

# The Hyperion 2 Green Aircraft Project

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Student engineering teams collaborated across three international universities to develop a 3 m wingspan unmanned aircraft in a single academic year. The original aircraft, named Hyperion, was inspired by the NASA/Boeing X48-B blended wing body, and was designed to serve as a test platform for high efficiency aerodynamics, structures, propulsion, and autonomous flight control. A second iteration of the project is underway, evolving the internationally developed flying wing design into a blended wing design by classical definition. The design concept includes an optional novel hybrid gas-electric propulsion system. The aircraft features a high-lift blended-wing body design, composite materials, and advanced flight controls, with the second round flight testing expected in the Spring of 2012. Hyperion's unique architecture and advanced subsystems establish novel technologies that may be incorporated into UAV, general aviation, or other commercial markets.

**KEYWORDS:** Global design, international teamwork, aircraft design, green aviation.

## Nomenclature

<i>AVL</i>	=	Athena Vortex Lattice
<i>BWB</i>	=	Blended Wing Body
<i>CFD</i>	=	Computational Fluid Dynamics
$CL_\alpha$	=	Derivative of Lift Coefficient With Respect to Angle of Attack
<i>EM</i>	=	Electric Motor
<i>FEA</i>	=	Finite Element Analysis
<i>ICE</i>	=	Internal Combustion Engine
<i>IDT</i>	=	Interface Dimension Templates
L/D	=	Lift to Drag ratio
<i>SVF</i>	=	State Variable Feedback
<i>t/c</i>	=	Thickness/cord length
<i>UAV</i>	=	Unmanned Aerial Vehicle

## I. Introduction

The Hyperion project aims to investigate a variety of cutting-edge technologies with potential to dramatically improve aircraft fuel efficiency and noise generation. Ever-increasing fuel costs demand efficiency improvements in order for the commercial aircraft and UAV market growth to be sustainable. Aircraft noise is regarded most significant hindrance to national Airspace System.<sup>1,2</sup> The plan is to reduce the current noise footprint of aircraft close to airports significantly. The Hyperion aircraft is a test platform for a variety of high efficiency aerodynamic design ideas. In order to maximize aerodynamic performance parameters, a blended fuselage and wing configuration was implemented, inspired by the Boeing X-48B. The result was a new flying-wing aircraft, seamlessly blending two different airfoil sections to produce lift over the entire aircraft body, while still maintaining correct trim. The first generation Hyperion 1 aircraft was classified as a "flying wing" and was successfully flown in the Spring of 2011.

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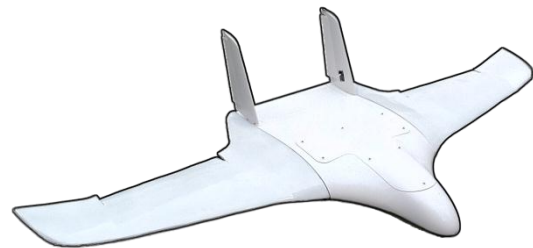
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The newly-designed, 2<sup>nd</sup> generation Hyperion aircraft moves away from a flying wing classification and into the blended-wing category with increased sweep wings. The aircraft shall demonstrate efficiency improvements over conventional designs and serves as a platform for a unique hybrid engine development. This paper highlights the design evolution of the Hyperion Project and unveils the second generation Hyperion aircraft designs.

## II. 1st Generation Aerodynamic Design

Blended-wing body (BWB) aerodynamic design has been thought by many to be the future of subsonic air transport. A number of vehicles, including the NASA/Boeing X-48B, promise estimated fuel savings of as much as 30%, increased cargo capacity, and reduced acoustic signature compared to traditional “tube and wing” aircraft.<sup>3-6</sup> In order to build upon the improvements demonstrated in past designs, the Hyperion was initially inspired by NASA/Boeing X-48B, but later fully optimized for the slower flight regime of the design mission. The primary drivers were an optimal lift distribution for high lift to drag ratio and good handling qualities over the entire flight envelope. The result was an entirely new aircraft architecture with significantly reduced wing sweep compared to transonic designs which improved the maximum lift coefficient of the platform shown in Fig. 1.

The first generation aircraft had a 3 m wingspan, weighed approximately 19 kg fully-loaded, and cruised at a velocity of approximately 30 m/s. It was statically and dynamically stable in all axes except for slight spiral mode instability. A single rear elevator, two ailerons, and two rudders sufficiently control the aircraft—a large decrease in complexity over the X-48, which can exceed 20 control surfaces in some configurations.<sup>4</sup> An iterative optimization script was developed in XFOIL, Athena Vortex Lattice (AVL), and MATLAB software to optimize wingtip design. The final design employed raked wingtips, which achieved increased span efficiency and L/D without increasing the risk of stall at low Reynolds numbers. A twin vertical tail was selected using similar methodology, while considering directional stability and piloting simplicity.



