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North American Aerospace Project - Adaptable Design/Build Projects for Aerospace Education

Edward Crawley,

MIT, Cambridge, Massachusetts 02139

Robert Niewoehner, Peter Gray

USNA, Annapolis, Maryland 21402

Jean Koster

University of Colorado, Boulder, Colorado 80309

ABSTRACT

The North American Aerospace Project (NAAP) is a NASA/industry sponsored effort to accelerate penetration of the project-based educational concept of “Conceiving, Designing, Implementing, and Operating” (CDIO) into US Aerospace Engineering programs. NAAP is developing innovative educational approaches, tools, methods and concepts specialized for the education of the future aerospace engineers. Several projects have been made available in a standardized template format. The template is designed to help an interested faculty member to quickly adopt a project and introduce it in a class.

KEYWORDS

Education, workforce, projects, template

I. Introduction: A project relevant to industry needs

Aerospace generally, and aeronautics particularly, is a key sector of the US economy, contributing significantly to the gross domestic product, positive balance of trade, and national security. Yet the sector is facing a systemic challenge – maintaining a world-class workforce. Over the next decade, the demographics of the sector suggest that there will be a significant shortfall in technically competent engineers and other technical specialists necessary to keep this sector healthy, and preserve the nation’s aeronautics core competencies.

From a national policy perspective, this need has been clearly recognized. The *National Aeronautics R&D Policy* instructs that “executive departments and agencies with responsibility for aeronautics-related activities should continue to invest in educational development of the future aeronautics workforce...” The *NASA Strategy Plan of 2006* references the need for NASA’s own Strategic Management of Human Capital, and in the section on Strategic Communications: Education Initiatives reinforces NASA’s responsibility to “strengthen NASA and the nation’s future workforce” and to “Attract and retain students in STEM Disciplines”. The NASA goals include taking “responsibility for the intellectual stewardship of the core competencies of aeronautics” which certainly includes their retention by the workforce. The importance of STEM workforce is paramount to other organizations as well, including the NAE, the AIAA and the AIA.¹ In 2005, bipartisan requests from the US House of representatives and the US Senate prompted the National Academy of Sciences to conduct a study, known as the “Gathering Storm” report, of America’s competitiveness in the evolving global market. The study led to the American COMPETES Act. The revised report² of 2010 concludes that the gathering storm has reached “Category 5”. In their overall assessment the committee concludes that

“overall the United States long-term competitiveness outlook has further deteriorated” since 2005, and that “America’s younger generation is less well-educated than its parents.”

Our consortium has proposed a solution that is designed to have widespread systemic influence on the university preparation of the aeronautics workforce. The program seeks to strengthen US university programs that prepare aeronautical engineers, and to develop and disseminate curricular materials and methods in a form that is easily transferred to and adopted by others, to use in reforming and strengthen their programs. Our architecture will furthermore encourage participation from the extended community of aerospace programs, adding their innovations to a readily accessible library.

II. Impacting the knowledge and skills of graduates

Over the past eight years, a growing number of international engineering schools have formed a collaboration to develop a new vision of engineering education called the CDIO Approach (www.cdio.org).³ CDIO is designed to deliver the knowledge and skills needed by industry. It provides an education stressing engineering fundamentals, set in the context of the **C**onceiving, **D**esigning, **I**mplementing, and **O**perating process.

The CDIO approach identifies and implements 12 Standards of Effective Practice. Critical to them is the extensive use of Project-Based Learning (called here PjBL to distinguish it from the more general Problem Based Learning). A key innovation is the integrated use of PjBL in both the earlier and later years of the undergraduate education. Such use of PjBL has been shown to increase the acquisition of deeper knowledge and develop in students desired product and team skills.⁴⁵ Such active learning approaches attract and retain more students in engineering. Interestingly, it has been demonstrated that exposure to Project-Based Learning in the first and second year preferentially retains women (and potentially minorities) in engineering,⁶ and exposure in the junior and senior years influences the career choices of students away from non-engineering paths, back to careers in engineering.

In the ongoing effort, we are developing modularized curricular materials around aerospace PjBL.

