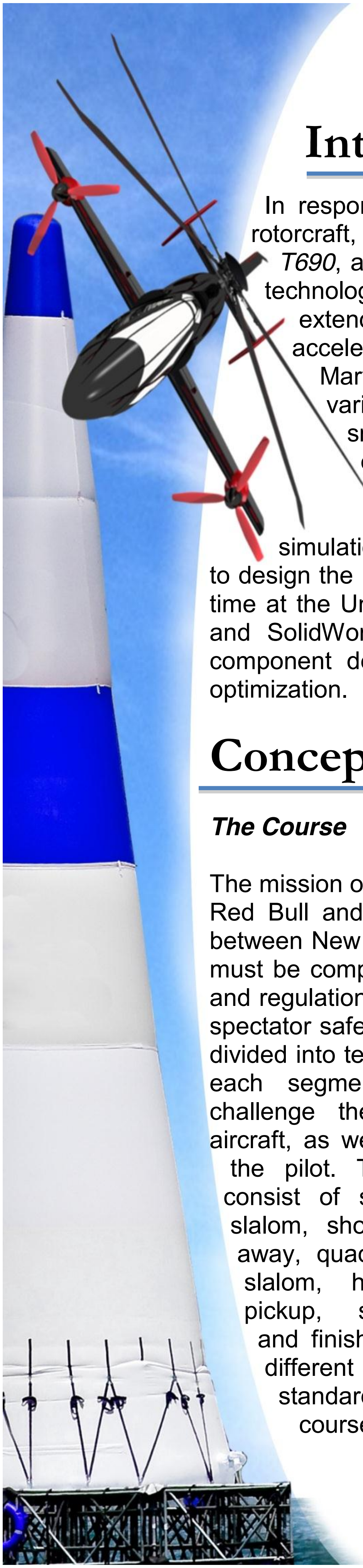


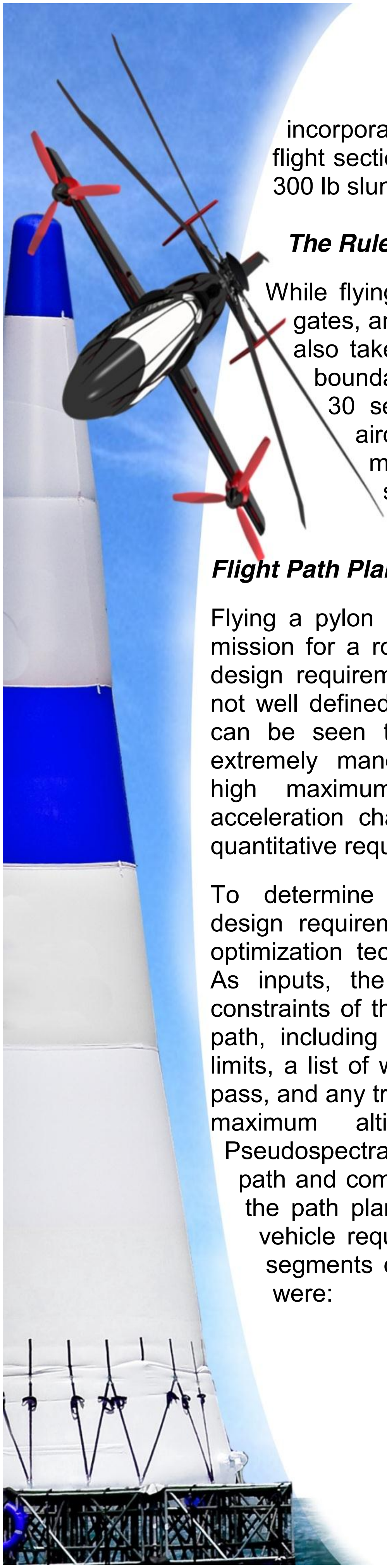
Introduction

In response to the AHS 2012 Request For Proposal for a pylon racing rotorcraft, the University of Maryland graduate design team presents the *Dart T690*, a lift and thrust compounded VTOL rotorcraft. Utilizing advances in technology and innovative design concepts, the *Dart T690* is designed to extend the reach of contemporary rotorcraft in terms of speed, acceleration, maneuver, and load factor capabilities. The University of Maryland graduate team consists of seven students that specialize in a variety of areas such as aerodynamics, dynamics, stability and control, smart structures, computational fluid dynamics, and flight path optimization. Using these skill sets, the team designed the *Dart T690* and its electric counterpart, the *Dart E550,* during one academic semester. The team also developed an X-Plane simulation to complement the design process. The analysis methods used to design the *Dart T690* were developed, validated, and implemented during this time at the University of Maryland. Other computer-aided tools, such as CATIA and SolidWorks, were integrated with the in-house methods and used for component design, concept visualization, structural analysis, and flight path optimization.

Concept Design

The Course

The mission outlined by the RFP is to fly a pylon race course similar to that of the Red Bull and Reno Air Races. The course is located on the Hudson River, between New York City and Weehawken, New Jersey. The course, in this case, must be completed in the fastest time possible in accordance with all the rules and regulations of the Race, while maintaining good fuel efficiency and pilot and spectator safety. The course is divided into ten segments, with each segment designed to challenge the limits of the aircraft, as well as the skill of the pilot. These segments consist of staging, start, a slalom, short stop, straight away, quad pylon, another slalom, hover, pirouette, pickup, sideward flight, and finish. This course is different from the standard air racing courses because it



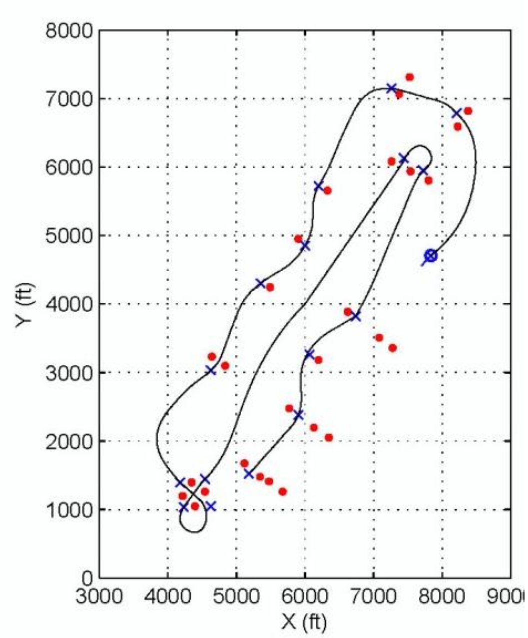
incorporates the use of VTOL capabilities with hover, pirouette, and side-flight sections. In addition, the aircraft must fly the side-flight section with a 300 lb slung load.