**Figure 1. Hyperion 1.0 Configuration.** *Picture of the completed Hyperion1 flying wing airframe.*

The baseline configuration design was done by the Sydney team using 2-d and 3-d panel methods to meet the requirements defined by the Colorado team.<sup>7</sup> A half scale model was then tested in the Sydney wind tunnel on a two axis balance designed for this project. The University of Stuttgart team performed a 3-d computational fluid dynamics (CFD) simulation using the DLR Tau code to provide high-fidelity modeling and analysis of the airframe. The CFD data was compared to the wind tunnel results with good agreement. Therefore the CFD data can be used in the future to explore design changes and obtain aerodynamic derivatives and stall patterns without the need of costly wind tunnel work for each modification.

## III. 2<sup>nd</sup> Generation Aerodynamic Design

Two successive architectures of the Hyperion aircraft have been designed, Hyperion 1.0 and 2.0. Hyperion 1.0 featured a narrow leading edge sweep angle and raked wingtips to achieve increased span efficiency and L/D without the risk of stall at low Reynolds numbers. The Hyperion 1.0 design proved to be aerodynamically efficient, reaching a maximum L/D approaching 20. However, the Hyperion 1.0 design geometry could not be considered a true blended wing body. A new architecture (Figure 2) was developed featuring redesigned wings to favor a true blended wing body configuration: sweep angle, taper, and twist were optimized so that stall first occurs at the midwing. The original model’s center body was kept and new wings were designed to blend geometrically while maintaining structural integrity.<sup>8,9</sup> The 16 kilogram, 3.2 meter wingspan aircraft has the same designed cruise velocity and wing loading as the first generation model.

The aircraft geometry was developed to support a wing loading of 10 kg/m<sup>2</sup> and achieve a cruise speed of 30 m/s. Final comparative parameters are listed in Table 1. Next, various airfoils were investigated using the Airfoil Investigation Database (AID) and different combinations for the wings and center body were optimized in the

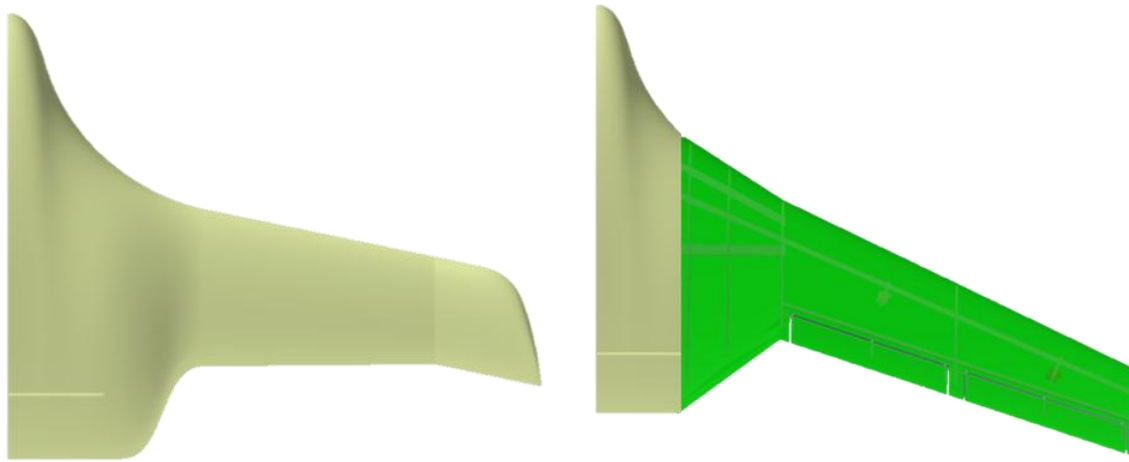
modeling program Athena Vortex Lattice. Airfoils were chosen to meet BWB specifications: high  $t/c$ , negative camber for pitch stability, and high  $L/D$  for low Reynolds numbers.

