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HYPERION UAV: An International Collaboration

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The Hyperion aircraft project was an international collaboration to develop an aerial vehicle to investigate new technologies with a focus on performance efficiencies. A delocalized international team of graduate and undergraduate students conceived, designed, implemented, and operated the aircraft. The project taught essential systems engineering skills through long-distance design and manufacturing collaborations with multidisciplinary teams of students located around the world. Project partners were the University of Colorado Boulder, USA, The University of Sydney, Australia, and the University of Stuttgart, Germany. The three teams are distributed eight hours apart; students can relay select work daily so that developments can "Follow-The-Sun". Select components are manufactured and integrated both in Stuttgart and Colorado, giving the students an opportunity to learn multifaceted design tactics for manufacturing and interface control. Final flight testing was conducted by the global team in Colorado during the month of April 2011.

KEYWORDS

Global design, international teamwork, aircraft design, green aviation.

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Nomenclature

AES: Aerospace Engineering Sciences
AY: Academic Year
BE: Bachelor of Engineering
BWB: Blended Wing Body
CAD: Computer Aided Design
CDR: Critical Design Review
CFD: Computational Fluid Dynamics
CNC: Computer Numerically Controlled (machinery)
CU: University of Colorado
EE: Electrical Engineering
FTS: Follow-The-Sun
FTW: Follow-The-Week
I&T: Instrumentation & Testing
IDT : Interface Dimension Template
ITAR: International Traffic in Arms Regulations
MBA: Master of Business Administration
PDR: Preliminary Design Review
WBS: Work Breakdown Structure

I. 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, doors are produced in France and Sweden. In a field 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.

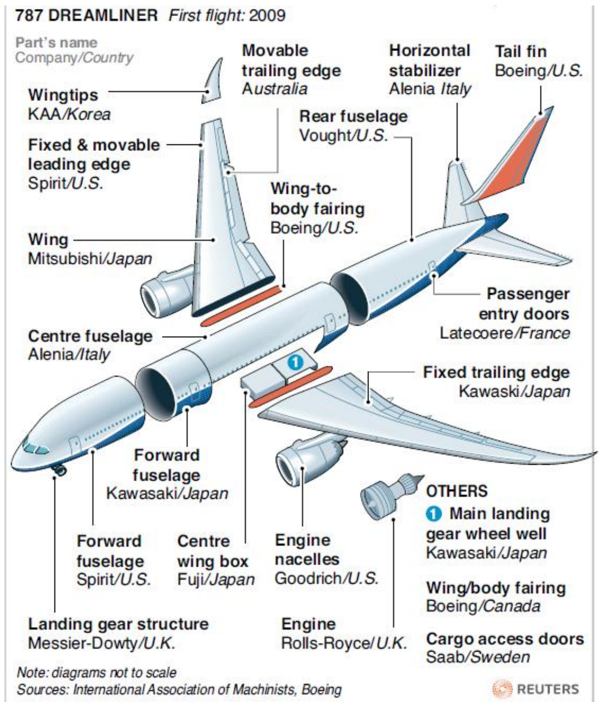

Figure 1. Boeing 787 Global Work Breakdown Structure.[1]

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.[2] According to the 2010 NASA report, the U.S. commercial airline industry is projected to 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 20-50 years of the aerospace industry, educating the next generation of engineers who will be responsible for addressing these challenges is of paramount importance. While aerospace engineering studies typically focus on engineering fundamentals, courses lack opportunities for students to gain experience in extensive systems engineering principles, manufacturing, and project management. While many universities have capstone senior design courses set to instill these values, modernizing the learning experience to better represent the global workings and pains in industry has habitually been omitted due to the perceived level of scope attainable in 2-semester academic projects. 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.[3]

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. Team members share information, exchange ideas and influence attitudes and actions as well as understanding of the issues at task. Communication is also required to develop interpersonal relationships, inspire team members, and handle conflicts and different opinions. Most students are trained in communication on a local level where face-to-face meetings are common. 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. The English language used can no longer be casual and the underlying innuendos of individual words have to be evaluated carefully from a linguistic point of view. This is most important when there is different cultural interpretation at work. In different cultures the educational program itself may provide students with different skill levels in similar fields of study.[4] 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.

In an engineering design project, engineers work iteratively at the beginning of the project in order to come up with the best design solutions for the top level project requirements leading to system requirements that get “frozen” allowing a transition to manufacturing. That design phase is extremely dynamic and prone to misinterpretation which may not be caught on time and which could lead to failure of some kind of the project. Design choices have to be negotiated by the delocalized team members. All the technical analyses have to be done with the same software, comprising even the same version of the software.

The Hyperion project, 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.

II. INTRODUCTION

At the University of Colorado Boulder during the summer months of 2010, a small team of continuing education (B.S./M.S.) aerospace engineering seniors were challenged to develop a global academic project that would assess the feasibility of simulating known pains of the modern global industry. This undertaking became known as the Hyperion project.[5] The Hyperion project was to span 2 academic semesters during 2010-2011, consist of a minimum of 3 delocalized international student teams, and conceive, design, implement, and operate a completely new type of aircraft. In essence, the proposed academic project was to incorporate two major elements:

1. A global project management element with three participating teams located on three different continents, and
2. A technical design, implementation, and operation element to teach systems engineering principles required in aeronautics.

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. The University of Stuttgart, Germany and the University of Sydney, Australia both agreed to participate with the

University of Colorado at Boulder (CU), U.S.A in the experimental project. In addition to the stated goals, the Hyperion project is intended to foster global relationships among aerospace engineers and expose members to different philosophies and techniques. Integral to achieving this is the exploration and adoption of technologies that facilitate the sharing of ideas, real-time collaboration and interaction.

The blended-wing-body (BWB) NASA/Boeing X-48B aircraft was set as the inspiration for the aircraft design.[6,7] The BWB architecture was chosen as the initial design focus, as it is one of industry's leading fuel efficient platforms demonstrating the latest developments in green aircraft technology. The X-48 BWB concept was originally designed by Liebeck, Page, and Rawdon in 1998.[8] The airframe is a merger of efficient high-lift wings and a wide airfoil-shaped body, causing the aircraft to generate lift in its entirety and minimize drag, thereby increasing fuel economy. It is expected that the aerodynamically efficient BWB design will reduce fuel consumption up to an estimated 20-30%.[9] Unlike conventional tube and wing architectures, the optimal design of a BWB vehicle requires a much more tightly coupled systems engineering analysis, including aerodynamic and structural analysis of the vehicle, flight mechanical design, management of mass properties, and the development of modern control systems. The use of composite materials throughout the construction of the vehicle was also to be maximized in order to increase the experience and exposure of the students to the challenges and techniques used in modern aerospace manufacturing.

III. PROJECT DESCRIPTION

A. Project Requirements

Top-level project requirements were driven primarily from the two project elements, incorporation of the hybrid engine, and the Boeing/NASA X-48B architecture. Above all the Hyperion project shall conceive, design, implement, and operate a blended fuselage and wing aircraft. The aircraft shall have a wingspan between 1.8 and 3 meters. The Hyperion aircraft should have a lift to drag ratio approaching 20. The aircraft shall be designed to allow integration of a hybrid propulsion engine system. The Hyperion aircraft structure shall have a composite material outer skin and internal structure. The Hyperion aircraft shall have a modular design, allowing for shipping of the vehicle internationally without necessitating a freight shipping classification. The Hyperion aircraft shall be capable of takeoff and landing on a 750ft runway.