The Rules

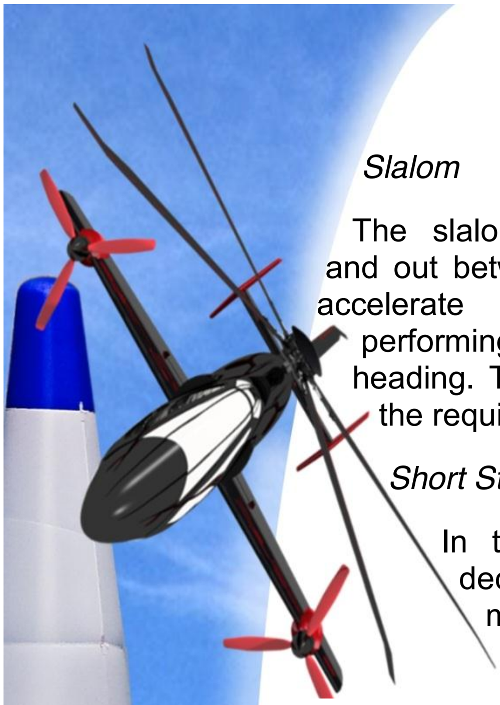
While flying the course, the aircraft must pass cleanly through the pylon gates, any contact results in an immediate disqualification. The pilot must also take care to fly within the safe region of the gates and within the boundaries of the course, with every second of deviation resulting in a 30 second penalty to the final course time. During the flight, the aircraft cannot bank more than 90 degrees. Furthermore, the pilot must maintain full control of the vehicle in the event of any loss of stability augmentation. The airfraft must also have the ability to perform sideward flight at a minimum speed of 60 kts.

Flight Path Planning

Flying a pylon race is an unconventional mission for a rotorcraft and, as such, the design requirements for the aircraft were not well defined. Examining the course, it can be seen that the aircraft must be extremely maneuverable, agile, have a high maximum speed, and superior acceleration characteristics. However, no quantitative requirements are obvious.



To determine the quantitative aircraft design requirements, a novel flight path optimization technique was implemented. As inputs, the path planner takes the constraints of the vehicle and its intended path, including vehicle dynamics, control limits, a list of waypoints the vehicle must pass, and any trajectory limitations such as maximum altitude, etc. A Radau Pseudospectral Optimizer was then implemented to determine the optimal flight path and completion time for a given set of vehicle parameters. By executing the path planning optimizer for a range of realistic vehicle parameters, the vehicle requirements that minimize the course time were determined. The segments of the course that were found to dictate the design parameters were:

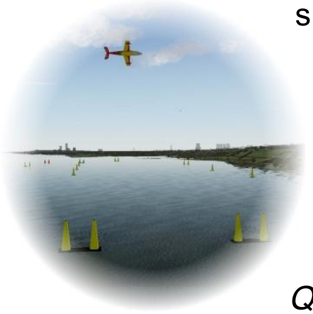


Slalom

The slalom requires the pilot to weave in and out between three pylons. The aircraft can accelerate throughout the maneuver while performing banked turns to achieve a desired heading. This segment of the course dictates the required roll rate of the aircraft.

Short Stop

In this segment of the course, the pilot immediately decelerates coming out of the slalom and performs a hammer head maneuver to pass through both pylon gates within the boundaries of the course. The optimization showed that to perform this maneuver, the aircraft requires high pitch and yaw rates. The short stop also provided one of the critical design points for the aircraft. As the pilot enters the first gate, the aircraft must pitch up rapidly at a speed of 110 kts. This requires the aircraft to pull a maneuver with a 5g normal load factor at a relatively low speed, setting structural, sizing, and aerodynamic constraints for the aircraft.



Quad Pylon

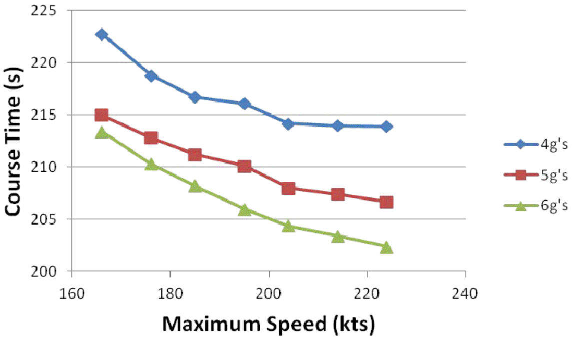
For the quad pylon, the aircraft flies through two sets of adjacent gates and must then perform a maneuver that positions it to fly back through the gates perpendicular to its previous flight path. In the Red Bull Air Race, this maneuver is generally a tight, banked turn. However, the flight path optimization showed that for this course, another hammer head like maneuver, similar to the short stop is the fastest way to pass through both sets of gates.

The final consideration for the design of the *Dart* is the load factor requirements. In the Red Bull and Reno Air Races, pilots typically pull up to a 9g normal load factor. This is an unheard of requirement for rotorcraft, and as such, the flight path optimization was constrained over a range of upper limit vertical load factors and the total course times were calculated. The results of the optimization showed that after a load factor higher than 5g, there were diminishing returns in the overall course time and so a 5g normal load factor was chosen for the *Dart*.

Flight Path Optimization Results

The results from the flight path optimization provide the design requirements for the aircraft. Ultimately, a pylon racer capable of flying the course outline in the RFP must have four capabilities:

- ✓ **Maneuverability** (High load factor)
- ✓ **Agility** (High turning rates)
- ✓ **Dash** (High forward acceleration)
- ✓ **Speed** (High forward speed)

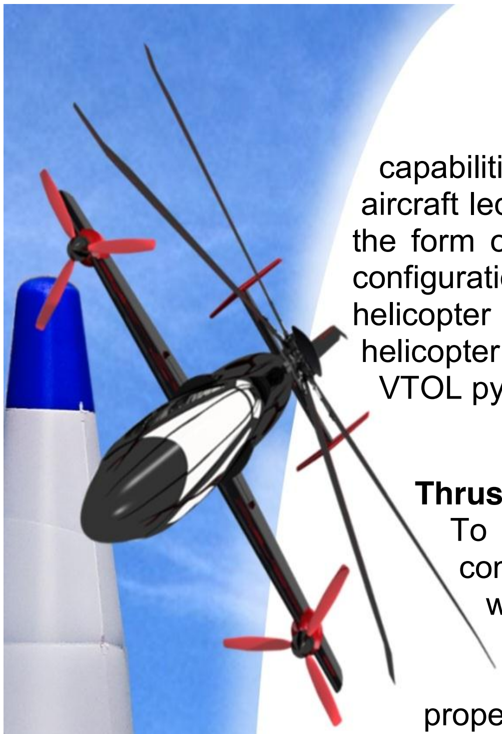


These four qualities dictate what type of rotorcraft needs to be designed to successfully complete the race course. In this regard, insight can be drawn from the automotive world. An SUV or truck is comparable to a cargo helicopter as it must carry a certain amount of payload with reasonable endurance and range. A drag racer is designed to accelerate quickly and drive at high speeds with the ability to turn rapidly, much like an X^2 type design. The *Dart* is most like a rally racing car, which is designed to drive fast while maintaining good acceleration, deceleration, and agility characteristics.

Every design decision for the proposed aircraft, from the configuration selection down to the type of landing gear, was made with a focus on maneuverability, agility, dash, and speed. The resultant design is the *Dart*, a VTOL rotorcraft specifically optimized for pylon racing.

Configuration

The opportunity to design a rotorcraft meant purely for the sport of pylon racing is an unconventional challenge since the required vehicle configuration is not an obvious choice. The configurations studied included: single main rotor (conventional helicopter), coaxial rotor system, tiltduct, tiltrotor, quadrotor, fan-in-wing, compound, tip-jet driven autogiro, and tailsitter. To objectively compare the large number of configurations being considered, a process that rigorously quantified competing design objectives based on an Analytical Hierarchical Process (AHP) was used to rank the critical design requirements. The extreme



capabilities (speed, dash, agility and maneuverability) required of this aircraft led to the selection of a thrust and lift compounded configuration in the form of a dual thruster design. Furthermore, the resulting compound configuration of the *Dart T690* is an elegant fusion of fixed-wing and helicopter design. The flight characteristics of both fixed wing and helicopter designs complement one another to create a truly optimized VTOL pylon racer.