**Table 1: Original and New Aircraft Parameters**

	<b>Hyperion 1.0</b>	<b>Hyperion 2.0</b>
$C_{L_{max}}$	<b>0.85</b>	<b>~1</b>
$L/D_{max}$	<b>16</b>	<b>~18</b>
$V_{stall}$	<b>13.04 m/s (29.2 mph)</b>	<b>13.2 m/s (29.5 mph)</b>
$V_{TO}$	<b>17.9 m/s (40.04 mph)</b>	<b>15.8 m/s (35.4 mph)</b>
$V_{CR}$	<b>27 m/s (60.4 mph)</b>	<b>30 m/s (67 mph)</b>
$S$	<b>1.648 m<sup>2</sup> (17.74 ft<sup>2</sup>)</b>	<b>1.693 m<sup>2</sup> (18.22 ft<sup>2</sup>)</b>
$b$	<b>3.0 m (9.84 ft)</b>	<b>3.2 m (10.5 ft)</b>
$W$	<b>20 kg (44.1 lb)</b>	<b>16 kg (35 lb)</b>
$W/S$	<b>10.4 kg/m<sup>2</sup></b>	<b>9.45 kg/m<sup>2</sup></b>
$\Lambda_{LE}$	<b>17°</b>	<b>35°</b>

A unique aspect of the Hyperion 1.0 design was the raked wingtips, implemented to minimize induced drag and profile drag at cruise speed. Raked wings were preferred over winglets due to a Reynolds number of 550,000. Hyperion 1.0 was designed to contain three different control surfaces: flaps for roll, rudders for yaw, and a single elevator for pitch stability. Two vertical stabilizers were chosen for the configuration to avoid splitting the elevator. A V-tail would be more stable during spiral and dutch roll modes but the flight mechanics as well as manufacturing are more complex but a U-tail has the advantage of less wetted area and less structural complexity; therefore, the U-tail design was chosen. The control surfaces were sized based on recommendations from Raymer<sup>10</sup> and kept at the upper limit in order to reduce the required angle of deflection.

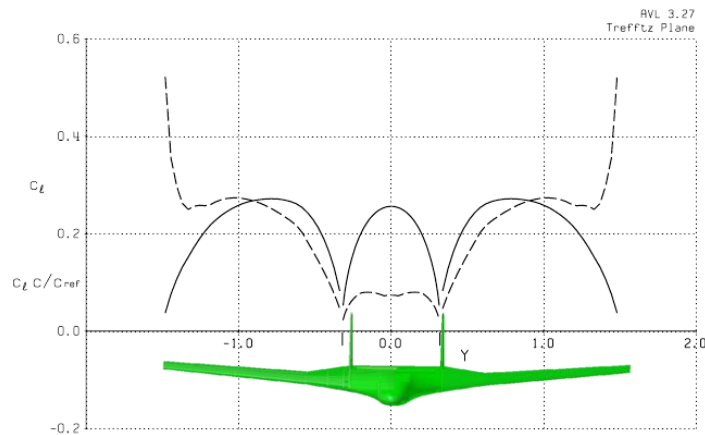
For Hyperion 2.0 critical parameters for achieving a BWB configuration were changed and combinations iterated in AVL. Most notably, the leading edge sweep angle was increased by 12°. An analysis was done to determine if raked wings or winglets would help the aerodynamic stability or increase  $L/D$  of the new architecture. A raked wing geometry with a chord distribution of  $y(\text{span})=4x(\text{chord})$  was used with Hyperion 1.0 with a chord of 0.3 m at  $b=1.2$  and a sharp ending at  $b=1.5$ . A geometrical dihedral of 6° was used. AVL analysis showed a slightly higher  $L/D$  at 15.5 for the raked wing model as compared to the flat wing model with an  $L/D$  at 15.4. No significant change was observed in any mode of the root locus. Comparing the lift distributions of the 2.0 model with raked wings and the same model with flat wings suggested that raked wings bring the stall area slightly farther inward, toward the center body. This is less desirable, since the stall area needs to occur on the mid-wing for a blended wing body. Even though the raked wings provide a slightly better aerodynamic advantage with the higher lift to drag ratio, the added structural weight and manufacturing complexity outweighed the benefit, and flat wings were ultimately favored for Hyperion 2.0.



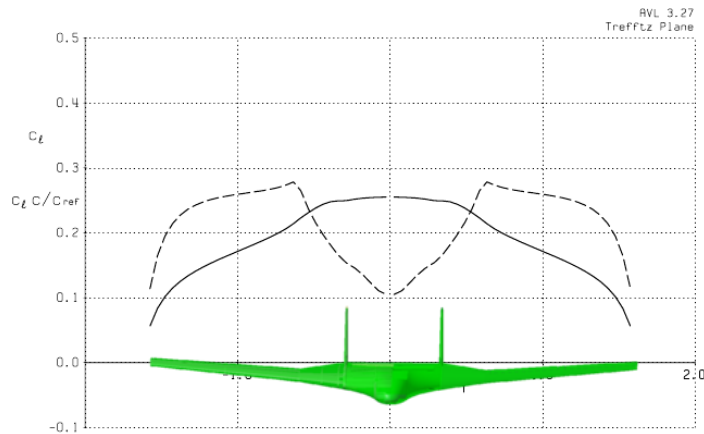
**Figure 2: Wing Redesign Modifications. Hyperion 1.0 Flying Wing left. Hyperion 2.0 BWB on right.**