B. Schedule

The international team was composed of students from the University of Colorado in the USA, from the University of Stuttgart, Germany, and from the University of Sydney, Australia. Compared to a conventional academic project, the Hyperion schedule was orders of magnitude more complicated to develop as special consideration had to be made to accommodate the out of sync university's semesters. The Sydney semester began first, with Colorado's a close second, and Germany starting third in mid-October. Figure 2 shows a simplified schedule as well as each University's semester dates and overlap.

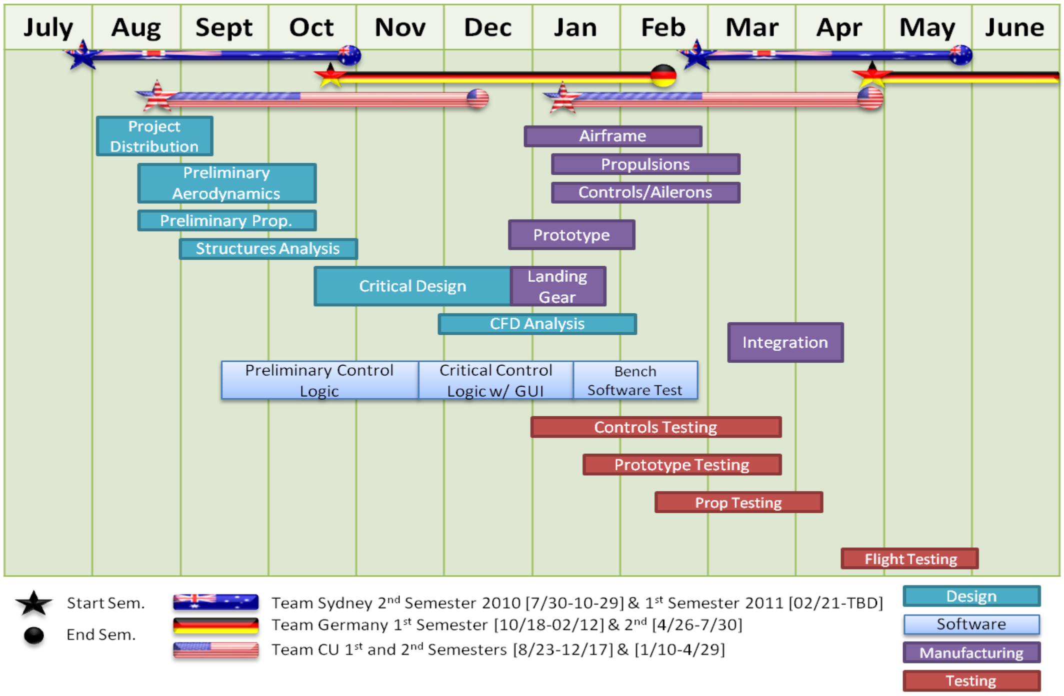

Figure 2. Simplified Project Schedule

The project schedule is based on the University of Colorado's Course timeline, which encompasses an entire project experience over the span of 2 semesters. The project is divided into two primary phases, in sync with the CU semester schedule: design in first semester (August to December) and manufacturing and testing during the second semester (January to April).

The first semester, or phase of the project course, is focused entirely on design, analysis, and prototyping. Starting with a statement of work and the top-level-requirements, students begin the semester organizing themselves, defining system and sub-system requirements, developing team and work break down structures, and conducting preliminary design. During the first design phase of the project students develop project and systems requirements and the architecture. There are two major decision gates based off of industry practices, a Preliminary Design Review (PDR) and a Critical Design Review (CDR). At CDR, the entire design development of each subsystem of the project is to be complete and frozen in terms of future development. This serves as a critical milestone for the teams to work towards.

The second phase of the project, after CDR, encompasses the manufacturing, integration, and testing aspects. Each component must be manufactured, tested at a subsystem level, integrated to the system level, and tested again to both verify and validate all project requirements.

The project deliverables are set to ensure both systems engineering principles and project management are projected throughout the educational experience. Students are able to gain real world technical experience, not by just designing, but by building their creation in a hands-on environment. Seeing manufacturing processes and learning to understand the technical limitations of production are an extremely valuable experience for every engineer.

The student team in Sydney comprised undergraduate students led by a PhD student. The activities of the students in Stuttgart were organized within the framework of diploma theses.

C. Global Project Team

The Hyperion project was divided into 4 student teams:

1. A Graduate team from CU
2. A Graduate team from University of Stuttgart
3. A graduate/undergraduate team from The University of Sydney
4. An undergraduate team from CU

The overall management of the project resided with the project initiating Colorado graduate team. Colorado was responsible for electronics, internal structure and systems integration. The aerodynamic design was started and developed by the Sydney team. Stuttgart complemented their work with full 3D CFD analysis. Raked wingtips and vertical stabilizers were designed by the Stuttgart team. Colorado and Stuttgart shared manufacturing tasks.

Projects in the academic environment are notably different from industry due to two primary factors. Collegiate students have varying class schedules with respect to one another, compared to industry teams' steady work hours. This makes scheduling the necessary daily meetings of a college team difficult for the students to internally manage. A second notable difference is that students who work on an academic project are motivated by a grade not salary. Their work is largely voluntary rather than mandatory. This requires a more subtle approach to project management, as the monetary motivational leverage is not available to the manager. Fortunately students have another strong motivational driver—passion.

The architecture of the Hyperion project team is shown in Figure 3. The goal of the team design was to expose senior and graduate students to the need for collaborating in a global industry with design offices and manufacturing facilities around the world. As the Colorado team is self-directed, the external advisers include Department faculty members which are consulted and industry advisers from the Boeing Company. Colorado's graduate team leads the development of the project and distributes and incorporates work from the CU undergraduate team, the German and Australian teams through the use of configuration control documents. These living documents are essential to maintaining consistency and direction of the designs. The requirements on quality of these documents are very high due to several factors. Tasks, revised at the end of workday for the next team, must be defined with great precision and extreme clarity. Each team works eight hours and updates the configuration control document, then passes it to the next team to work eight hours, and so on. 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.