Thrust Compounding

To achieve the higher speeds required of the *Dart*, thrust compounding was a necessary addition to the design. In a design where wings can be used, the placement of the propellers is logical and the alignment between the engine, gearboxes, propellers and rotor is relatively straightforward. Because the propeller diameter is limited by ground clearance issues for this specific aircraft, having two propellers significantly augments the speed and acceleration capabilities of the *Dart T690*. This assessment was also tested and validated in the X-Plane simulations.

Lift Compounding

The addition of wings for lift augmentation has two major benefits; they can carry a significant fraction of the 5g load factor and can also off-load the rotor in other flight conditions; the wings on the *Dart T690* were designed to carry 1.5g of the 5g maneuver at 100 kts. Furthermore, in forward flight, wings are more efficient lifting surfaces than rotors. By off-loading the lift on the rotor, additional power is available to drive the propellers, achieving higher accelerations and a faster maximum airspeed. The wings provides augmented maneuverability and ailerons on the wing add agility to the aircraft.

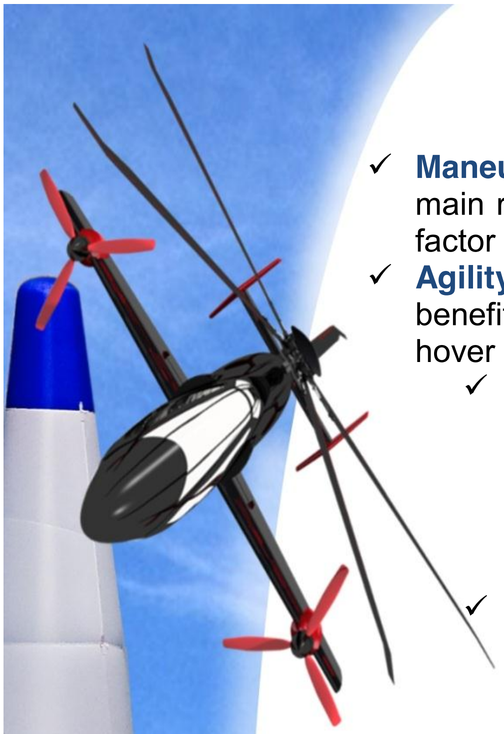
Load Sharing

The team performed a trade study to determine the optimum load sharing between the rotor and the wings. If all 5g are loaded on the rotor, it becomes very heavy. Likewise, if all 5g are loaded on the wings, the wings become extremely large, raising structural, weight, and download concerns. The load sharing was optimized by minimizing vehicle weight, while also maintaining realistic overall dimensions and a low installed power. The optimal solution was loading 3.5g on the rotor and 1.5g on the wing. The resultant sizing and performance characteristics are given on the left.

No. of Blades	5
Rotor Diameter (ft)	26
Rotor Disk Loading (lb/ft^2)	4.33

Load factor, maneuver (total)	5
Load factor, maneuver (rotor)	3.5
Airspeed during critical maneuver (kts)	110

Wing Aspect Ratio	5
Wing span (ft)	17.93
Wing download (% GTOW)	14.5%



- ✓ **Maneuverability:** The wings carry a load factor of 1.5g allowing the main rotor to be designed to carry 3.5g for an unprecedented 5g load factor capability for the vehicle.
- ✓ **Agility:** The ailerons on the wings augment the roll rate of the vehicle, benefiting its performance in the slaloms and in the turn before the hover point.
- ✓ **Dash:** The wings provide a more aerodynamically efficient means to produce lift, off-loading the rotor and consequently providing additional power for the propeller to be used in acceleration. Having two propellers provides added thrust that can be used to accelerate the vehicle across its entire flight regime
- ✓ **Speed:** The propellers provide the extra thrust required to reach airspeeds above 200 kts in forward flight.

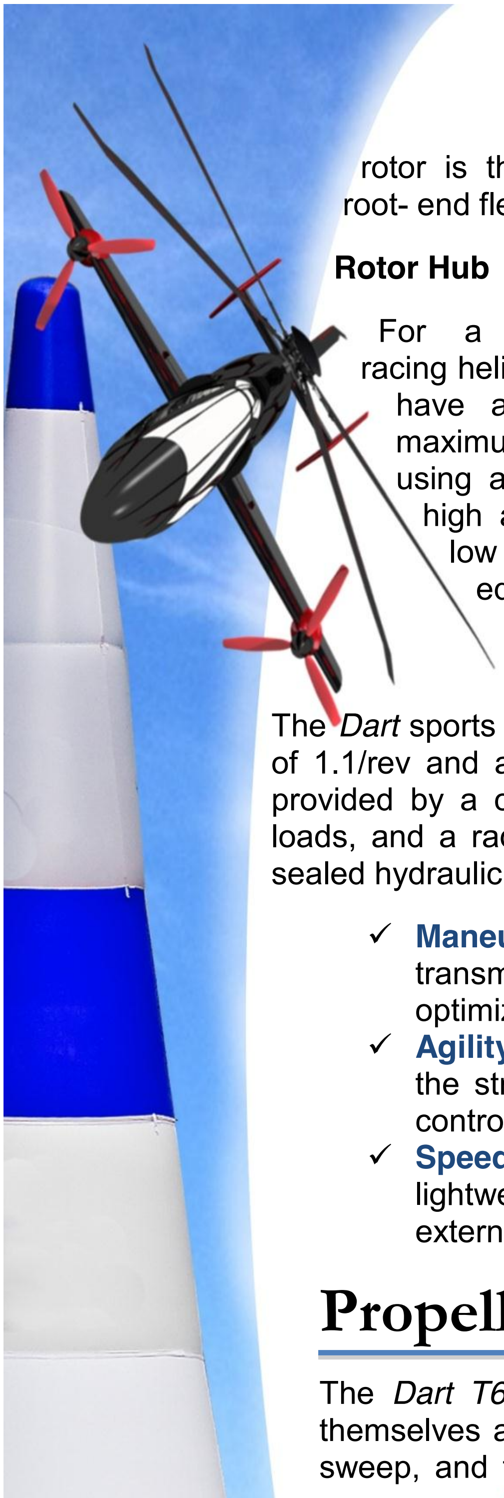
Main Rotor and Hub

Rotor Blades

The *Dart T690/E550* is a highly agile vehicle that demands rapid control response and up to 3.5g of normal load factor from the rotor alone. The rotor system has a high hinge offset of 11% of the rotor radius to transform the large lifting capability of the rotor into the agility required to complete the course quickly. The blades are designed to handle this high load and challenging fatigue environment. A hingeless rotor is used that meets these structural and maneuverability concerns, while maintaining a clean aerodynamic profile and a compact hub.

The unique aerodynamic design of these rotor blades allows the vehicle to reach a high maximum speed of 220 kts while maintaining good aerodynamic efficiency. The blade tips incorporated sweep and taper, with both being optimized such that the vehicle can perform a sustained 5g maneuver. This capability allows the *Dart T690* to not only complete the course outlined in the RFP in record time, but also makes it a compelling option for other racing competitions.

The main rotor blades use composite materials for their high specific stiffness, excellent fatigue characteristics, and ability to manufacture complex shapes with relative ease. Detailed attention is given to the load paths along the blade that sustain the high loads. The primary structural backbone of the rotor is the D-spar of the lifting surface that connects to the primary root- end flexure structure, and the yoke.



