Designing a Blended Wing Body Aircraft Globally

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ABSTRACT

The goal of the “Hyperion” aircraft project has four components: (1) design the wing structure of the Hyperion to improve aerodynamic efficiency and reduce energy consumption, (2) implement autonomous control, (3) Flight test a coaxial hybrid propulsion system, (4) develop a global student collaboration. A first design of the modular frame was a flying wing geometry. The second design adopted blended wing architecture with appropriate sweep and control surfaces. For testing purposes cheap half-scale models were built with electric motor to test the RC controls and assure flight stability before the full size aircraft is flown. Wind tunnel tests are done with half scale models and 1/12 scale models manufactured with a 3D printing technique. The full size aircraft flight test is expected in Spring 2013. Initially the aircraft will be flown in RC mode. When the control of the aircraft is fully understood the electric motor will be replaced with a novel coaxial hybrid propulsion system. After reliable flights the aircraft will be flown with autonomous control. Select design efforts and manufacturing were done in collaboration with students from the University of Stuttgart and the University of Sydney in a virtual and physical collaboration environment.

KEYWORDS

Global Design, International Teamwork, Aircraft Design, Control System

MOTIVATION

There is a growing trend of global, multi-company collaboration within the aerospace community. With the growing maturity of information technology and ever-increasing complexity of modern engineering and education, many parent companies form partnerships with specialty teams in order to facilitate rapid development across all subsystems of a project. For example, the Boeing Company purchases roughly 65% of the newly developed 787 Dreamliner airframe from outside companies.[1] Boeing has 28 suppliers located outside the USA: e.g. wings are produced in Japan, ailerons are produced in Australia, Fairings are produced in Canada, and doors are produced in France and Sweden. Within the USA there are multiple manufacturing suppliers in multiple states.[2] This business model makes the company a high-end systems integrator which is a move to increase productivity and quality.[3] Not so obvious reasons for global collaboration are that a) the costs of design and development are spread throughout its network and b) relationships may lead to increased sales in other countries. Parts are designed and built concurrently by partners in a virtual environment accessible to all. All data are checked in real time and select parts can be manufactured in delocalized facilities. These parts will then be shipped for final integration into an airplane. In an environment where work is traditionally performed by small, localized teams of engineers, these complex global projects present new challenges for overcoming cultural differences, language barriers, and bureaucracy. As a result, project management is more significant than ever before. Figure 1 shows an example of Boeing’s global distribution and breakdown of work performed on the 787 Dreamliner.