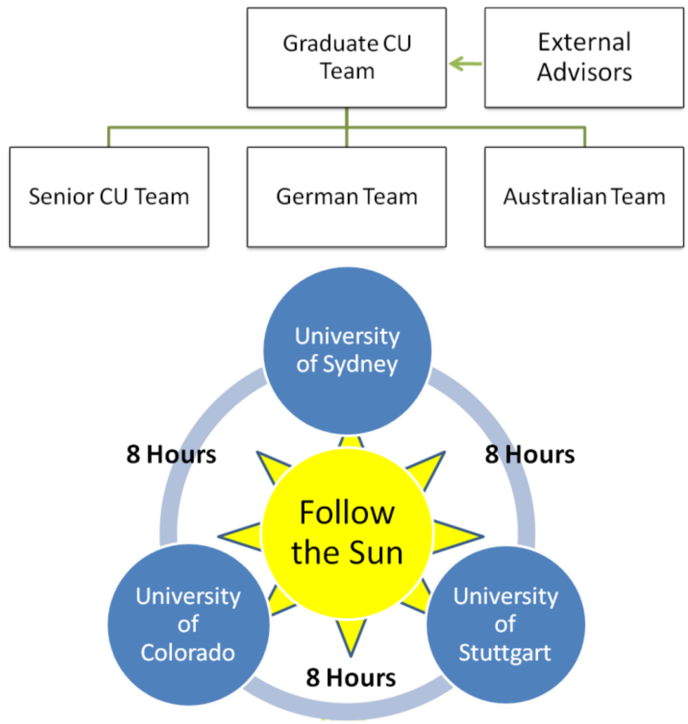

Figure 3. Hyperion Team Architecture

1. The Graduate University of Colorado Team

The CU graduate team at the University of Colorado Boulder led the project's development. The team focused on all of the integration, management, and internal designs of the aircraft. The master designs of the aircraft are kept in Colorado, for quality control and logistics. Multi-disciplinary backgrounds are essential to a successful systems engineering experience.

Each of the 13 team members was given ownership to single subsystem or managerial position of the project, which trains each student in leadership skills. Table 1 shows the breakdown of ownership amongst the CU graduate team. Students work toward a degree in Aerospace Engineering Sciences (AES), Electrical Engineering (EE), and Master in Business Administration (MBA).

The idea behind assigning team leads is to instill a sense of ownership over that particular item or subsystem of the project. That allows for each team member to be involved directly, and allows the team as a whole to divide and conquer. Each sub-team lead is responsible for organizing their own respective meetings with secondary members to delegate and micro-manage the work effectively. This allows the Project Manager to efficiently delegate work and easily identify the performance of the team.

Table 1
Graduate CU Team Leadership Roles

Primary Responsibility	**Secondary Subteam(s)**
Project Manager	Business, Manufacturing
Configuration & Systems Manager	Controls, Propulsion
Systems Engineer	Controls
Propulsions Lead Engineer	Aerodynamics, I&T
Structures Lead Engineer	Aerodynamics, I&T
Controls Lead Engineer	Computer Aided Design (CAD), I&T
Electrical Lead Engineer	Controls, I&T
Mass Properties Manager	CAD, Controls
Integration & Testing Lead Engineer	Electrical, Structures
Aerodynamics Lead Engineer	Mass Properties, Structures
Manufacturing Lead Engineer	CAD, Structures
CAD Lead Engineer	I&T, Structures
Business Operations Manager	I&T, Accounting, International

The graduate CU team holds a formal 1-hour weekly Configurations & Systems meeting where all sub-teams report on the progress, problems, and plans of their system development. The meeting also serves as an opportunity for external advisors and the customer to provide input and guidance for problem solving strategies and risk mitigation. In addition, weekly internet meetings are held between CU/Stuttgart, CU/Sydney, and Stuttgart/Sydney. The agenda is similar with updates on progress, problems, and plans.

2. The University of Sydney Team

Of the three international Universities, The University of Sydney's semester scheduling was the most significantly different from the other two universities. Not only did Sydney's semester begin before both Colorado's and Stuttgart's, it was also the second semester with regards to their academic year. This early beginning drove the early decisions with regards to the work breakdown of the project. It also required that a sub-team of students at Colorado started work on the project during their summer break prior to the semester start.

In order to maximize the amount of work produced by the Sydney team, they were given the task to perform the preliminary aerodynamic trade studies regarding the geometric shape of the aircraft. In this manner, the work could begin immediately, without waiting for the Colorado and Stuttgart teams to be formed. By the time the Colorado team was fully populated and structured, Sydney had several preliminary models complete for designs to be evaluated and discussed between the teams.

After the design work was complete, the efforts in Sydney shifted to produce a ½ scale static wind tunnel model of the Hyperion aircraft to be tested at the University of Sydney's 7 x 5ft wind tunnel. Of the three universities, Sydney was the only institution with an adequate wind tunnel for testing the Hyperion aircraft, so it was a natural fit to have Sydney lead the aerodynamic design efforts. Continued work was performed during their summer break. A PhD student and undergraduate students built multiple models and performed aerodynamic analysis and testing on the aircraft. This led to preliminary sub-scale flying model to verify stability and control characteristics of the design concept, followed by the wind tunnel testing of a half-scale model in a 7 X 5 ft wind tunnel, which verified the confidence of the earlier computational fluid dynamics (CFD) analyses, and provided guidance to set up the full-size flight test prototype. Figure 4 shows the half-scale model installed in the wind tunnel at The University of Sydney. Table 2 denotes the responsibilities of the University of Sydney team.

Figure 4. Half-scale model installed in the 7 by 5 ft wind tunnel in Sydney

Table 2
University of Sydney Team Leadership Roles

Responsibilities
International Aerodynamic Lead / Team Manager / Wind tunnel testing Lead
Performance Engineer / Wind tunnel model construction and testing
Structures Engineer for wind tunnel model / CAD
Structures Engineer for wind tunnel model / CAD
Sensors and Autopilot Engineer

3. The University of Stuttgart Team

Last to form and begin their semester, the University of Stuttgart team of four diploma candidate aerospace engineering students was brought on board. Their focus was on aerodynamic modeling and composite manufacturing. The students received manufacturing help from two undergraduate students. Stuttgart joined the project after the preliminary trade studies had been performed on the shape of the aircraft.

Similar to Sydney being well prepared for aerodynamics studies, the German team brought a unique set of skills in advanced computational fluid mechanics (CFD) and composite manufacturing which were absent on the Colorado and Sydney teams.

The CFD computations performed at Stuttgart served mainly three purposes: first of all was the computation of a half-scale model with symmetric flow conditions. These results were used as a cross check for the results obtained at Sydney during the preliminary design process. The second purpose was the assessment of the engine integration and its impact on the aerodynamic characteristics of the aircraft. The third task was the investigation of the manoeuvrability of the aircraft. Several configurations with control surface deflections were investigated for symmetric and asymmetric flight conditions to evaluate the effectiveness of the flight control system. The aerodynamic derivatives obtained in this part are needed by the team responsible for the flight control software.

All of the German team members were also experienced with CATIA®, the primary design software used for the plane's development. Table 3 denotes the Stuttgart team member responsibilities.