Rotor Hub

For a highly maneuverable racing helicopter, it is important to have a hub that allows for maximum control authority using a high hinge offset and high airspeed by striving for low drag area. The *Dart* is equipped with a compact hingeless rotor hub to meet these requirements.

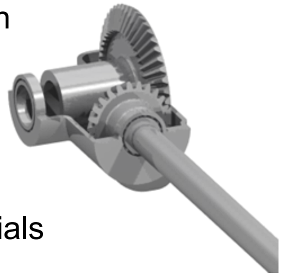
The *Dart* sports a five bladed, soft-in plane hingeless rotor with a flap frequency of 1.1/rev and a lag frequency of 0.6/rev. The torsional degree of freedom is provided by a conical elastomeric bearing, which takes centrifugal and radial loads, and a radial sealed self-lubricating needle bearing. A maintenance free sealed hydraulic lag damper is included for aeromechanical stability

- ✓ **Maneuverability:** The rotor blades are structurally designed to transmit loads efficiently to the hub. The blade tip is aerodynamically optimized such that the rotor can pull a sustained 3.5g load factor.
- ✓ **Agility:** A large hinge offset, 11% of the rotor blade, is designed into the structure of the blade to allow the lift of the rotor to translate to control authority.
- ✓ **Speed and Dash:** The innovative compact hingeless rotor hub is lightweight and presents a low small flat frontal area with minimal external linkages, greatly reducing the overall drag of the vehicle.

Propeller Design

The *Dart T690* sports two 3-bladed, 5 ft diameter propellers. The blades themselves are aerodynamically optimized in terms of twist, taper, planform, sweep, and tip speed to achieve maximum translational accelerations over the entire flight envelope. The 5 ft diameter of the propellers also ensures that the landing gear can remain a modest size, while also maintaining good propulsive efficiency and high accelerations. At lower airspeeds, the propellers provide the anti-torque to counter the reaction moment produced by the main rotor. To produce this anti-torque, as well as yaw control, the propellers have

independently variable pitch. In forward flight, when the vertical stabilizer can provide most of the anti-torque, the propellers are used to provide propulsion.



The propellers are designed to be as light as possible while maintaining sufficient stiffness. To minimize weight, the blades are made out of composite materials wrapped around a Rohacell foam core.

The propeller hub is a controllable pitch design with a faired spinner to minimize drag. An electro-hydrostatic actuator controls the pitch of the propeller through a slider in the propeller hub. This mechanism gives the pilot direct control of the propeller thrust, while the rpm of the entire system is maintained by the FADEC.

- ✓ **Agility and Maneuverability:** The controllable pitch propeller design allows the *Dart T690* to have excellent yaw control at low airspeeds, an important capability to meet the pirouette and sideward flight requirements.
- ✓ **Speed and Dash:** The aerodynamic design of the propeller blades is tailored to produce high maximum thrust over the flight envelope of the *Dart T690*.

Turbine Engine and Drivetrain

The dual thruster configuration of the *Dart T690* provides the opportunity to implement an elegant approach to distribute power from the main engine to the rotor and the propellers. The engine shaft connects directly to a nose gear box that transfers the power to a main gear box, which then serves to split the power amongst the main rotor and two propellers.

The main gearbox contains a 2-stage transmission including a spiral bevel collecting and distribution stage, as well as a planetary stage that performs the rpm reduction for the main rotor. 6,000 rpm composite supercritical shafts connect to propeller gearboxes. The propeller gearboxes provide a 15:8 gear reduction and a 90° turn from the 6,000 rpm propeller driveshafts to the 3,200 rpm required at the propellers.

- ✓ **Speed and Dash:** The “rubber” engine provided by the RFP has forgiving off-design characteristics allowing the engine to directly govern the main rotor and propellers. The low

mechanical complexity of the transmission allows the rotor to be slowed for the vehicle to achieve high forward flight speeds.

✓ **Maneuverability:** The main rotor shaft is designed to meet dynamic axial and radial shearing loads. The 11% hinge offset of the blades contributes a significant mast moment. The shaft is sized (with a margin of safety) for the maximum 5g pull-up load factor.

The *Dart E550* Electric Option

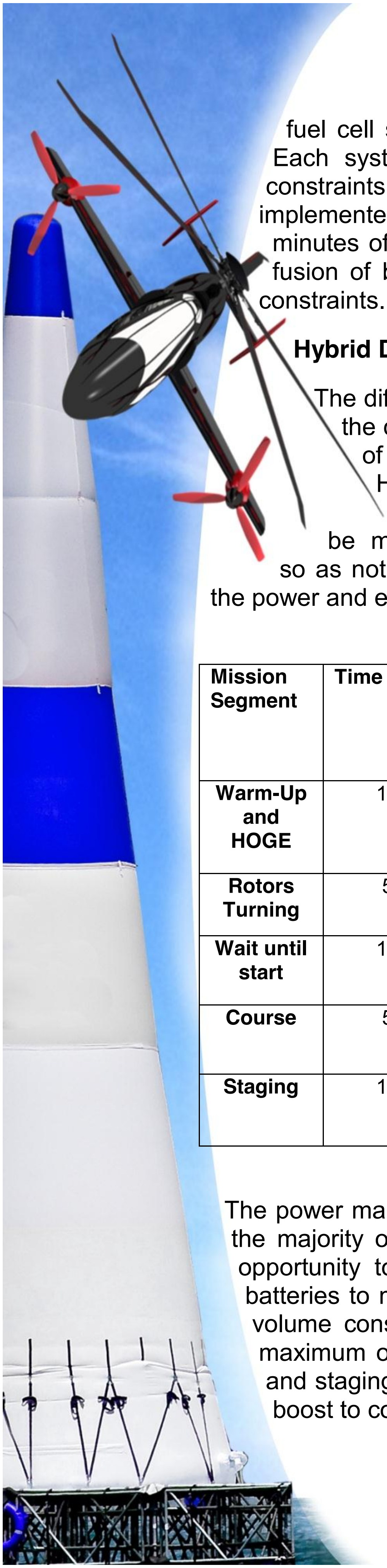
In compliance with the RFP request for an alternative propulsion system for the aircraft, the *Dart E550* option was designed. This option provides an innovative alternative power source that meets and exceeds all flight requirements. The *Dart E550* takes advantages of the recent advances in battery and fuel cell technology to create a fully electric hybrid propulsion system with no penalty in the course time, while remaining environmentally friendly. The *Dart* E550 propulsion system consists of a 250 hp PEM fuel cell and state-of-the-art Lithium-ion batteries. The electric power plant powers three Halbach array motors to drive the main rotor and propellers. The *Dart E550* option was designed specifically to minimize differences with the *Dart 690*. The similarities between the two options result in lower aircraft manufacturing and maintenance costs.

System Selection

Three different propulsion systems were considered before deciding on the fully electric battery-fuel cell hybrid: piston powered, gas electric hybrid, and fully electric. The first two systems were found to be heavier than the fully-electric system. While the fully electric system can also be heavy, it has the advantage of being environmentally friendly. Furthermore the weight issue can be overcome because the electric motors that power the main rotor and propellers have high specific powers, and can be placed directly at the rotor and propellers, eliminating the need for heavy transmissions and shafting.

Why a Hybrid?