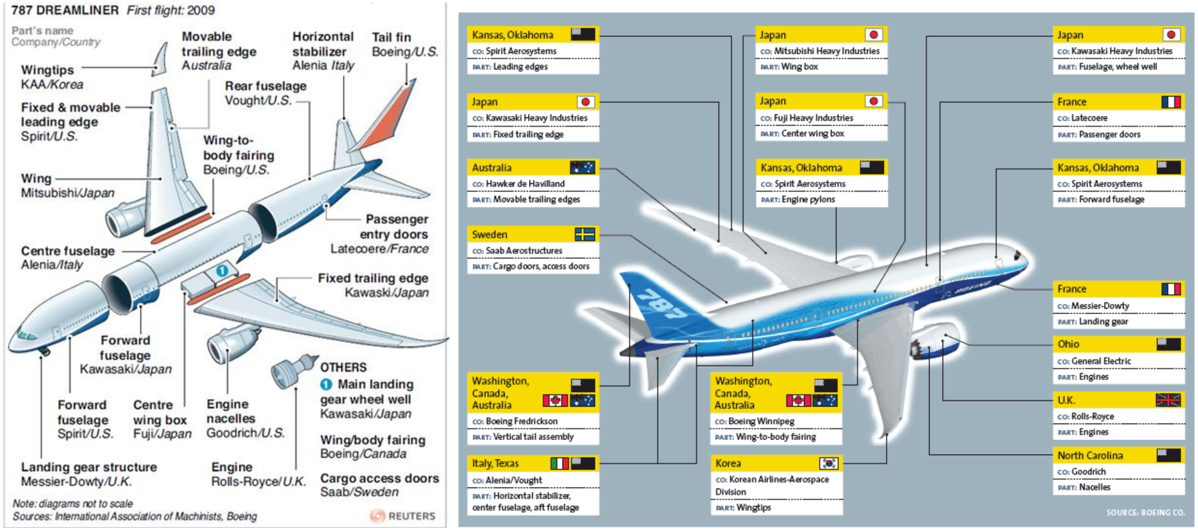

Figure 1. Boeing 787 Global Work Breakdown Structure.[1,3]

Aside from project planning and logistics, there is also a movement towards green aviation and improving the sustainability of the products produced in the aeronautics field. Green aviation is of global significance, with the Asian commercial airline industry flying in 2009 more passengers than the U.S.[4] According to the 2010 NASA report, the U.S. commercial airline industry is projected to double and fly 1.21 billion passengers per year by 2030. The increase in fuel consumption, associated air pollutants, and noise from this growing industry is a mounting concern. Therefore, NASA has issued a new set of industry challenges including reducing fuel burn and nitrogen oxide emissions by 50% by 2020 and restricting the nuisance noise footprint produced by aircraft to the airport boundary. These challenges are being directed to the aerospace industry as a whole, with intended performance improvements in all aircraft subsystems and successful implementation of green aviation technologies.

With both of these industry trends set to define a large focus of the next years of the aerospace industry, educating the next generation of engineers who will be responsible for addressing these challenges is of paramount importance. Efforts to train students in the global design effort have been reported before, and they were mainly limited to virtual computer design studies and did not include delocalized manufacturing.[5, 6]

Nissan, as a global company also introduced global collaboration and remote data access in its operations after several units have grown too independent and Nissan became one company operating as different companies. This led to major inefficiencies in operating and scheduling. Consolidating just the telecommunication into a global virtual environment saved the company about $135M “over a few years”.[7]

Design engineering is based on customer requirements. These requirements have to be communicated to and continuously discussed by all the team members. To communicate well, both verbally and in writing, is essential for project success. Communication is also required to develop interpersonal relationships, inspire team members, and handle conflicts and different opinions. In a global team, members may not know each other personally or have the possibility to pick up the phone at any point of time to clarify an encountered concern. This requires at the onset a very clear description of the requirements and the development of interface documents. In different cultures the educational program itself may provide students with different skill levels in similar fields of study.[8] Global industry realized that more and more highly skilled engineers work in foreign countries. A good business strategy is always to use the best resources.

The Hyperion project [9], besides being a challenging technical UAV project, was designed to train students to learn to reduce communication noise inherent in all communications and prepare them to become global engineers. This paper is focusing on the technical and educational outcomes of the student's work.

Follow-The-Sun

To satisfy the global project management aspect of the project, the Follow-The-Sun (FTS) concept was identified as a promising model for improving the productivity of delocalized teams. The FTS concept revolves around three teams, spread eight hours apart, who relay their work every eight hours, realizing 3 working days in a single 24-hour period.

Top-level project requirements were driven primarily from the two project elements, incorporation of the hybrid engine, and the Boeing/NASA X-48B architecture. The development of the project was well described in several papers. [9, 10, 11, 12] The focus in this paper is on lessons learned in structures manufacturing and in controls.

PROJECT DESCRIPTION

Global Project Team

The architecture of the Hyperion project team is shown in Figure 2. The model allows packing three regular working days by three teams on different continents into 24 continuous hours, accelerating project development by the FTS principle. Robust internet communication is essential. Students are challenged to communicate effectively and efficiently on a daily basis across all sub-teams.