The existing center body's U-tail as well as its corresponding control surfaces were implemented with the new architecture. The addition of separate flaps and ailerons to the new Hyperion wing surfaces are an improvement to the former design. The flap design from Hyperion 1.0 was reused, keeping the chord fraction at 20 percent; however, the flaps were shifted in the spanwise direction to allow for aileron placement at the wing tips. Design of the ailerons depends on the roll rate: the number of degrees per second the aircraft can withstand during a roll turn. For this aircraft, a roll rate of 30 deg/s was selected from the upper limit roll rate for similarly sized RC aircraft. This is a much higher value than is expected to be experienced during flight. Spanwise locations and chord fractions of the ailerons were iterated until they produced a roll angle helix greater than what is desired.

The Hyperion 2.0 design demonstrated the key characteristics of a blended wing body in its lift distribution. The full line in Figure 3 below shows the lift distribution of the original model as lift per unit span (dashed line =  $c_l$ ). Here, stall first occurs at the wingtips with localized stall close to the center body/wing interface. The Hyperion 2.0 model, shown in Figure 4 achieves a much more elliptical lift distribution with stall occurring at the midwing, as desired for a true BWB. Initial AVL analysis shows an L/D of 17, closely matching AVL's output for the original Hyperion model, which demonstrated a higher value with experimental and high fidelity modeling data. However, AVL's results are rudimentary and do not take into account vorticity effects. More accurate validation of lift and drag characteristics will be confirmed with future CFD analysis.



**Figure 3: Lift Distribution Hyperion 1.0. Solid Line represents the lift per unit span. Dashed Line represents local lift coefficient  $C_L$ .**



**Figure 4: Lift Distribution Hyperion 2.0. Solid Line represents the lift per unit span. Dashed Line represents local lift coefficient  $C_L$ .**

Once the final aerodynamic design was completed, the controls team could use the stability derivatives and eigenvalues to begin accurately simulating the new Hyperion model. The most important stability derivatives are summarized below in Table 2, along with the predicted  $L/D$  value of 16.7 from AVL. All values were verified to be within a reasonable range for this size and type of aircraft. The lift curve slope was analyzed for the previous model and was shown to be 4.09 experimentally. For Hyperion 2.0, it is slightly lower but still acceptable at 3.98 calculated.

**Table 2: Stability Derivatives Summary**

Parameter	Value
$C_{L\alpha}$	3.982
$C_{m\alpha}$	-0.368
$C_{n\beta}$	0.02178
$C_{l\beta}$	-0.03676
$C_{lp}$	-0.3628
$C_{Lq}$	5.153
$C_{lr}$	0.0470
L/D	16.7

The eigenmodes, shown in terms of damping and natural frequency, were determined from an AVL root locus output and are summarized in Table 3. An improvement from last year is that the spiral mode and dutch roll mode are dynamically stable. The rolling mode damping increased but the addition of ailerons helps to mitigate that effect. More accurate computer modeling is expected to refine and verify these parameters.

**Table 3: Eigenmodes Summary**

Mode	Damping ( $\zeta$ )	Natural Frequency ( $\omega$ )
Dutch Roll	-0.395	5.248
Dutch Roll	-0.395	-5.248
Roll	-20.19	0
Short Period	-5.532	8.436
Short Period	-5.532	-8.436
Spiral	-0.0414	0.386
Spiral	-0.0414	-0.386

#### IV. Propulsion Design

Hyperion is intended to provide a test vehicle for a novel hybrid propulsion system<sup>11</sup> developed at the University of Colorado in 2009-2010, currently licensed by Tigon EnerTec, Inc. The second-generation of the hybrid propulsion system<sup>12</sup> was developed concurrently by a team of undergraduates during AY2010/2011. The team utilized Tigon EnerTec, Inc.'s patent-pending gearing system to seamlessly blend the torque from an internal combustion engine and an electric motor, which are arranged in an in-line configuration to maintain symmetry. This configuration is termed "parallel hybrid," since each motor operates independently and additively, rather than the traditional serial hybrid systems commonly found in automobiles.