A fully electric vehicle can be run on batteries, fuel cells, or a combination of both (i.e., a hybrid). The *Dart E550* uses a fully electric hybrid power plant because it minimizes the weight and volume of the overall propulsion system. Removing the propulsion system from the *Dart T690* leaves 850 lb of replaceable weight and 12 ft^3 of replaceable volume. A pure battery system would weigh 3,000 lb and require a volume of 24.6 ft^3, while a pure



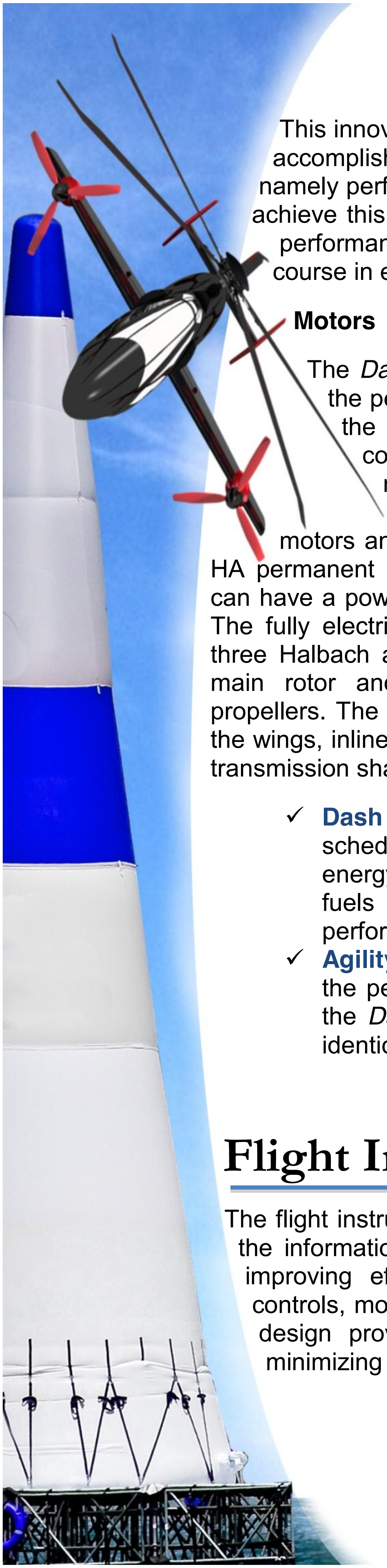
fuel cell system would weight 730 lbs and require a volume of 16.3 ft^3. Each system individually exceeds the allowable weight and/or volume constraints of the aircraft. Even if a purely fuel cell system were implemented in the aircraft, there would be no fuel available to meet all 35 minutes of required flight time. Therefore, for the *Dart E550*, an optimized fusion of batteries and fuel cells is used to fit in the weight and volume constraints.

Hybrid Design

The difficulty in designing a fully electric vehicle is not in just completing the course, but in performing the overall mission, which is 35 minutes of total flight time, an unprecedented time for a fully electric aircraft. However, by parsing out the power schedule in all sections of the mission, the power supplied by the hybrid propulsion system can be managed to keep the weight and volume of the system low so as not to incur any loss in performance. The table below summarizes the power and energy distribution required by the *Dart E550*.

Mission Segment	Time (min)	Max Power Req.(kW)	Energy Required (kWh)	Required Specific Power (kW/kg)	Required Specific Energy (kWh/kg)
Warm-Up and HOGE	10	37.3 (50 hp)	6.2 (8.3 hp-h)	0.097 (0.06 hp/lb)	0.016 (0.010 hp-h/lb)
Rotors Turning	5	97.7 (131 hp)	8.1 (10.9 hp-h)	0.25 (0.15 hp/lb)	0.021 (0.013 hp-h/lb)
Wait until start	10	186.4 (250 hp)	31.1 (41.7 hp-h)	0.48 (0.29 hp/lb)	0.080 (0.049 hp-h/lb)
Course	5	410.1 (550 hp)	34.2 (45.8 hp-h)	1.1 (0.65 hp/lb)	0.088 (0.054 hp-h/lb)
Staging	15	72.3 (97 hp)	18.1 (24.3 hp-h)	0.19 (0.11 hp/lb)	0.047 (0.029 hp-h/lb)

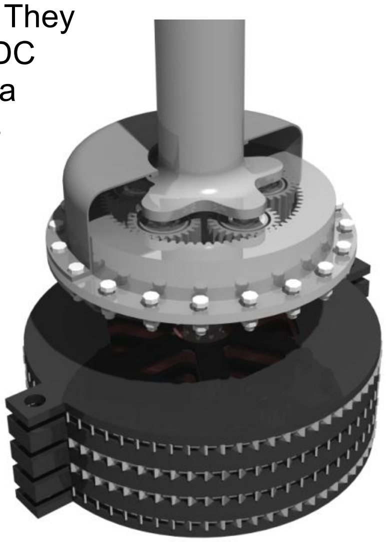
The power management shows that the power required is less than 250 hp for the majority of the flight. This relatively low power requirement presents the opportunity to implement a power sharing between the fuel cells and the batteries to minimize the weight of the total system, while keeping within the volume constraint. In the *Dart E550*, the fuel cells are sized to provide a maximum of 250 hp to complete the warm-up, rotors turning, wait till start, and staging portions of the mission. Li-ion batteries provide a 300 hp power boost to complete the race course in the required time.



This innovative power distribution and sharing utilized in the *Dart E550* has accomplished what no other helicopter has been able to achieve so far, namely perform a 35 minute, fully electric flight. Not only does the *Dart E550* achieve this goal, but it surpasses expectations by showing *no loss* in flight performance; the fully electric option of the vehicle can complete the course in exactly the same time as the *Dart T690*.

Motors

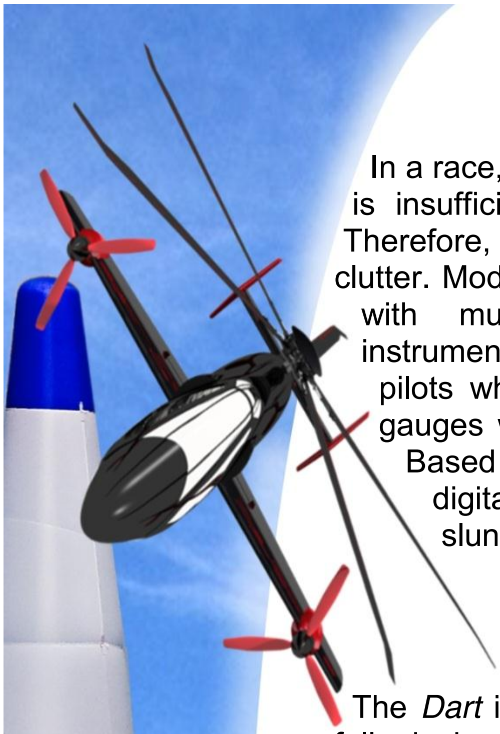
The *Dart E550* boasts a number of cutting-edge technologies to match the performance of its turbine counterpart. One of these innovations is the use of Halbach Array (HA) motors. HA motors have components similar to DC and AC motors, but have the benefit of running off of either AC or DC. They have all the benefits of brushless DC motors and are lighter from the inclusion of a HA permanent magnet section. These HA motors can have a power-to-weight ratio of up to 5 hp/lb. The fully electric option of the aircraft includes three Halbach array motor stacks, one for the main rotor and two smaller ones for the propellers. The propeller motors are located in the wings, inline with the propellers, eliminating transmission shaft weight.