Figure 2. Hyperion Team Architecture

Hyperion 2.0: Blended Wing Body Configuration

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. This configuration was flight tested. A new architecture (Figure 3) 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 mid-wing. The new blended wing body design was kept such that the original model's center body could be re-used. The new wings were designed to blend geometrically while maintaining structural integrity. The 16 kilogram, 3.2 meter wingspan aircraft had 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^2 and achieve a cruise speed of 30 m/s. 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.

Figure 3. Hyperion 1.0 Flying Wing and Hyperion 2.0 Blended Wing Body (from left to right)

The Hyperion 2.0 design demonstrated the key characteristics of a blended wing body in its lift distribution. 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.

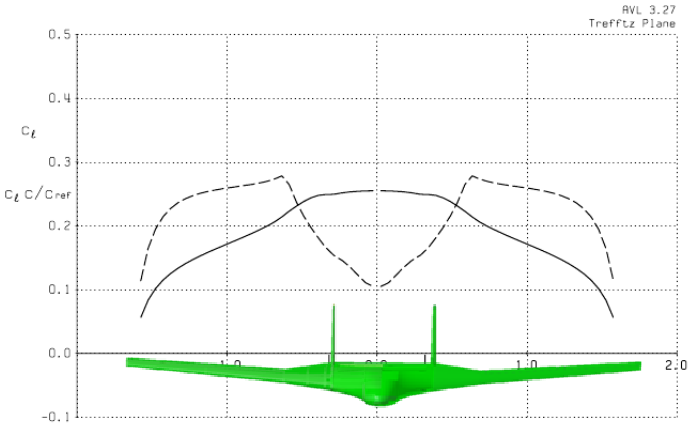

Figure 4. Lift Distribution Hyperion 2.0. Solid Line represents the lift per unit span. Dashed Line represents local lift coefficient C_L.[11]

Wing Manufacturing and Integration

The Hyperion wings were fabricated with two key components: The internal rib/spar structure and the skin. For the internal wing structure, the ribs and spars were constructed out of the same material used for the internal structure of the centerbody which was a 3 layer carbon fiber Airex Foam Core (Figure 5). The center body integration spars are carbon fiber braided tubing.

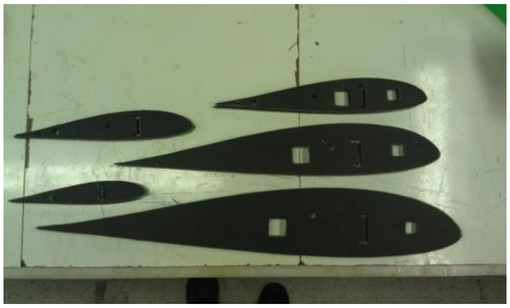

Figure 5. One set of Internal Ribs

The next step was to manufacture the external wing skin. The purpose of the external wing structure is to facilitate the proper aerodynamics of the wing design. It is also meant to protect the load-carrying internal structure and electronic components along the wing. A negative mold process was selected (Figure 6).

Figure 6. Carbon Fiber Layup molds made in 3D printer at EBS Carbon Inc.

Propulsion System Design

One of the main goals of Hyperion was to provide a test vehicle for a novel hybrid propulsion system developed at the University of Colorado. The system seamlessly blends the torque from an internal combustion engine and an electric motor, which are arranged in a co-axial configuration to maintain symmetry. This configuration is termed “parallel hybrid,” since each motor operates independently and additively. The hybrid propulsion system has been successfully bench-tested and shall be flown on the Hyperion 2.1 aircraft in 2013.

Autopilot Trade Study

From the beginning of the Hyperion project, it was recognized that the Hyperion aircraft required a robust control, guidance and navigation system. Hyperion was designed to be a showcase for green aircraft technology, and has a blended-wing body (BWB) design and a hybrid engine. In order to provide quantitative data on the effectiveness of these technologies in reducing emissions, noise, and fuel consumption and conduct scientific analysis on test flights, as much environmental and state information as possible needs to be collected. Control of the aircraft through specified flight plans would be standardized by an autopilot control system, allowing the team to compare flight performance between various aircraft configurations.