III. Sustaining the program

In order to address the aerospace workforce agenda over the next decade, innovations must be sustainable - in terms of faculty members’ time, skills and interests, the financial resources, and the effort required to identify appropriate industrial projects. The first element of sustainability is to directly produce project-based materials that are easily available and ready to use. We are developing and refining modules for project-based learning of aeronautical knowledge and skills that are well described, and available in a standardized format on the Web. A project module includes instructor notes, activities, material descriptions, student activities and learning assessment tools. We are deploying a Web-based mechanism by which the aeronautics industry becomes involved in defining the projects for a given school year, without having to interact individually with each of the hundreds of programs across the nation. Finally, we are addressing the most fundamental issue, the skills of the faculty in delivering project-based learning. A Faculty Development Workshop has already been created and already delivered at our participating institutions.

IV. A broad-based approach with national impact

The project is led by three core universities: MIT, the US Naval Academy, and the University of Colorado, Boulder. But, we are already engaged in the North American CDIO region with three

other universities, and recently been joined by several others. About 10 major aeronautics programs have expressed strong interest, motivated significantly by strong industry endorsements. We have an inclusive approach, and invite all to participate. As described below, we have entered into partnership with many of the leading US-based aerospace companies, and will work through them to engage their “feeder” programs around the nation. Our hope is that in two to three years, 20 to 30 of the major programs around the nation will be involved in the CDIO in Aerospace Education network. We view this goal as achievable, with over forty universities and 70 programs are now involved in the international CDIO Collaborative spanning all fields of engineering.

V. Technical Approach - Forming an alliance

The project has assembled a national team of educational scholars, developers, deliverers and customers. We have formed an integrated project team, built around a core group of the three key North American CDIO programs in aerospace: MIT, the US Naval Academy, and the University of Colorado, Boulder. This core group was joined by four other existing CDIO programs in the US and Canada: Arizona State University, Daniel Webster College, California State University at Northridge, and École Polytechnique de Montréal. Daniel Webster College students were partnering in the Helios project at the University of Colorado, which is described below.

We have approached the Boeing Company, General Electric Aviation, Lockheed Martin, Northrop-Grumman, Orbital Sciences, and Raytheon to form an industry-university steering group for the program. These industries are contributing direction, participation in project learning, and supplemental funding.

VI. Developing aeronautical project-based learning and assessment materials

The core of the technical effort is the development of design-implement-operate laboratories and project-based experiences. We are developing a set of at least six learning experiences for the first and second year of aeronautical instruction, and about six third/fourth year learning experiences. Working in close coordination, and with the guidance of the industry-university steering group, each of the three core universities has developed one experience at the freshman/ sophomore, and one at the junior/senior year level this past year, and will develop a like number in the coming year. First results were reported at the AIAA Annual Meeting in January of 2010⁷.

A. First and second year project-based experiences

It is important to begin the education of engineering students with an authentic experience in engineering, often delivered through a project-based subject in the first or second year. We are developing two types’ experiences. In one model, the laboratory or project-based experience is a simple but rather complete aeronautical vehicle, at the scope that can be successfully developed by students, but with an interdisciplinary perspective. In the second freshman/sophomore model, the laboratory project will be based on the design and development of an important aeronautical subsystem.

B. Third and fourth year project-based experiences

We are developing third and fourth year experiences of two types. In one, the entire class work as one team in the execution of the project. In the second, smaller groups work in teams of 6-10 on the project. In most cases, the projects have a real customer, and deliverable “flying” article. Projects are interdisciplinary spanning modern aerospace disciplines (aeronautics, propulsion and structures, avionics, software, control and autonomy). The projects build

awareness of other issues, including financial, regulatory, environmental and public policy, although this broader interdisciplinary scope may not be a primary focus of every project.

The underlying innovation in these projects is the incorporation into the mainstream curriculum of the design, building and testing of realistic, in fact in some cases real, aerospace vehicles and systems.

Upper-class projects are being readied for publication and will be available in 2011. The project teams will then move to documenting additional projects by the summer of 2011.

VII. Develop dissemination and faculty development support materials

Two important barriers to adoption of innovative instructional approaches such as project-based learning are the lack of well-developed examples from which individual faculty can draw, and the lack of confidence and competence of university instructors in such approaches.⁸ We develop a comprehensive approach to dissemination of our results, which include making the curricular materials that we develop openly available on the web, and creating Faculty Development Workshops and Master Teacher Seminars. These workshops were publicly offered at the 2010 national meetings of both the AIAA and ASEE.