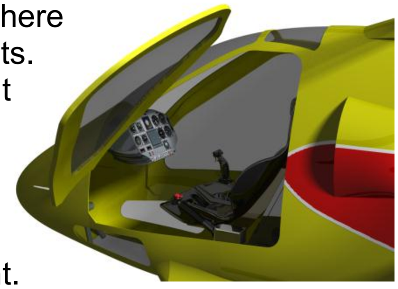


- ✓ **Dash and High Speed:** The power scheduling is used to maximize the energy stored in the batteries and fuels cells such that there is no performance loss with the electric option.
- ✓ **Agility and Maneuverability:** The system was designed to have all the performance characteristics and fit in the exact same airframe as the *Dart T690*. Consequently, all the control surfaces and forces are identical, maintaining all of the agility and maneuverability capabilities.

Flight Instrumentation

The flight instrumentation in the *Dart* is designed to provide the pilot with all of the information necessary to fly the helicopter while reducing workload and improving efficiency. The *Dart* accomplishes this by using digital flight controls, modern sensors, and a minimalist approach to cockpit design. This design provides the pilot with the largest possible line of sight while minimizing weight, cost, and maintenance time.





In a race, the pilot's focus is on the course and there is insufficient time to focus on the instruments. Therefore, it is important to minimize cockpit clutter. Models of the *Dart* were flown in X-Plane with multifunction displays and analog instruments. The team members and trained pilots who flew the model found that analog gauges were much easier to read during flight. Based on this information, an analog based cockpit was used with one digital flight display that incorporates a camera that focuses of the slung load and a Caution-and- Advisory display.

Control Mixing

The *Dart* is a unique rotorcraft, and the Flight Control System (FCS) was carefully designed to match the environment flown by the aircraft. The advanced flight control architecture of the *Dart T690* allows for an innovative flight control arrangement. Traditional cyclic/collective/pedal are used to control the rotors, propellers, ailerons, elevator, and rudder in all flight regimes from hover through transition to forward flight and in all maneuvers.

Fly-by-Wire

This architecture is implemented by use of a fly-by-wire system. These systems have been shown to be extremely flight worthy and safe, and give a number of distinct advantages over mechanical systems:

- Sophisticated control laws can be incorporated into the aircraft.

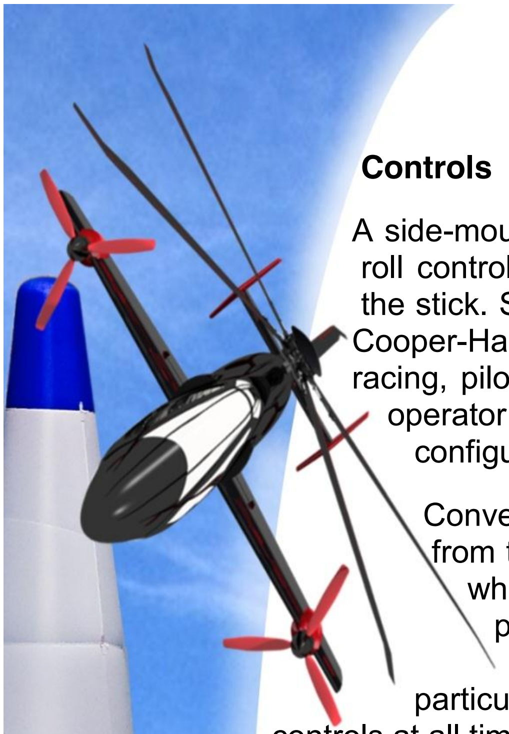
- Reduced weight: no mechanical push-pull rods, linkages, or heavy hydraulic circuits; these are all replaced by electrical wires

- A power-by-wire system is used to power the electro-hydrostatic actuators. This reduces weight and is inherently compatible with the *Dart E550*

  - Greater control accuracy: no mechanical control linkages that can wear and correspondingly reduce the accuracy and responsiveness of the system.

  - Triple redundancy: wires that carry control signals are routed along different paths throughout the fuselage for increased safety.

  - Improved ability to detect and correct system failures.



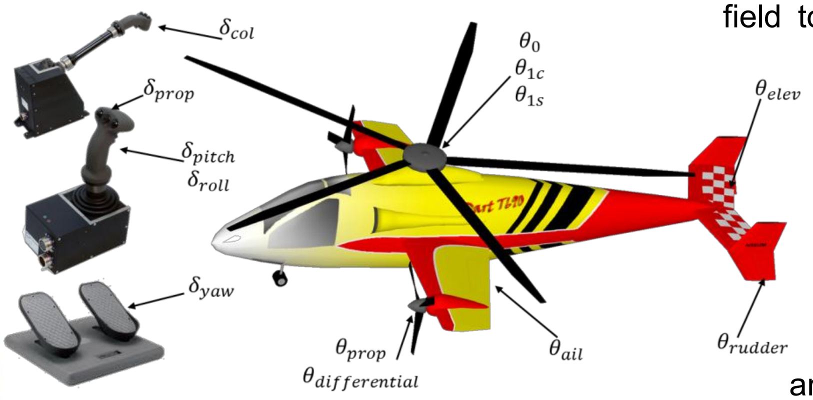
Controls

A side-mounted control stick is incorporated for two-axis control. Pitch and roll control is obtained by using longitudinal and lateral displacements of the stick. Small displacement side-sticks have been shown to give Level-1 Cooper-Harper handling qualities. Given the higher risk environment of racing, pilot safety is critical, therefore the side-mounted control improves operator comfort, further increasing pilot safety and performance. This configuration also improves the ease of ingress and egress.

Conventional foot pedals are used to modulate the anti-torque thrust from the propellers. Located to the left of the pilot is a collective stick, which controls main rotor pitch. Two helicopter pilots tested many propeller flight control options in X-Plane, and the preferred solution was two buttons placed on the cyclic stick. This particular configuration allowed the pilot to keep his/her hands on the controls at all times, and to change the propeller pitch with one finger.

Control Mixing

The control mixing implemented on the Dart *T690* reduces pilot workload by coupling multiple flight control inputs that are inherently linked aerodynamically. Mixing flight controls electronically allows the control inputs to be modified in the field to reflect changing flight environments, and also provides a more robust overall control system. This arrangement will reduce life cycle costs and increase reliability. To improve vehicle performance, reduce pilot workload, and also increase pilot effectiveness, some control inputs are mixed and scheduled as a function of flight speed, namely:



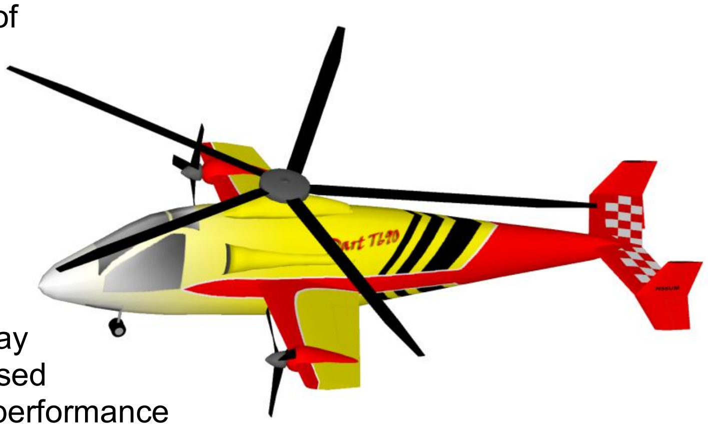
- Propeller Pitch: Propeller pitch angles are scheduled so as to never exceed the thrust limit. When the pilot commands the “max” propeller pitch at a given airspeed, the propeller operates at the optimum pitch for that particular airspeed. The goal of this pitch scheduling is to prevent the pilot from ever stalling the propeller or otherwise imposing adverse loads on the propeller during a maneuver.
- Yaw Control: To achieve maximum forward acceleration, and also maintain yaw control of the aircraft, a rudder was added to the vertical fins. It is important to minimize the use of differential propeller blade pitch for yaw control at high airspeed, so that the propellers can be used just to provide thrust. However, testing in X-Plane, as well as performing a

helicopter trim analysis, showed that it would not be efficient to completely eliminate differential pitch from the control scheme at high airspeeds. Instead, rudder control is phased into the control system starting at 50 kts until 70 kts, when it is fully effective