The use of an autopilot system allows the Hyperion aircraft to become a testbed vehicle, operated by students, for testing these aircraft technologies or other scientific and engineering payloads, with application to commercial vehicle development and unmanned aerial system (UAS) development. Additionally, the students involved with the project gain valuable systems engineering experience on using this type of a system as it is integrated into a novel type of aircraft.

Iterative Development of the Control System

As the Hyperion aircraft has been developed over the course of three academic years, the components and design have shifted as the rest of the structure has evolved.

Hyperion 1.0

The first Hyperion team was very ambitious and planned to design and implement a sophisticated flight control and sensor suite that would control and log all aspects of the flight of the Hyperion aircraft. The flight control system was designed to combine pilot control input with an on-board stability augmentation system to successfully fly the aircraft. Table 1 provides a list of the electronics and control systems components that were selected for this design.

Table 1. Hyperion 1.0 Electronics/Control System Design Selection

Component	**Selection**
Flight Computer	National Instruments sbRIO
Flight Software	MATLAB/Simulink, Labview
Alpha-Beta Probe	RCATS Alpha-Beta Probe
Pitot Tube	Eagle Tree Systems Pitot Tube
Inertial Measurement Unit	Memsense Nano IMU
Transmitter/Receiver	Futaba 10C FASST Radio System
Battery	A123 Systems 46mAh 2S2P $LiFePO_4$
Data Logging System	Eagle Tree Seagull Pro 900MHz 200mW
GPS Receiver	Eagle Tree GPS-V4
Vision System Camera	Fatshark FS-HD1

Development of the flight control system was begun using a plant and controller model in Simulink. However, difficulties in verifying the model to a sufficient degree of confidence were quickly encountered. Due to the high degree of risk in this subsystem and the necessity of finishing the aircraft structure, the subsystem team members re-scoped the system to simple data logging, control surface actuation directly by the pilot via the remote-control console, and control of a Commercial Off-The-Shelf (COTS) electric motor (EM) rather than the more complex hybrid motor. The controls and electronics team members worked extensively on manufacturing and prototype testing tasks.

The final flight test of the semester was a successful flight of the full-scale Hyperion aircraft at Arvada Airfield, a model airplane airfield in Colorado. The flight was approximately three minutes and utilized the Eagle Tree data logger, Pitot probe, and GPS. Students from Germany and Australia visited the Colorado team to finalize and experience the flight test.

Hyperion 2.0

The main goals of the year were redesigning the flying wing design of Hyperion 1.0 into wings that met the BWB technical specifications (Hyperion 2.0) and manufacturing it out of carbon fiber using advanced manufacturing techniques, and incorporating an autopilot into the system, both requests by the team's customer and sponsor, Boeing (Fig. 3)

Trade studies conducted by the team determined that using a COTS autopilot would satisfy the aircraft requirements and have less risk than developing an autopilot system from scratch. After an extensive search of available products, the team selected the Piccolo SL autopilot and Piccolo Command Center (PCC) flight software, made by Cloud Cap Technologies, as the autopilot system used.

An aerodynamic model of the new aircraft design was generated with Athena Vortex Lattice (AVL) and put integrated into the PCC software with a CAD model of the aircraft and a simple default engine model. This system was "flown" through a simple flight plan in the Software-In-The-Loop (SIL) simulation environment. The Piccolo hardware was connected to the existing centerbody hardware (from Hyperion 1.0) and various actuators and sensors were calibrated at the component level, such as a long-range communications test, an outdoor GPS acquisition test, and gyro precision tests. At that point, "Dream Mode" tests occurred, where the autopilot or the flight console would fly through the software environment and actuate control surfaces on the physical aircraft.

Hyperion 2.1

<u>*Fall Semester 2012*</u>

The main goals of the third year of the project were to continue system integration and conduct successful flight tests of the Hyperion aircraft in various system configurations. The team determined that the flight test program should progress by first verifying the aerodynamic stability of the aircraft with an R/C flight with the COTS EM, then adding in the hybrid engine capability and the Piccolo autopilot control.