Currently, hybrid propulsion systems for aircraft are nearly nonexistent. However, implementation of this parallel hybrid technology could have a variety of benefits spanning multiple fields of aviation. An aircraft that is able to utilize a traditional, high-efficiency combustion system during normal flight and then transition to a quiet electric motor during landing would greatly alleviate noise pollution that is rampant at today's airports. This same hybrid application would allow for reduced acoustic signature of a UAV over a target area. This technology could provide increased safety for general aviation applications, where engine failure is the root cause of an inexcusable number of accidents.<sup>13</sup> Furthermore, using a smaller ICE that is sized for optimal operation at cruise and providing additional required power from the EM, the engine has demonstrated fuel savings of approximately 15%. This propulsion system allows for the aircraft to fulfill concepts of operations of both long-endurance and quiet-loiter UAV platforms without sacrificing performance.

A lack of maturity of the second-generation hybrid system prevented integration for initial flight testing with Hyperion 1.0. Since, the hybrid propulsion system has been successfully bench-tested in the concentric shaft configuration, including reliable remote-restart of the internal combustion engine and is to be flown on Hyperion 2.0 aircraft in 2012 after initial flight tests are conducted on a RASCAL model airplane.

The Hyperion aircraft has been designed to cruise at 30 m/s. A curve relating cruise velocity with internal combustion engine power requirement was plotted using Mathematica. This plot is given in Figure 5. For the Hyperion aircraft to cruise at 30 m/s at the altitude of Boulder, CO with a propulsion system efficiency of 0.7, the required calculated engine power is 1.04 HP. Chosen will be a propulsion system that has at least 2 HP to offer some factor of safety.

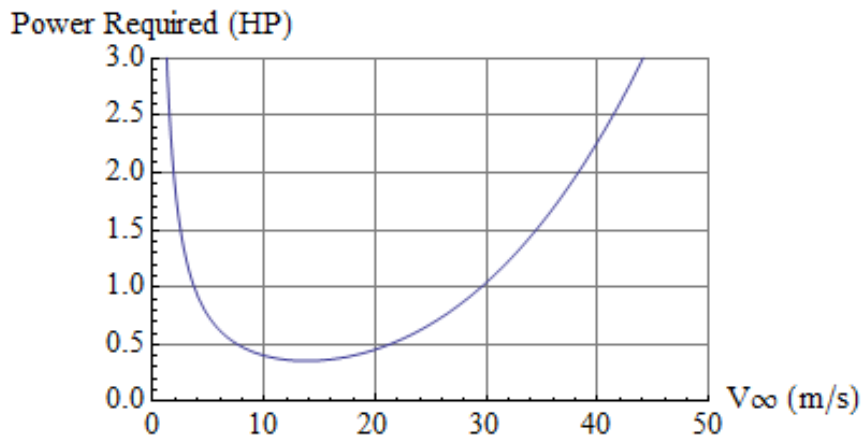


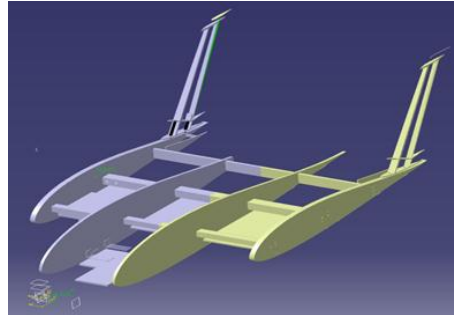
Figure 5: Required Power Curve

#### V. Structural Design

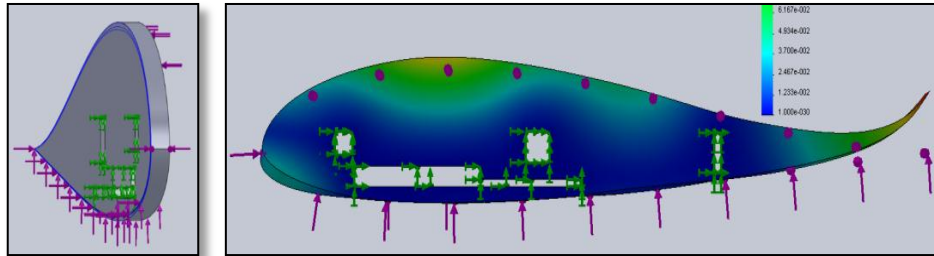
In order to minimize the mass of the aircraft, the vast majority of Hyperion is constructed from composite materials. The design for a one of the primary structural components—the wing spar—can be optimized, since BWB aircraft typically have highly elliptic lift distributions.<sup>3-5</sup> Two carbon-fiber spars to bear the loads in each wing, and transfer stress to four carbon-fiber foam-core ribs to form the internal structure, shown in Fig. 6.