Table 3
Graduate Stuttgart Team Leadership Roles

Primary Responsibility	**Secondary Subteam(s)**
Stuttgart Project Manager	Structures, Manufacturing
Aerodynamics Engineer	CATIA Contact, CFD
Aerodynamics Engineer	CFD Engineer
Propulsions Lead Engineer	Aerodynamics, I&T
Manufacturing	
Manufacturing	

4. The Undergraduate University of Colorado Team

With no previous project experience, the undergraduate team at Colorado was formed per the requirements of the capstone aerospace senior design course. Their focus was on the hybrid propulsion system, an attainment which was considered a stretch goal for implementation in the Hyperion aircraft. Eight students were assigned to the team, all seniors in aerospace engineering. In order to maximize the undergraduate teams learning experience the team operated largely independently, with their primary project goal to design, build, and operate the hybrid propulsion system for the Hyperion aircraft. Taking ownership of the propulsion subsystem allowed for minimal overlap and dependency with the rest of the aircraft's design development. One graduate team member assumed the liaison position with the undergraduates. The undergraduate team was given a set of requirements recognized in an interface document for their propulsion system to meet, which included dimensions and performance criteria. This organization allowed for the Stuttgart, Sydney, and Graduate Colorado teams to move forward with the designs without constant involvement with the senior CU team. In the event the undergraduate team fails to produce a working engine, a basic electric motor propulsion system was designed to be used as an off-ramp for the airframe. This allowed for the senior team to have an adequately scoped project, while minimizing the risk to the international Hyperion project failing being able to fly due to lack of engine delivery. In the same sense the success of the undergraduate team needed to be independent of success or failure of the graduate team designing the Hyperion airframe.

The undergraduate CU team is structured under the same principles as the graduate team, with team leads and specific subsystem ownership assigned to individuals, shown in Table 4.

Table 4
Undergraduate CU Team Leadership Roles

Primary Responsibility	Secondary Subteam(s)
Project Manager	Aerodynamics
Electrical Systems Engineer	Controls
Mechanical Systems Engineer	Aerodynamics, Mechanical
Chief Communications Liaison	Software, CAD
Chief Financial Officer	Controls, CAD
Chief Safety Officer	Mechanical, Electrical
Chief Test Officer	Controls, Structures
Chief Equipment Specialist	CAD, Software

D. Work Breakdown Structure

The work breakdown structure (WBS) of the Hyperion project served as a challenging logistics problem for students inexperienced in project planning. The question, "who can do what and when?" is easier to identify in an industry environment, where employees are hired for specific jobs and titles. For a student team comprised of varying degrees of skill-sets and schedules around the world, there is little time to waste in determining who is responsible for each subsystem and deliverable. There were two primary drivers for the WBS distribution, *skills* and *schedules*. In determining which teams were assigned tasks and related ownership in the project, the skill-sets of each university were weighed with respect to one another to identify strengths. The schedules were then evaluated to determine what work correlated with the development stage of the project. Since Australia began their semester first and were strong in aerodynamics, they were given the responsibility of the aerodynamic shape of the aircraft, the preliminary configuration design, the sizing of the control surfaces and contributing to weight and balance analysis for stable flight. Germany, with their CATIA strength and fabrication skills, were given the lead in developing the wingtip and vertical stabilizer designs, CFD analysis, and manufacturing of the center body skin. The Colorado graduate team led the structures, electronics, controls, software, mass properties management, financial operations, and overall project management.

The development of the logistics of collaboration was a major undertaking. The skills of all the participating international students had to be incorporated in the work distribution management. The WBS was first split in 5 categories which followed the systematic order of the project's development, with the exception of management which was constant across the 9 months. The top level WBS is shown in Fig. 5. From this WBS and the items identified as the top level systems of the project, further more in-depth WBS were developed, which were then decomposed further.

The systematic approach to the WBS resulted in an effective use of team skills, maximizing production and minimizing risk.

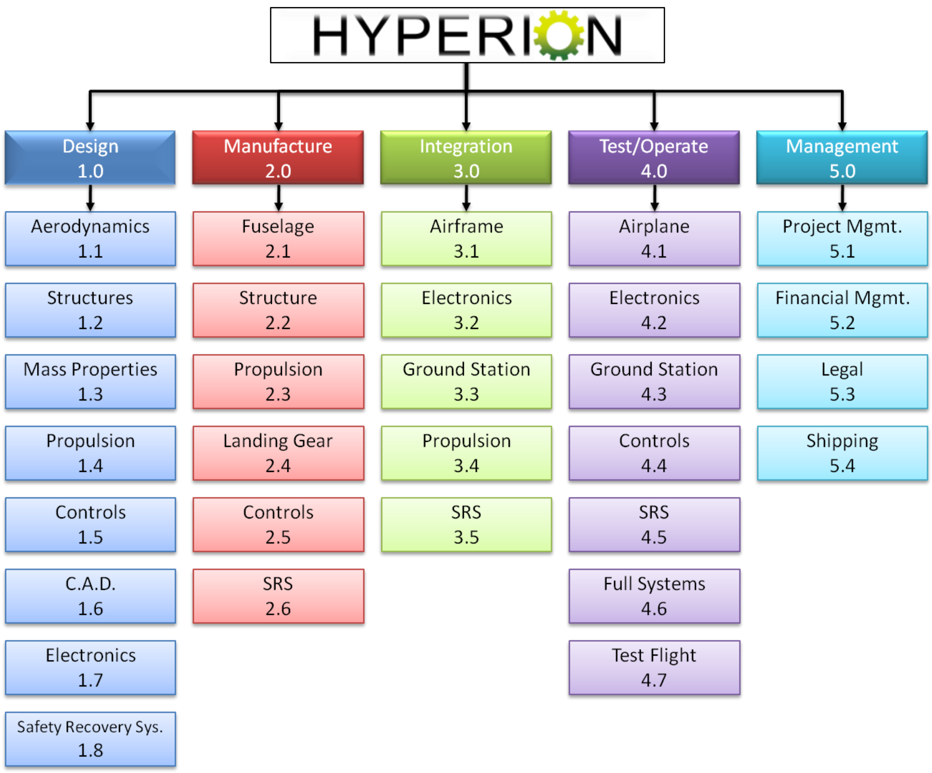

Figure 5. Top-Level Work Breakdown Structure

E. Collaborative Work Flow-Down

A typical example of a work flow is shown in Figure 6. Sydney students developed a ½scale model for wind tunnel measurements that include lift measurements and stall conditions. They communicated their results to Stuttgart where adjustments were made to the computational modeling and new results were generated, which then were communicated to Sydney for additional testing.

The internal structure was manufactured by Colorado students and shipped to Germany. Students in Germany made the molds and fabricated the skin for the center body. The finished center body was shipped back to Colorado where in meantime students have manufactured the wings.