A number of interfaces that had not been thoroughly integrated the previous year were subjected to component-level testing. The brakes, flaps, and aileron surfaces on the new wings were integrated for the first time, and the Pitot tube air data system was tested inside a wind tunnel to verify the accuracy of the readings. Ground planes were installed for the communications and GPS antennae. The Piccolo was mounted to a special board and the accelerometer and gyroscope readings were noted during a temperature and vibration test. The PCC was updated with an improved EM model rather than the default model and the plane model was refined with new data as the wing manufacturing concluded.

Attention turned to the hybrid engine interface with the control system. The internal combustion engine cannot be restarted in flight, so it is run at 100% during take-off and landing. During cruise, the ICE is set to a given percentage and the electric motor is modulated. Originally, the team planned to use the sbRIO from Hyperion 1.0 to control the modulation commands to the hybrid. However, the RIO was deemed overly complex for this task and an Arduino Uno microprocessor was selected to simplify the task and save on weight.

Because the flight plan had progressed to a graduated approach, the team decided to add additional sensors to gather additional data and allow verification of the software model. These sensors involved re-incorporating the Eagle Tree GPS and data recorders, a flow meter sensor, and a temperature sensor. Additionally, due to some shorting issues, the power harnesses to connect all the components were redesigned, fabricated, and tested, adding color-coding, fuses, and removing connectors that could be attached incorrectly. These are valuable “on-the-job” lessons learned by all students involved.

Spring Semester 2013

The tasks for the spring semester will focus on preparing the aircraft for flight, as the structural components have neared completion and are accessible for integration. A software model of the hybrid engine must be developed in PCC and validated, and the Arduino interface software completed. The various sensors and actuators must undergo final calibrations and be tested in a full-system configuration. Then the GNC system will be ready for flight and the flight tests.

Final Guidance, Navigation, and Control (GNC) System Design

As the design process of the GNC system has been described, a brief overview of the final deployed system configuration (flight by autopilot and with the hybrid engine) is now presented.

Flight Hardware

The Piccolo SL autopilot, made by Cloud Cap Technologies, was purchased in Fall 2011, as the autopilot option. The Piccolo has an integrated 6-degree of freedom inertial measurement unit (IMU) with gyros and accelerometers. The system also came with a small GPS patch antenna, installed on the top of the aircraft, and a 2.4 GHz communications antenna, installed on the belly of the aircraft. Each antenna has a custom-designed ground plane coated with an adhesive copper sheet to aid signal reception. A Pitot-static probe system was installed approximately halfway down the span of one wing, facing the airflow direction. The Piccolo is installed with a vibration isolation kit of small rubber bushings on a wood plate. This system is aligned with the body axes of the aircraft inside the centerbody and installed as close to the center of mass as possible.

The Piccolo will control eight control surfaces via servo controls: the elevator, two rudders, two flaps, two ailerons, and the nose wheel steering. It will also power the brakes on landing. The engine throttle control signals and state variables will be sent to the Arduino microprocessor, which will modulate the hybrid engine. This flight hardware description is shown in Figure 7.

Table 2. Hyperion 2.1 Electronics/Control System Design Selection

Component	**Selection**
Flight Autopilot	CCT Piccolo SL (IMU Included) + Developers Kit (Communications Antenna, GPS)
Flight Ground Station	CCT Portable Ground Station
Flight Software	CCT Piccolo Command Center
Hybrid Microcontroller	Arduino Uno microcontroller
Pitot Tube	Eagle Tree Systems Pitot Tube
Pilot Console	Futaba 10C FASST Radio System
Battery	A123 Systems 46mAh 2S2P $LiFePO_4$
Additional GPS Receiver	Eagle Tree GPS-V4 + Seagull Pro Data Logger