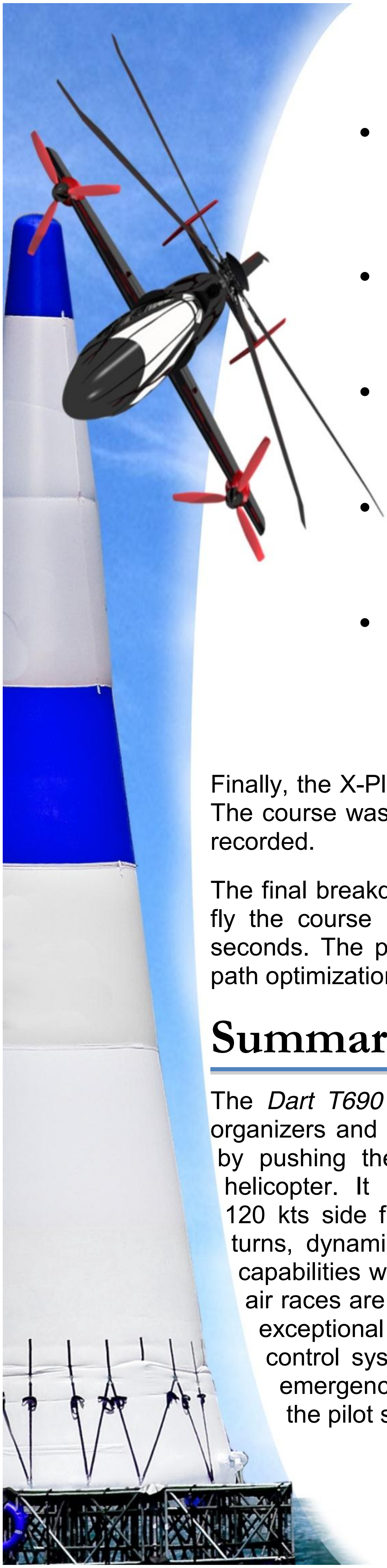
- Pitch and Roll Control: To improve agility and maneuverability at high airspeeds, the elevator is scheduled to phase into the control system at a airspeed of 50 kts and become fully active by 70 kts. The elevator acts in conjunction with the longitudinal cyclic inputs to control the aircraft pitch. Following this same philosophy, the ailerons phase into the roll control system at 50 kts and become fully effective at 70 kts. By adding aileron and elevators to the vehicle control system, maneuverability in forward flight can be increased dramatically.
    - ✓ **Agility and Maneuverability:** The controls mixing scheme has been set to optimize the control of the aircraft for over the entire flight envelope. The control mixing maximizes the effectiveness of the control surfaces and provides a rapid response to control inputs.
    - ✓ **Speed and Dash:** To maximize both forward speed and acceleration capability, the controls in the *Dart T690* are scheduled such that the propellers provide pure thrust at higher airspeeds.

X-Plane Simulation

The team designed an X-Plane model of the *Dart T690* and ran a simulation of the course in the X-Plane software. The aircraft model is 100% true to the engineering specifications of the *Dart T690*. The simulation was a requirement in the RFP, however, the design team also took the opportunity to use the X-Plane simulation as a design aid.



The simulator provides a way to quickly model proposed designs and then test the performance with different design choices. Another significant benefit of X-Plane is that all of the aircraft states are output in real-time so that performance metrics such as power, wing lift, rotor thrust, drag, etc., can be compared to the calculated engineering data. The simulations were used within the design loop as a form of "flight testing," and helped to validate the design decisions that were being made. This design methodology proved to be a significant benefit and significantly influenced many design decisions, including:



- Configuration Selection: Multiple configurations were tested, including the coax+pusher and dual thruster. The dual thruster had better forward acceleration and roll moment characteristics, and so the simulation confirmed the engineering analysis that had arrived at the same conclusion.
- Roll Moment Analysis: The simulation identified an inherent rolling moment caused by the addition of the pusher propellers. This effect turned out to have a significant affect on the vehicle design.
- Control surfaces: The simulation found that standard cyclic controls did not provide the agility for the vehicle to complete the course, making conventional airplane control surfaces a necessary addition.
- Control Strategy: The control mixing was not an obvious choice until the X-Plane simulation was performed. The initial control mixing options were tested on X-Plane before being used in the engineering analysis.
- Cockpit Design: The *Dart T690* was originally envisaged as an all-glass cockpit. However, after multiple simulations it was decided that analogue gauges were much better because they are much easier to see and made switching from instruments to outside the cockpit relatively benign.

Finally, the X-Plane simulation provided the validation of the flight path planning. The course was flown multiple times, with the flight data output in real-time and recorded.

The final breakdown of the course is given above. The student pilot was able to fly the course in 222 seconds, which is close to the predicted time of 219 seconds. The pilot followed all the maneuver recommendations from the flight path optimization to achieve this time.

Summary

The *Dart T690* is designed to satisfy two distinct customer groups, the race organizers and racers themselves. The *Dart T690* satisfies the race organizers by pushing the boundaries of maneuverability beyond any yet seen by a helicopter. It is capable of performing 225 kts maximum forward speed, 120 kts side flight speed, sustained 5g load factor pull-ups and coordinated turns, dynamic yaw maneuvers, and could even hover at 27,000 ft. These capabilities will excite audiences and make helicopter races as popular as the air races are today. The *Dart T690* achieves this at a high level of safety with exceptional autorotative performance, a triple redundant power-by-wire flight control system, advanced HUMS monitored by a dedicated ground crew, emergency floats for a water landing, and an airframe designed to allow the pilot so survive crashes, all for a price of $1.6 million per unit.