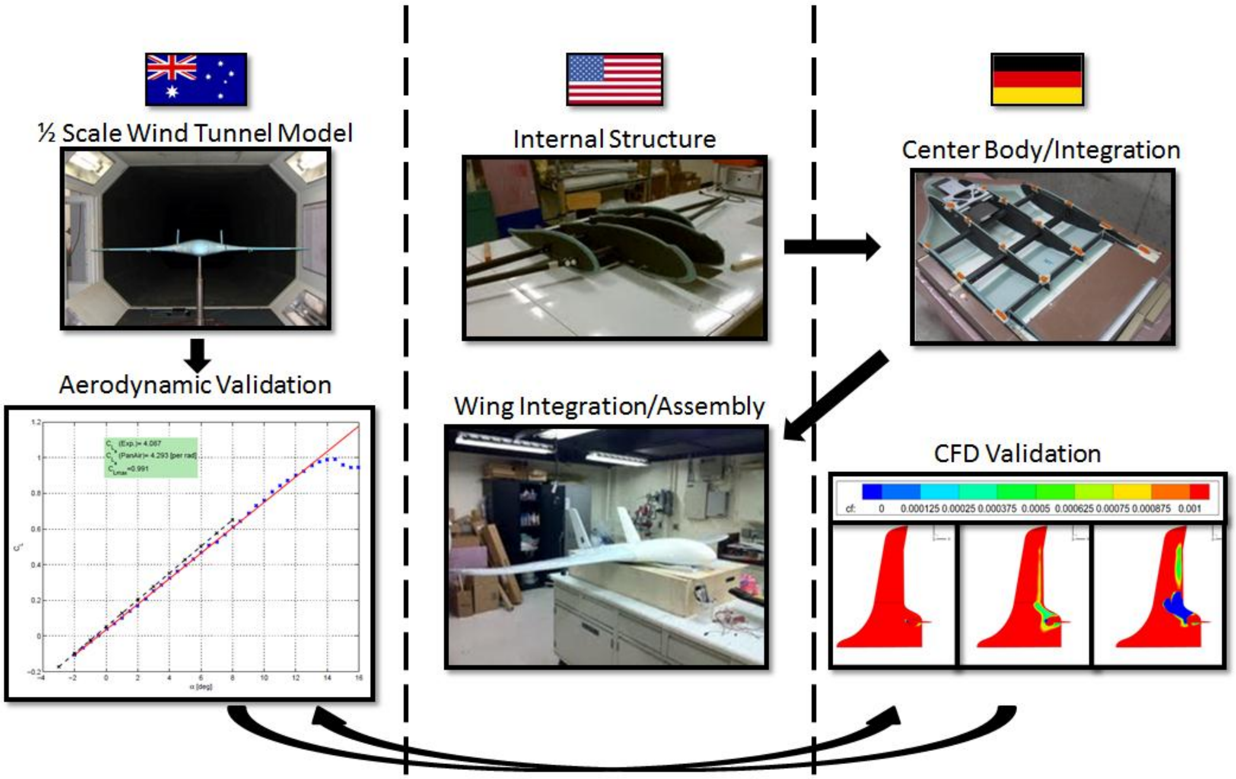

Figure 6: Example of the International Aerodynamic Design and Manufacturing.

A typical Follow-The-Sun design and development example is given here. The Colorado team makes some changes to a structure component. It evaluates if the changes still meet requirements and reflects on what the outcome of the change has on manufacturing and aerodynamics. After 8 hours work data and results are forwarded to the team at Sydney where the structural implications on the aerodynamic design are evaluated with computer modeling or wind tunnel experiments. From their 8 hour work new design changes are proposed. These new results, together with the original change request are forwarded to Stuttgart. They evaluate the manufacturing implications on the aerodynamic and structural designs; add some new CFD calculations to the analysis and evaluate the outcome of their research on the initial change requests. In 24 hours a full analysis of a change request could be performed, adopted, or appended with new change requests. The Figure 7 details the manufacturing in more detail and shows the delivered center body returned from Germany.

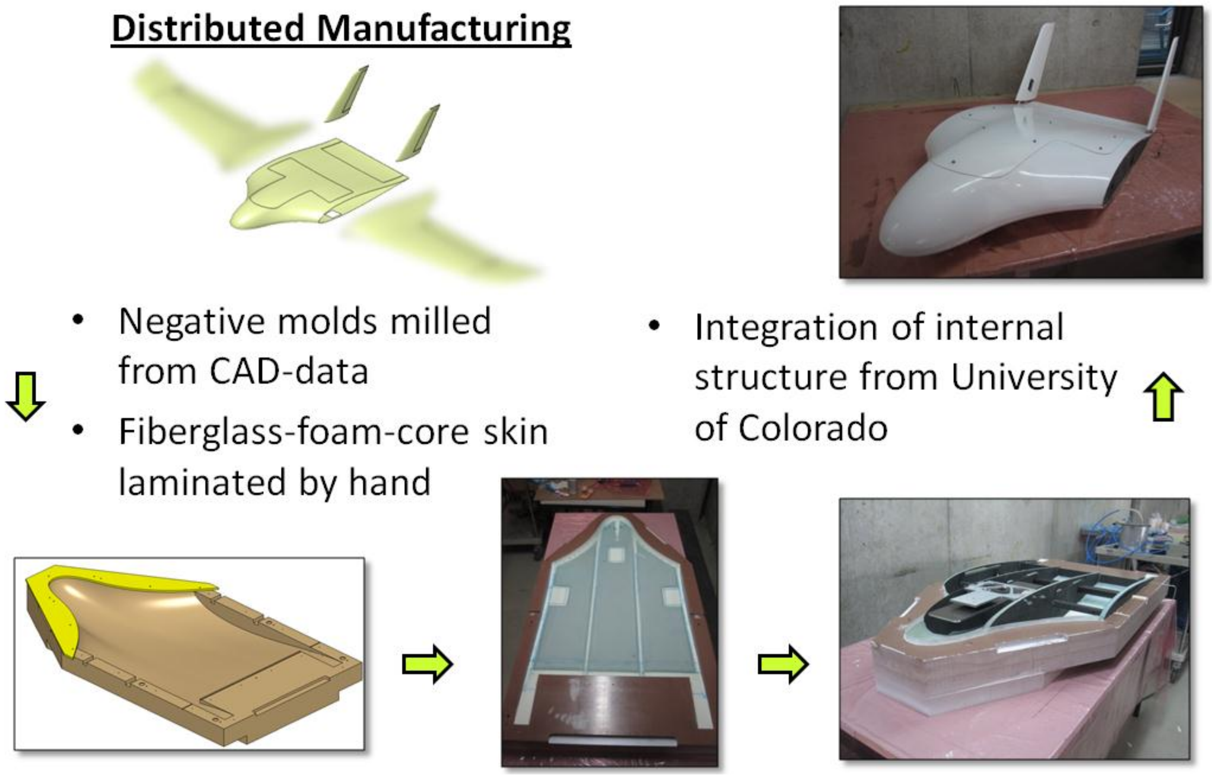

Figure 7: Detailed Manufacturing of Center Body at Stuttgart.

While the center body was fabricated in Germany, the Colorado team manufactured the wings. As both sub systems must be integrated and fit the interface between the center body and the wings must be exactly the same. This is a high risk in all delocalized manufacturing. In order to achieve that assembly goes smooth an Interface Dimension Template (IDT) was cut from Plexiglas (Figure 8). One template was sent to Germany and an exact copy was kept at Colorado. Germany designed the center body for joining with the IDT and Colorado designed the wings to join with the IDT. With this technique the wings could be attached to the center body without pain. The same method was applied for the interface between the wings, manufactured in Colorado, and the winglets, manufactured in Stuttgart.

At the same time where the center body was manufactured, the electric system had to be readied for installation as soon as the center body returns. In order to assure that the electrical system will fit the so-called Flat-Sat layout of the electronic components was used by the Colorado team.[10] A flat-sat is a procedure adopted from the Cubesat community. It is a full size flat horizontal cross sectional layout of the aircraft electrical system (Figure 9) with model spars and ribs at the right locations. It allows for testing the electronics and helps in defining the optimal routing of cabling in the aircraft center body and wings.