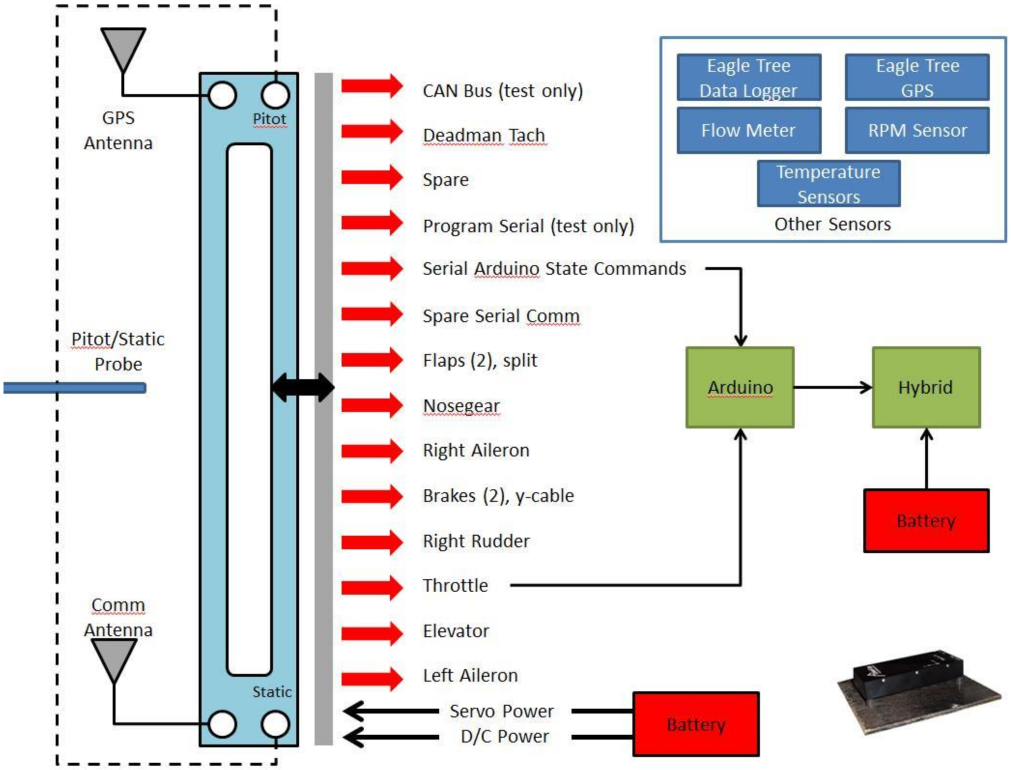

Figure 7. Flight hardware configuration

Additional sensors, as previously mentioned, will also be employed for data logging of state information but are not necessary for control and navigation.

Ground Station Hardware and System Software

The aircraft status, location, radio-control to autopilot hand-over, and operator commands are displayed and transmitted via two-way communication between a ground station and the Piccolo on the aircraft. A Piccolo-specific ground station and associated user interface are used to send and receive necessary data while in flight, and during ground tests. The ground station consists of a GPS receiver, a 2.4 GHz antenna, a flight console for R/C control, the ground station unit, and a PC computer with the PCC software on it, as shown in Figure 8. The ground station and PC can be used for extensive lab testing of the hardware in incremental steps where some hardware is used and other hardware is simulated to develop full-system confidence.

PCC has the ability to develop detailed flight plans, simulate the aircraft system within software, and control the various actuators or payloads that might be present. Figure 9 shows how the control loops within the system command the aircraft.