Using the flight path optimization along with the X-plane simulation, it was determined that the fastest flight time of the *Dart* is **183 seconds**. With the flight time and an installed power of 740 lb, it was determined that the fuel consumption during the course is 19.6 lb. Using the efficiency metric provided:

$$\eta = 2 * CourseTime(\mathrm{sec}) + 5 * \mathrm{Fuel(lb)} + \mathrm{MRP}_{\mathrm{S.L./ISA.,uninstalled}}(SHP)$$

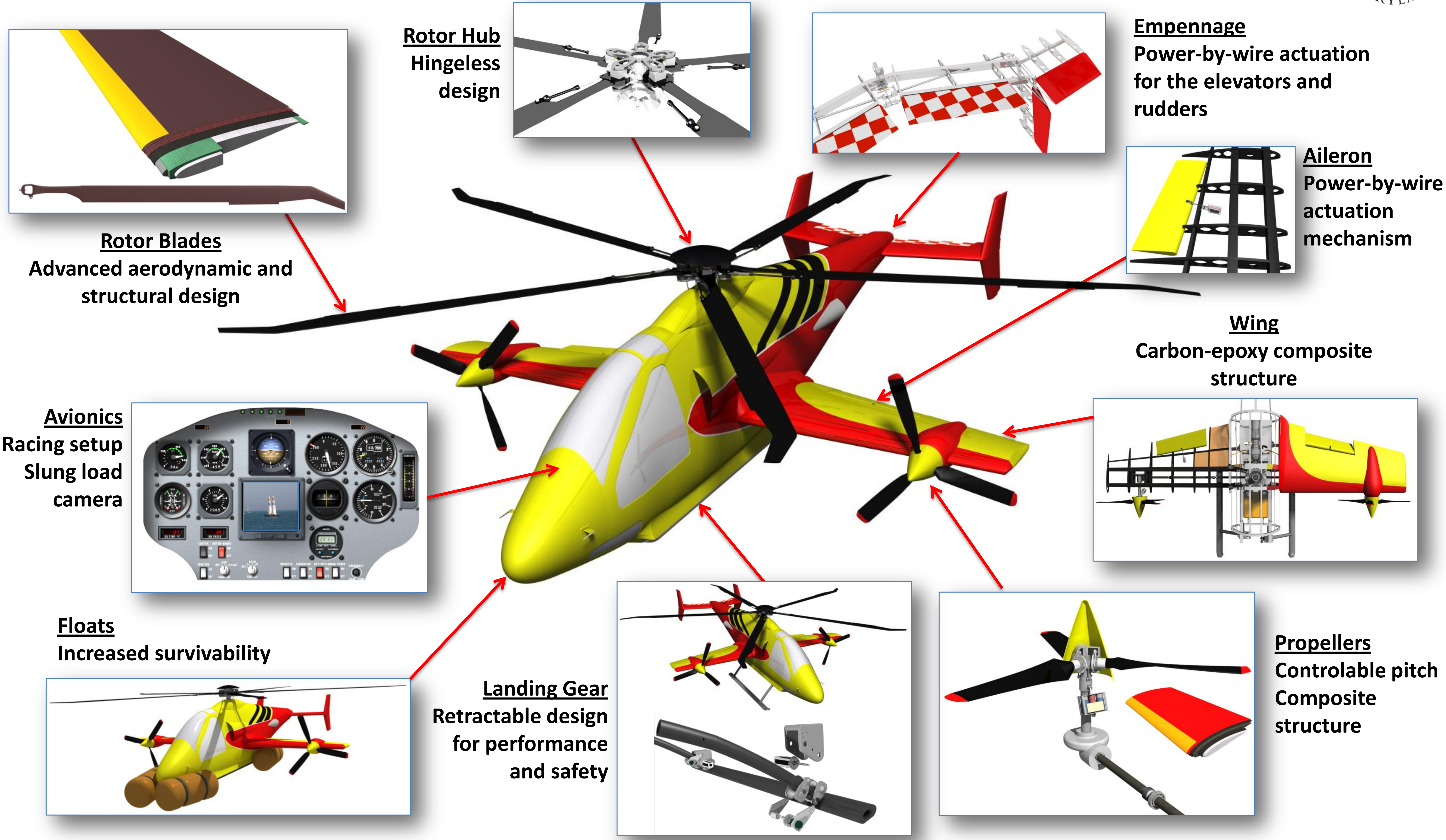
This gives the *Dart T690* an **efficiency rating (η) of 1204**.

The *Dart T690* has superior maneuverability, agility, dash capability, and speed than any other helicopter in its class, truly hitting the bullseye in rotorcraft pylon air racing.

Vehicle Performance Characteristics			
Maximum Gross Weight (lb)	2515	Cruise Speed (kts)	200
Empty Weight (lb)	1700	Maximum Endurance (hr)	2.7
Intermediate Rated Power (hp)	690	Maximum Range (nm)	256

Overview: The *Dart T690 / E550*

DART T690



Rotor Blades
Advanced aerodynamic and
structural design

Rotor Hub
Hingeless
design

Empennage
Power-by-wire actuation
for the elevators and
rudders

Aileron
Power-by-wire
actuation
mechanism

Wing
Carbon-epoxy composite
structure

Avionics
Racing setup
Slung load
camera

Floats
Increased survivability

Landing Gear
Retractable design
for performance
and safety

Propellers
Controlable pitch
Composite
structure

RFP Requirements and Compliance

General Capabilities

Requirement	Design Solution	Section
225 lb pilot	Single seat cockpit	4.5
Never bank more than 90 degrees	Included constraint in Radau Pseudospectral flight path optimization	2.2
Side flight of 60 kts at S.L./103°F, TOGW, at more stringent of ±90°	Max sideflight speed - 111 kts at S.L./103°F, TOGW	13.6
Pilot visibility must adhere to MIL-STD-850B	Large polycarbonate cockpit windows	9.5, 11.1
Engine weight and dimensions must not be less than specified equations	Engine sized to RFP equations	4.1
Carry 300 lb slung load, provide a means of extending and retracting the hook	Winch with sub-flush hook storage	9.8
HOGE at S.L./103°F, TOGW	HOGE at 17k/ISA+25°C, TOGW	13.3
Cruise minimum of 125 kts at 90% MCP, S.L./103°F, TOGW	At S.L./80°F, TOGW: cruise speed - 204 kts at MCP, max speed - 225 kts at MRP	13.5
Aircraft must fit within the 40 yard lines of a football field	Aircraft 21.5 ft long and has a rotor diameter of 25 ft. This size fits within the football field	5
Minimum of one rotor radius around all rotating components	Rotor radius - 13 ft, propellers contained under the rotor	5
Meet Minimum FAA requirements for flight within the NY VFR corridor	Cockpit is equipped with instruments necessary for VFR flight	11.1.2
Provide flotation for the pilot, a minimum of 5 minutes	Emergency flotation attached to the fuselage, pilot wearing inflatable life vest	15.5
Vehicle designed taking into consideration alternative forms of propulsion	*Dart E550* - complete integration a fuel cell/battery hybrid electric power system	8.2
Aircraft must be capable of an autorotation	Autorotational index - 21, wings supplement glide slope	15.3
Pilot must be able to control the vehicle without a stability augmentation system	Doubling times of all modes are more than half a second	12.2

Mission Profile Requirements

Requirement	Design Solution	Section
Pilots and crew will be required to start their engines before given the rotors turning signal to allow warm-up and system check-out	Inclusion of sprag clutch	8.3.3
The aircraft completes a complicated pylon racing course	Maneuverable, Agile, Speed, and Dash, examined in detail throughout the report	13, 17
There must be enough fuel onboard for 15 minutes of flight at TOGW at VBE to account for traffic pattern flight	Low fuel consumption at VBE, additional fuel storage included	4

Final Report Content

Content	Section
Detailed weight breakdown of all components to MIL-STD-1374	10
Inboard and outboard profiles of the aircraft showing locations of major components	8, 9, 10
Weight, inertia, and c.g. analysis of the aircraft throughout its flight	10
Safe load paths for the major systems on board the aircraft	9.2
Considerations for the unfortunate event of a crash	15
Create a flight simulation of the aircraft and the course in X-Plane so that a pilot may fly it in a simulator	17
Plots of altitude, velocity, heading, pitch, and bank for a flight in X-Plane, noting pylons	17
Fastest Time finishing metric	18
Most Efficient finishing metric	18