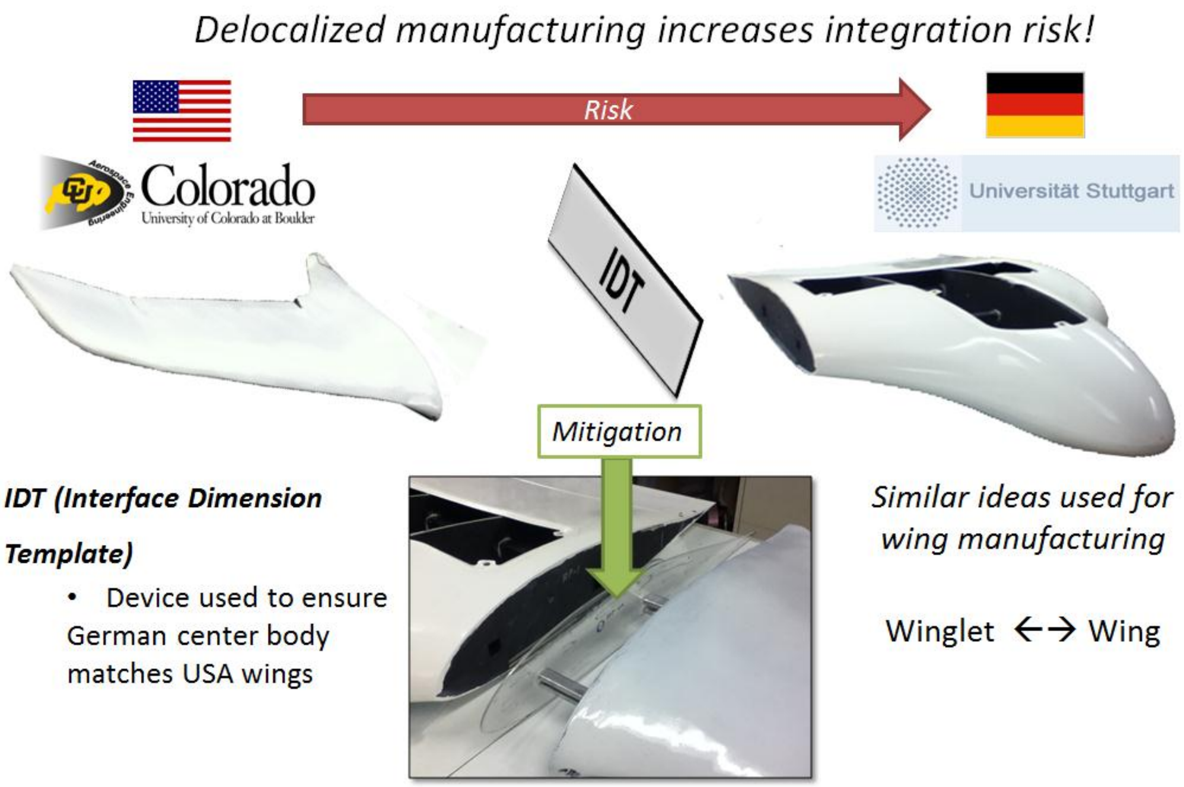

Figure 8. The Interface Dimension Template Guaranteed Wing & Center Body Integration.

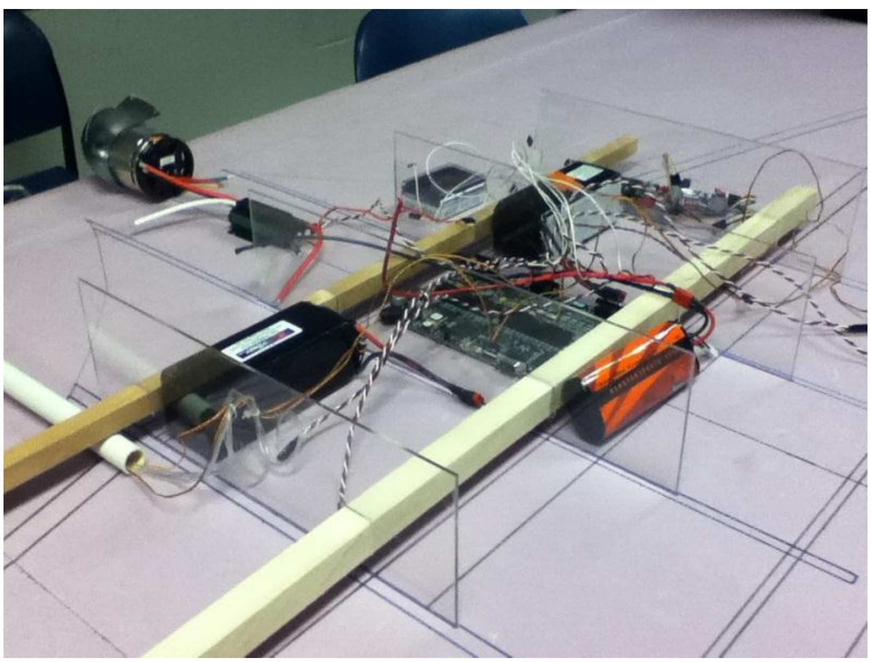

Figure 9. Flat Sat Simulation and Test Bed

IV. BEST PRACTICES

A. Communication

Coordinating the efforts of multiple international teams, each with their own language and culture, is complicated at best. It can lead to higher productivity and quality in a shorter time but also to misunderstandings and setbacks. These in turn are amplified by the constraints of different time zones and challenges of international shipping. More significantly, team members gained valuable international experience.

Communications management is perhaps the most critical aspect of the Hyperion project. With multiple teams operating in separate locations, constant contact is necessary to make sure efforts are in sync. Fortunately, the options provided by the internet have enabled all three teams to share documents, test technical models and maintain synchronization. Weekly conference calls are held via Skype™, or Polycom® allowing for both audio and visual communication. Documents are shared through cloud computing using Huddle™.

An example of this successful communication and work flow can be found in the aerodynamic design experience. Engineers in Australia would work with model dimensions and upload their CAD files to the cloud with appropriate documentation and verbalize ideas over Skype™. This allowed for seamless continuation in Germany, where the Stuttgart team could refine. Towards the end of the Stuttgart work day, updated files and ideas would be shared with the Colorado team who would add their expertise to the aircraft's design and check development with the requirements. After a day's work, they in turn would post their contributions on Huddle™, document and discuss changes over Skype™, and the Australia team would resume their efforts. This constant effort allowed for three days' worth of work to be completed in 24 hours.

The large number of team members makes tasks complex. Between the three universities there are 32 students and several professors. Adding the 20 industry and academic advisers brings the number to 52 and the possibility for 1,326 one on one communication channels. With so many opportunities for communication, a small percentage of miscommunication is already a large number of miscommunications (Figure 10)! At one end a person writes or encodes a message and sends it to a remote person that must decode the message. Encoding and decoding impact the tone, which may depend on mood, the intent which includes cultural interpretations and body language is not included. The same word may have different meaning for people from different cultures and schooling in the language, especially when English is not their first language. Although the technical terms may be understood, the more descriptive wording may lead to an incomplete or filtered communication. To mitigate or reduce the occurrence of miscommunication, interface and configuration control documents were implemented to be able to track and manage critical pieces of information on a daily or weekly basis. The precision and clarity of these documents must be at the highest achievable level. Collaboration must also be rooted on of trust because there is limited control over non-local team efforts. Understanding the skills and capabilities of each partner also remains a challenge. Lastly, free sharing of technological information may also lead to intellectual property issues.