These ribs also serve to maintain the aerodynamic shape of the skin. Minimal rib deflection was desired to prevent buckling of the fiberglass skin, so finite element analysis (FEA) was performed to validate rib and spar

integrity with safety margins against expected loads. FEA results increased confidence that the internal structure would provide the required rigidity. The max deflection was determined by setting the ratio of max deflection to span length equal to 0.025 (Figure 7). This ratio was determined based on information from Tam<sup>14</sup> and not wanting the spar to be too rigid nor too flexible. The rib structure was shipped to Stuttgart where the team manufactured the molds and the skin for this center body wingelement.<sup>7,8</sup>

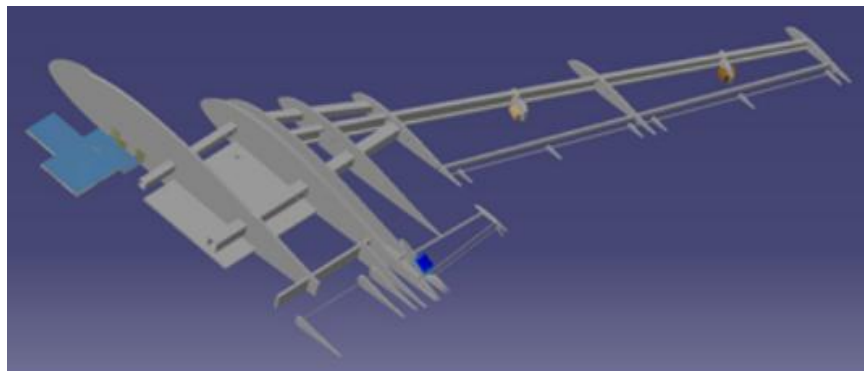


**Figure 6. Internal Structure Assembly.**



**Figure 7. Internal Structure Assembly. Deformation and load on the center body rib under flight loads.**

A driving force for Hyperion 2.0 is a focus on redesigning the internal structure of the aircraft wings to minimize weight while maintaining the structural integrity. To achieve this, the material of the wing spars was changed from Dragon Plate carbon fiber tubes to Dragon Plate Airex foam core. The foam core has a lower tensile strength than the carbon fiber tubes but the density of the foam core is significantly less than that of the carbon fiber tubes. To accommodate for decreased material strength the support for the leading edge of the wing was chosen to be a C-spar configuration. To create this spar, three pieces of foam core will be bonded together. These three pieces will form the vertical portion of the C-spar and the two “legs.” In addition to providing increased strength, the shape of the C-spar will help prevent torsion and shear. At periodic intervals along the wing, ribs will be attached to the spar and aircraft skin, also helping to provide support and prevent shearing. These ribs will also be made of Dragon Plate Airex foam core. One half of the internal structure of the aircraft is shown in the Figure 8.



**Figure 8: New Hyperion 2.0 BWB wing spar structure.**

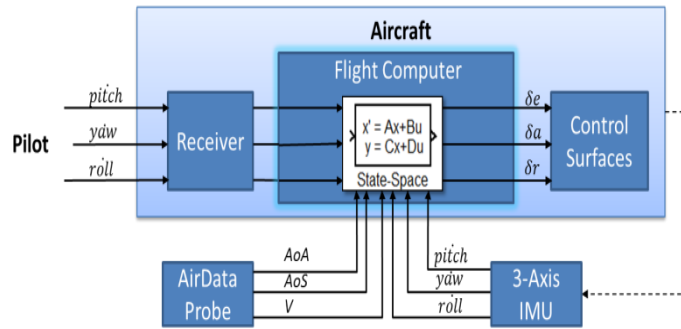
## VI. Electronics and Flight Control

The Hyperion also serves as a platform for advanced flight control system testing. A system was designed to combine pilot control input with onboard guidance, navigation, and control data to successfully fly the aircraft. Two onboard batteries and a consumer off-the-shelf (COTS) R/C communication and data logging system support this function. The control system architecture is developed and modeled in the MATLAB/Simulink environment for simulation and development. FAA regulations severely restrict flight testing university-developed autonomous UAVs, so preliminary Hyperion flight testing was conducted in a reliable R/C only mode. An FAA certificate of authorization is being pursued to allow for future autonomous flight testing.