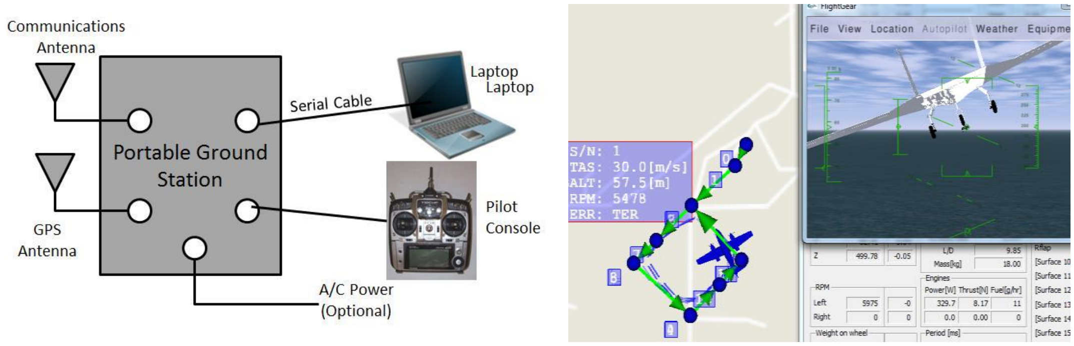

Figure 8. Ground station configuration and sample PC display with flight plan and flight display

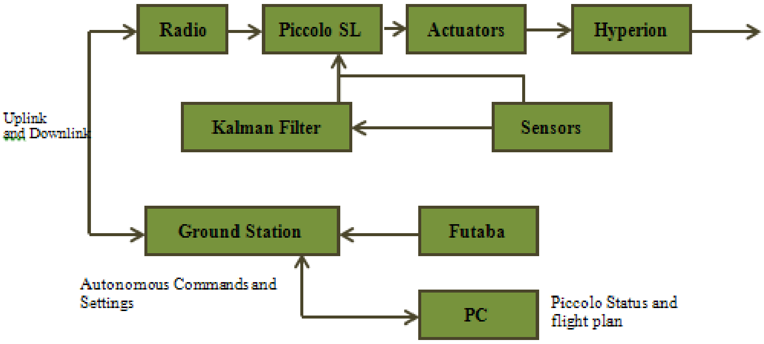

Figure 9. Control schema for flight with the Piccolo

Flight Plans

The team developed a simple racetrack-style for initial flight testing at the Arvada Airfield. This plan stays within the specified allowed flight areas and allows the aircraft to achieve stable flight under piloted remote control before transitioning to autopilot flight. This initial flight plan can be seen in Figure 10.

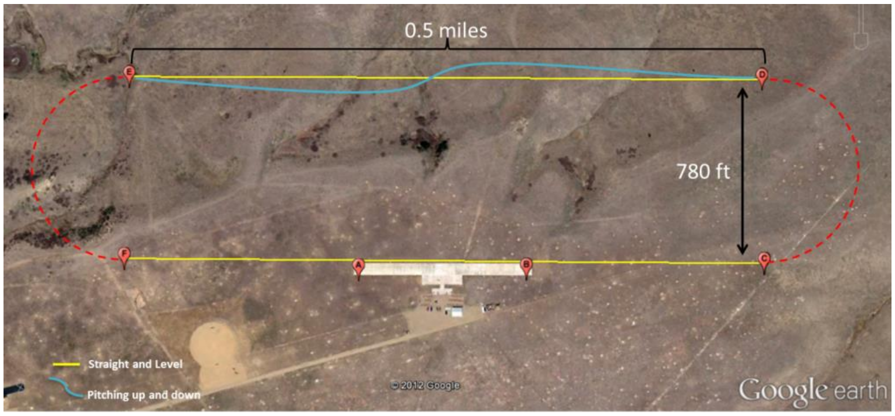

Figure 10. Arvada field initial flight plan.

LESSONS LEARNED

The design project teams at the University of Colorado are not micromanaged or directed by faculty advisers. Advisers are considered "consultants" to an engineering team of students that operate like a small start-up business. Student teams are self-directed and have to clearly evaluate their lessons learned in their final reports. Here is a selection of lessons learned for Hyperion.