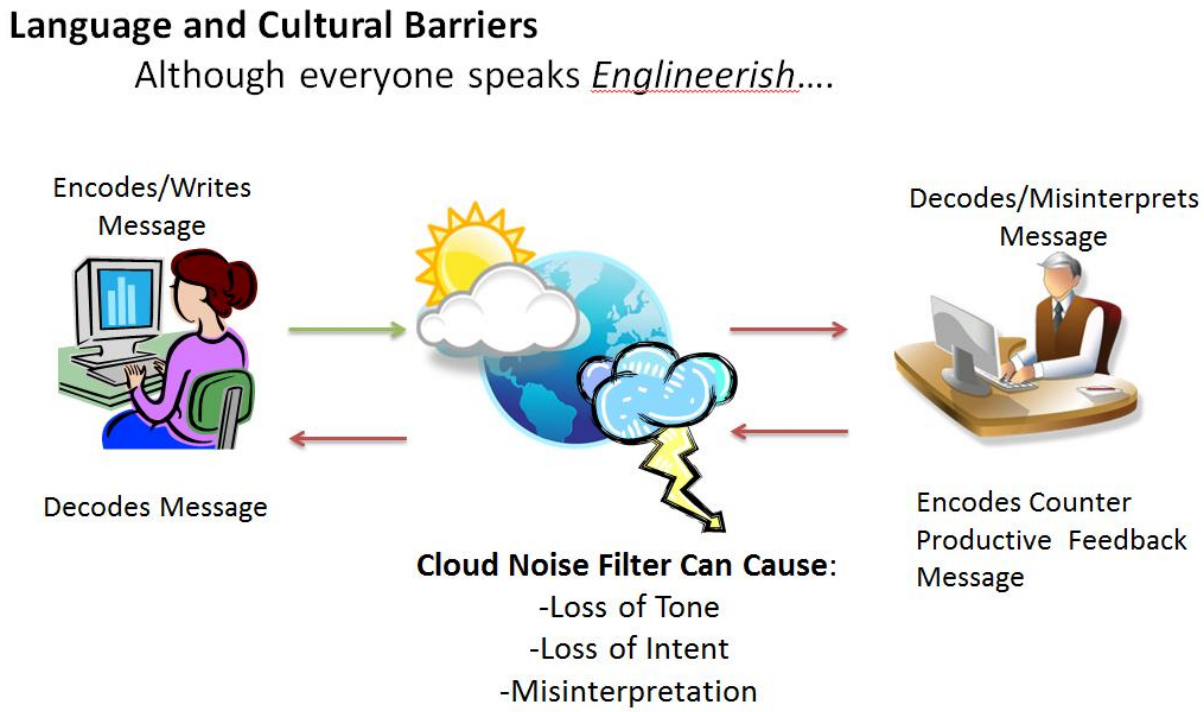

Figure 10: Remote Communications Suffer "Transmission" Errors.

Because of their academic nature, student projects are particularly prone to communication difficulties. Utilizing a managerial structure of the teams with defined responsibilities, decentralized decision making, and complex interfaces allows for multiple communication modes of failure. The person issuing a message with a purpose normally encodes that communication based on a personal bias. The bias is rooted in encoding the message based on the environment, culture, and knowledge of the sender. A recipient is biased by one's own hearing, listening, reading, language skills, ethical values, mood and motivation. Sender and receiver both have preconceived ideas, references, and interests in the project contributing to a certain noise level in the communication. The choice communication medium is known to have an impact on the communication success. Elements that is absent in virtual communication is body language, facial expression, tone of voice which have an tremendous impact on the decoding of a message by the recipient.

The CAD design work was accelerated effectively by using FTS techniques. With most student projects only comprising 1-2 CAD engineers, the Hyperion project was able to employ roughly 10 students with CATIA design work each week during the design phase. This allowed for far more design work to be completed in a very short amount of time. The entire structure, skin, landing gear, and propulsion system was designed in roughly 6 weeks. This included structural analysis and sizing of the ribs, spars, skin, landing gear attachment points and elements of the propulsion system, either by formulaic calculations or through CATIA with contributions from each university. The Hyperion design and model is shown in Figure11.

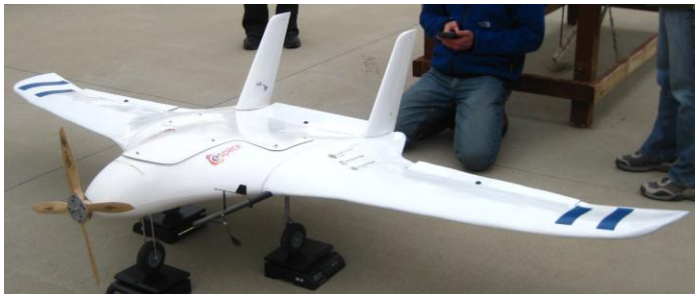

Figure 11. The Hyperion Aircraft

None of the collaborative CAD work could have been possible, had each university not had the same CAD program and version. Determining early on in the project which software to use proved essential.

B. Manufacturing

The problems faced by Boeing's Dreamliner team highlight the complexity of international manufacturing.[1] The CU-Hyperion team has benefited from access to different points of view as well as facilities otherwise unavailable. These include engineers who have extensive experience with aircraft design, advice from experienced professionals with international collaboration knowledge, as well as fabrication and testing facilities in the Australia, Germany, and the United States.

To ensure that final assembly will be completed once the center body arrives from Stuttgart, a laser cut Interface Dimension Template (IDT) was designed to be used to verify the center-body produced in Germany will line-up with the wings produced in Colorado. One IDT was shipped to the Stuttgart team, while one remained with Colorado.

The logistical constraints imposed by time and distance are another significant problem caused by international manufacturing. As Boeing experienced, millions of dollars' worth of sub-assemblies will sit idle while the appropriate fasteners are still being sourced.[9] The Hyperion supply chain is much less complex, but still at the mercy of late deliveries. The central internal body frame structure was manufactured at Colorado and shipped to Germany where the fiberglass skin was manufactured. The fiberglass body was produced at the University of Stuttgart, with very little margin to allow for time over-runs. If the production schedule is not met, it will be very difficult for the Hyperion team to meet their objectives. This constraint highlights problems faced by global industries.

Risk mitigation is undertaken to ensure that this possibility of failure to deliver does not come about. The German team, experienced in composite manufacturing, began work on the negative molds, while Colorado, manufactured the internal structure of the plane, Figs.6&7. Due to the size of the molds necessary, the German team contracted an outside firm, Plandienst, to CNC mill the molds of the center body, further requiring extensive planning and quality control, mirroring industry practices. While the molds were being constructed, other students were allowed time to build the shipping crate necessary to ship the center body to Colorado for integration with wings and engine for flight testing. One critical requirement was also identified early in the project to ensure expedited shipping would be possible if need be. The largest shippable box dimension had to be kept under international priority freight classification which is considerably more expensive.