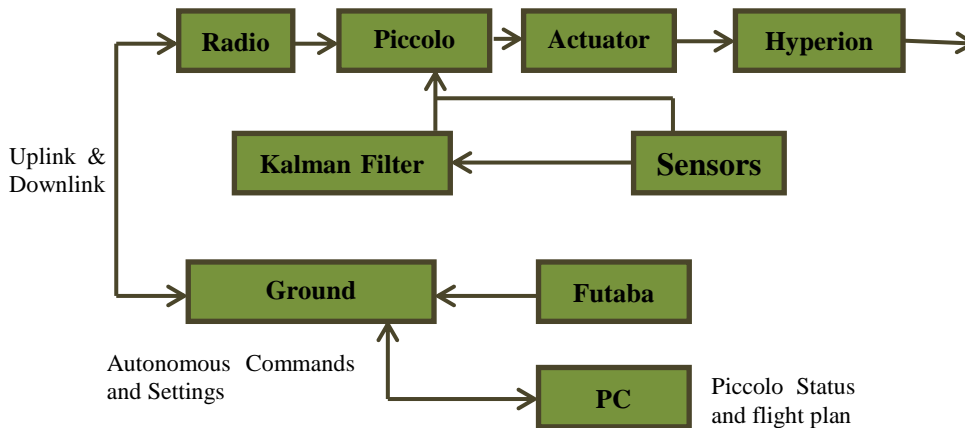
As flight control code matures and hardware is acquired, hardware-in-loop (HIL) tests are performed to verify and improve models, optimize controller performance, and to identify and debug integration issues. Upon successful integration of the flight code and hardware on a test bench, the code is recompiled into an embedded format and loaded onto the aircraft for additional bench testing and flight test.

The flight controller will perform stability augmentation using state variable feedback (SVF), where the aircraft states are monitored by two onboard sensors. This control scheme allows for the computer to make updates to aircraft attitude rapidly in order to more accurately track pilot input commands.<sup>7</sup> A block diagram illustrating the control system architecture is presented in Figure 9. This flight control system forms the foundation for the flight computer that will fly the Hyperion autonomously the next Spring.

The GNC subsystem of Hyperion 2.0 will equip the UAV with the capability of flying autonomously or by R/C pilot (Figure 10). Furthermore, the GNC subsystem provides the UAV with the ability to downlink telemetry, air speed, position as well as real-time fuel flow rate data, brake during landing, and control the mode actuators and throttle of the hybrid engine<sup>12</sup> or alternatively a common internal combustion engine. The commercial-off-the-shelf Cloud Cap Technology Piccolo SL autopilot is a complete integrated avionics system for UAVs. It satisfies all autonomous and R/C functional requirements. The National Instruments SB Rio has been programmed to control the hybrid engine and fuel flow sensor with custom software. The following Figure 10 displays the Piccolo SL system architecture as it interfaces with the aircraft.



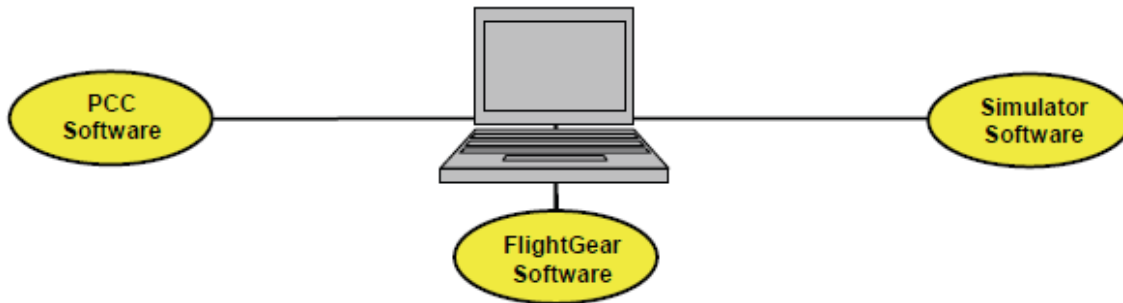
**Figure 9. Flight Control Architecture. Diagram of control baseline for future autonomous flight.**



**Figure 10: Piccolo control system.**

The Piccolo uses latitude, longitude, and altitude to define waypoints and performs a pre-turn algorithm to estimate when the aircraft should begin turning to the next waypoint. This algorithm causes the aircraft to turn prior to direct flyover of the waypoint, but can be turned off if desired.