Lessons Learned - Manufacturing

Over the span of two years, the Hyperion team has overcome several hurdles and solved a lot of technical issues related to its subsystems. Since light weight carbon fiber composites were being used for the structures, manufacturing the new wings was a serious challenge for the team. None of the team members had any prior experience working with composite materials and so it was a learning process from the beginning till the end. The task of manufacturing and finally integrating the new carbon fiber wings took more than twice as long as had been initially predicted. This was an important lesson for the team since the error in understanding the complexity of the design for the internal structure had caused the entire team schedule to be severely disrupted. The design team did not realize that the complex internal structure of the new wings would cause the manufacturing team to encounter serious problems during the structural analysis as well as the actual manufacturing phase. It would have been much more time efficient for the team to have designed a simpler internal structure.

The most crucial lesson learnt by the team management was the importance of sufficient time allocation and setting deadlines for the subteams which take into account any delays possible due to external unforeseen situations. Since, the team was working with EBS Carbon, it was necessary to abide by their schedules and work within the time frame they permitted. Additionally, delays due to shipping of critical materials and tools as well as lack of skilled man power led to several unforeseen schedule delays.

Lessons Learned - GNC

The 2.0 GNC group come upon a number of very important lessons learned that would have potentially eliminated the majority of the issues encountered during the semester. Each issue provided insight on how to approach the problem the next time around. For example: Flight critical hardware should be physically separated from other hardware to reduce the chances of damage to expensive components and reduce the chance of loss. Handling procedures and detailed usage logs should be created to reduce the chances if improper handling that could lead to damaged hardware and can help identify failure points.

When productivity is low due to halt in other subsystems, reallocate team resources to maintain forward momentum. Sometimes other subsystems' tasks are of higher priority and resources much be reallocated to ensure system success. In this vein, off-ramps should be considered early to anticipate changes to keep the entire system progress moving forward when roadblocks are encountered.

Owning hardware vs. borrowing hardware has huge benefits in terms of maintaining data and software. Having to return borrowed hardware between semesters led to lost parts and having to reconfigure software, which was not necessarily the same version, causing delays and rework.

Lessons Learned – Student learning assessment

The evaluation tools are a sequence of several documents and oral presentations. At the beginning if class students receive a document from the project customer detailing the top level project and the top level system requirement. The students then transform those requirements into a Project Definition Document which includes a first cut of more detailed project and system requirements. Students also develop an idea for project success and the possible risks. Next they provide a conceptual design document where they have to analyse at least three system options for achieving success. The next milestones are a Preliminary Design Review, an oral presentation, followed by a Critical Design Review. Here students have to show that they followed due systems engineering process.

Table 3: Student contributions to project as assessed by peers

Technical Contributions	Professional Contributions
Has required technical knowledge	Attends team meetings
Pays attention to accuracy and details	Produces work on schedule
Contributes good ideas	Effectively takes charge of tasks
Contributes to the required technical analysis	Willing to take on tasks
Finds information independently	Willing to help others
Willing to get up to speed on new topics	Communicates clearly with team
Understands the overall project	Informs others of teams progress
Effectively troubleshoots problems	Listens to other points of view
	Accepts advice about his/her work
	Gives criticism constructively

As part of the grade they submit a peer evaluation, giving their team members a grade for their specific contributions (Table 3) and also comment on their strengths, areas of improvement and general comments about their participation. All these comments will be considered by the faculty member, but not taken as absolute metric. Students meet with the adviser who shares the confidential feedback from the peers, first by mid semester of the Fall course; then at the end of the first semester, and finally mid semester during the following Spring course. The students can use the feedback to improve their teamwork, their contribution to success by rectifying any recognized weaknesses on their part. That pedagogical method has worked very well over many years and contributed to high quality project outcomes. Students assimilated the feedback and adjusted and improved their professional efficacy.

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BIOGRAPHICAL INFORMATION

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Gauravdev S. Soin is a senior graduate student in the Department of Aerospace Engineering at the University of Colorado, Boulder. He is the current Systems Engineer of the Hyperion Project. As an undergraduate he also led the original design and development team of the hybrid propulsion system. He has been involved with the integration and testing team of Tigon Enertec Inc.'s Hybrid Propulsion System for the past one year.

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