After the internal structure was shipped to Germany for integration with the outer shell, the Colorado team shifted their manufacturing efforts towards four ½ scale, fully functioning prototype planes and the full scale wings. The ½ scale models were used to test flight control systems of the novel aircraft design. The electrical sub-system was tested according to the “Flat Sat” procedure and was ready to be installed at return of the center body from Germany.

V. LESSONS LEARNED

A. Follow-the-Sun

A key component to the Hyperion project was the international work delegation and distribution. The underlying concept for each team to trade off work daily is conceptually ideal; however it is difficult in an academic environment. Each student team member has a unique schedule, due to variances in class schedules and part/full time employment. Being able to allocate even a single continuous 8-hour block to a FTS activity is unlikely for any student team. Although appropriate for initial CAD design Follow-the-*Week* (FTW) assignments became much more manageable and successful to implement during the later vehicle implementation phase. Rather than each person work 8-hour days, each person was given a specific design item to complete each week or over a defined number of days. At that point management decisions were made to which other team should review and/or amend the work from a different skill set.

The largest benefit to FTS activities came in the form of the CAD design of the aircraft. One week was dedicated to scheduling and identifying the design synergy which would allow for the most efficient use of time. Having each team distributed 8 hours apart allowed for the student’s ideas to be shared and critiqued amongst each team in a 24 hour period. The CU team was able to start with their ideas, and then obtain critical feedback from Sydney and then both CU’s and Sydney’s ideas and critiques could be reviewed by the Stuttgart team before the next day and vice versa. FTS allowed for each university to have a chance to learn from one another and facilitated a global exchange of knowledge. During the preliminary and critical design phase, every week had a new set of deliverables. Each part to be designed was identified as being independent of everyone else’s development for that respective week, allowing for the individual student to manage their own weekly time to devote to the work. At the end of the week, all of the newly developed parts were integrated into the model and verified based on the requirements. Each week the process repeated with a new round of distributed parts to be designed. As the designs matured and more parts became dependent on each other, fewer team members were needed to manage and continue the CAD designs, as the files become too large and complex for multiple people to manage. It was much more efficient to have 1-2 people leading the CAD designs in the later stages of development, rather than try and have 6-8 people trying to download and edit the master CATIA file simultaneously. Two advantages became apparent from shifting the design work from multiple CAD engineers at PDR to only a select few nearing CDR. The schedule risk was reduced first, as development was extremely fast. The entire Hyperion aircraft was drawn in CATIA from scratch in little more than 4 weeks.

As more and more detailed designs were produced, more personal attention was necessary to integrate and manage the files. Allowing two primary engineers take the lead (one at CU, one in

Stuttgart) after the “little stuff” was complete, also allowed the remaining students to shift their efforts on the remaining subsystems where more work was required. The second advantage was that it greatly reduced the integration risks. The primary CAD engineer at CU worked closely with the primary CAD engineer at Stuttgart, constantly in communication regarding the designs and manufacturing of the aircraft. After CDR and during manufacturing, both universities had a primary contact who was 100% up-to-date with the designs. This allowed for the rest of the team to quickly obtain the most current design information at any given time. The inability to secure funding for Sydney’s project efforts constrained the scheduling of the wind tunnel test program. This problem was eased significantly by the CU funding, but the smaller team size resulted in more work spread across fewer students.

Refinements to the global project course should be made. Academic advisors need to have a solid understanding of the different academic systems around the partner universities. The participating education programs may have different focus on technical fields and the desired learning outcomes may be different as well, as dependent on accreditation requirements. Students at the same official academic level at different universities may have different technical abilities and backgrounds and all need to be integrated in the skills profile of the global team. Development of teams based on team member skills is important in all team work, but at the international level the scrutiny whether these skills are met is much more difficult.

Aircraft manufacturing requires a very specific set of talents that one can best develop through actual experience. With much of the aerodynamic design completed in Australia and the bulk of the composite material manufacturing in Germany there were lost opportunities for the Colorado students to learn and perfect these skills. This reflects the great challenge faced by global industries’ core of domestic engineers which is the lost opportunity to hone technical skills through practice. It is common knowledge that systems engineering is a skill honed over many years in practice; it can not be learned from books alone, and certainly not acquired fast. Although industry benefits from finding special skills in all parts of the world, that skill may be diminished or lost in domestic facilities.

For the Colorado team the loss of opportunity in certain technical fields was offset by a gain of significant leadership experience in international project management. The Colorado team has benefited from access to different engineering points of view and intellectual resources as well as facilities otherwise unavailable. In addition the project could be accomplished in a short time frame as many tasks are serial and can not be done in parallel. The Stuttgart and Sydney teams could hone their skills in aerodynamic analysis but lost opportunities in e.g. electronics or structural analysis. It is reasonable to assume that none of the three teams could have developed and successfully flown the Hyperion within 2 semesters of work, lastly because it is difficult to assemble a local team of 32 mostly graduate students and ten fully vested advisers.

B. International Shipping

The internal ribs and spars for the aircraft manufactured at Colorado were shipped to Germany where the external skin was manufactured and the central body assembled. The parts were declared as part of a remote control aircraft frame and so did not encounter American ITAR constraints. Export documentation forms must be filed correctly by the sender and the recipient must fill out import documentation with correct content to allow adding value in Germany and shipping back to the sender. For the return shipment, the carrier’s pre-clearance team must have specific information on the bill of shipment. All these formalities are not in the mindset of most academics. Universities may not be well prepared to support international shipments correctly either. Academic and staff personnel and students who then have to handle the custom formalities do not have the appropriate education to handle import-export and mistakes are prone to be made. These mistakes may end in a quarantine of the shipment which can derail such a global project, especially because of the teaching time schedule. Customs have strict rules that need to be followed with highest precision and getting educated on that topic well ahead of shipment dates is adamant.

VI. CONCLUSIONS

The Hyperion project was intended as a design project for an aerodynamically efficient aircraft also using novel hybrid propulsion technology as a stretch goal. In addition the vehicle was designed to become a new test bed for future design improvements and further development of green aircraft technologies.

The Hyperion project not only produced and flew a new aircraft with novel architecture, but more importantly, incubated an educational experience for more than 32 students around the world unlike any other; preparing them for working in the global aerospace industry. The international collaboration by teams from three international universities became a great learning experience. Students at different universities introduced new and unique skills that benefited the design concepts in all aspects. The totally new design concept was brought from an idea to a finished product in about 9 months. This is an extremely fast development of a novel technology.

The lessons learned for engineering collaborations were substantial, but with a positive mindset of all international participants the operational procedures during the design phase and during the manufacturing phase were quickly absorbed by all the team members. A major bottleneck in the international manufacturing world is dealing with constraints by local governments and customs agencies, which remain a wild card in any international cooperation. Another major constraint is financial interaction between universities, which may be new territory for some departments.

Altogether, the Hyperion project was an exciting and rewarding experience for engineering students around the world. Honing clear and precise communication skills was a major challenge. Learning to write and work with dynamically changing interface documents was a most rewarding learning experience and prepared students well for today's industry requirements. Hyperion was a successful international design and manufacturing course which should be built upon with improved assignments including the lessons learned. A video of the development of Hyperion is available.[11]

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