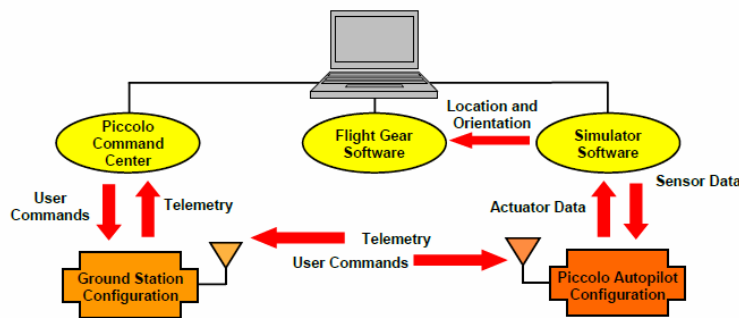
The software interfaces are used for Software in the Loop (SiL) simulation tests. The SiL configuration provides the same functionality as a Hardware-in-Loop (HiL) setup, but without the autopilot and ground station hardware connected. In the SiL configuration (Figure 11), PC applications take the place of the ground station and autopilot. The simulation environment allows the aircraft control laws and mission functionality to be tested without risking the aircraft in a flight test. The simulation environment provides an ideal training tool that can be used in the lab. Although simulation cannot replace flight-testing, it measurably reduces the likelihood of failure by detecting bugs and deficiencies before the aircraft and related hardware are put at risk.



**Figure 11. SiL flowchart**

The hardware-in-the-loop (HiL), Figure 12, simulation environment allows the aircraft control laws and mission functionality to be tested without risking the aircraft in a flight test. The simulation environment provides an ideal training tool that can be used in the lab. Although simulation cannot replace flight-testing, it measurably reduces the likelihood of failure by detecting bugs and deficiencies before the aircraft and related hardware are put at risk.

During HiL simulation the Piccolo Command Center sends user commands to the ground station, which are then sent to the Piccolo autopilot. The simulator reads the actuator positions from the Piccolo, applies them to an aircraft dynamics model, calculates new sensor data, and sends it back to the Piccolo. Piccolo sends telemetry data to the ground station, which is then sent to the Piccolo Command Center. Location and orientation information are sent to FlightGear™ software for visualization.



**Figure 12. HiL flowchart**

The simulator communicates with the Piccolo in real time and runs as a real time application. The Piccolo SL will be in control of the aircraft during autonomous flight. This means that the Piccolo must be able to “communicate” with the control surfaces, the engine, the brakes, and all data acquisition. In order for all of these to happen the Piccolo must be properly integrated with the various subsystems such as: structures, propulsion, and electronics.

## VII. Manufacturing

In order to best simulate industry practices in manufacturing, the University of Colorado subcontracted several critical components of the aircraft to the University of Stuttgart. The student team at Stuttgart contributed expertise in composite manufacturing as they have also a myriad of cutting-edge composite manufacturing facilities on campus. The internal structure of carbon-fiber spars and ribs of the center body was manufactured by the University of Colorado and shipped to Germany in February of 2011, where the fiberglass skin was applied to rib and spar

assembly to form the center body, illustrated in Figure 13.<sup>7</sup> This manufacturing schedule allowed the University of Colorado team to fabricate the two wings in parallel with the center body fabrication in Germany.



**Figure 13. Integration of Center Body.<sup>7</sup> Ribs and spar assembled into center body skin mold in Stuttgart, Germany.**

The primary goal of having a completed aircraft after 9 months meant that integration and schedule were major project risks. Effort was put into mitigating schedule risk through determination, long hours, and hard work, with only minor reductions in project scope. N-Squared diagrams of all subsystem interfaces were developed to outline subsystem dependencies. Interface Dimension Templates (IDT) were provided to ensure precise integration and joining of parts manufactured in two locations. Both teams manufactured their respective components to match the identical templates, which allowed for seamless interfacing of components during the final assembly.

After a final flight readiness review, the Hyperion aircraft successfully underwent a series of runway tests to verify stability on the landing gear. The first flight of the Hyperion 1.0 aircraft was successful; lastly because of adjustments coming from the intensive testing done with cheap half-scale models.

The first generation Hyperion wings were constructed using a positive mold method. This proved very inefficient and tedious. The second generation Hyperion 2.0 BWB wings for the center body will be manufactured at Colorado from a negative mold similar to the center body method. Flight testing is expected in April 2012.

## VIII. Conclusion

The Hyperion project successfully demonstrated the ability of three international universities to design,



**Figure 14. Hyperion 1.0 taking off.**

manufacture and test a novel aircraft architecture in a single academic year (Figure 14). The international collaboration became a great learning experience for the students involved, and was considered a complete success by project sponsors. The vehicle continues to serve as a platform for high-efficiency aerodynamics studies and innovative hybrid propulsion testing.

The reader may view video footage about the project on YouTube™.<sup>15</sup> Additional flight testing with the new Hyperion 2.0 with hybrid propulsion system and internal combustion engine is planned for Spring of 2012.

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