VIII. Pedagogic Foundation

Contextual learning is a proven concept that incorporates much of the most recent research in cognitive science.^{9,10,11} According to contextual learning theory, learning occurs when students process new knowledge in such a way that it makes sense to them in their own frames of reference. This approach to learning and teaching assumes that the mind naturally seeks meaning in context, that is, in relation to the person's current environment, and that it does so by searching for relationships that make sense and appear useful.¹² A contextual learning approach assists students in learning how to monitor their own learning so that they can become self-regulated learners.¹³

IX. Capabilities and experience of the team

The three lead institutions, MIT, USNA and CU Boulder, have each undergone significant curricular transformation as a consequence of adopting CDIO, and are viewed as important contributors to educational reform. The Department of Aeronautics and Astronautics at MIT developed the CDIO Syllabus and revised its undergraduate program in the context of CDIO. The Naval Academy has been a CDIO collaborator since 2002, contributing a strong emphasis on engineering operations, particularly manned and unmanned flight test. The Aerospace Engineering Sciences Department at the University of Colorado has redesigned the undergraduate curriculum to include laboratory experiments and design projects according to the CDIO Syllabus in 2000. In the sophomore and junior years the fundamentals are taught enhanced by experimental labs and small design projects. All courses in these two academic years make extensive use of the Integrated Teaching and Learning Laboratory. Senior design projects teach standard professional aerospace systems engineering practices, elements of conceptual and detail design, elements of fabrication, integration, verification and test.

Collectively, the three universities have already been working together for three years through their close working relation in the North American CDIO region. To date, the collaborative has influenced over 70 university engineering department programs worldwide, which graduate close to 10,000 engineering students annually.

X. Project Examples

A. First and second year project-based experiences

It is important to begin the education of engineering students with an authentic experience in engineering, often delivered through a project-based subject in the first or second year. We are developing two types experiences. In one model, the laboratory or project-based experience is a simple but rather complete aeronautical vehicle, at the scope that can be successfully developed by students, but with an interdisciplinary perspective. Our first selection of these projects included:

- The development of an RC lighter than air vehicle, capable of being flown under radio control over a closed course, teaching equilibrium and simple flight mechanics
- The design and testing of water rockets, a deceptively complex problem providing an interesting design optimization challenge, spanning gas dynamics, rocket dynamics, stability, aerodynamics, and launch system integration.
- The redesign and refinement of a simple RC electric aircraft.

In the second freshman/sophomore model, the laboratory project was based on the design and development of an important aeronautical subsystem. These include:

- The development of a flight control system for a 3 DOF helicopter simulation, including characterization of a helicopter's system dynamics and design of a simple feedback control
- Fabrication/test of a composite material truss member - a unidirectional glass fiber reinforced epoxy matrix strut that can sustain a theoretical load of 3500 lbs without failing
- Design and modeling of a high-altitude zero-pressure balloon carrying a payload with minimal altitude variation caused by thermal heating and cooling.
- Wind tunnel calibration and low-speed aerodynamics of the Lockheed Martin F-16

As an example of the approach we have used in these first/second year projects, we will describe one involving the redesign of a simple RC electric aircraft, currently employed at both MIT and USNA. This project is a major component of both programs, and consists of a series of labs and design exercises which culminate in a flight competition. The objectives of the project are to provide: a framework for the smaller course labs (wind tunnel tests, beam bending tests); a theoretical and hands-on application of the taught disciplines; an introduction to engineering tradeoffs and design optimization; an introduction to aeronautical terminology and practice; and to generate enthusiasm and camaraderie in our students.

Each student team designs, builds, and competes in a fly-off an electric RC airplane optimized for an assigned objective, such as maximizing a weighted combination of endurance, maximum speed and payload. The rules are carefully formulated to give each team sufficient design freedom to explore various design options, for example: wing aspect ratio, taper, and twist; airfoil camber and thickness; tail volumes; and configuration (tractor vs. pusher). The pedagogic approach is to teach design by redesign. Students start with an existing kit plane, and analyze and improve one or two aspects of it to increase the performance against the stated objectives. The rules emphasize operations, and are made sufficiently constraining to put all teams on roughly equal footing, and to simplify the structure to make the overall aero/structural optimization quantitatively tractable rules. A planned innovation in this project is to include a more detailed and realistic structural design, perhaps employing composite materials.

A second example involves the design and test of a spacecraft thermal system. Students are formed into teams of 3-4 students to evaluate the design of a radiator for a satellite. The project is a subsystem of a larger project to design, build, and launch a nano-satellite. Design

requirements are given to the students: power, orbit, orientation, operational thermal requirements, survival thermal requirements, spacecraft IR backload. They analyze the surface treatment of the radiator for highly efficient heat transfer. The radiator area is optimized to meet system requirements. Heater power as a function of time over one orbit is calculated. Currently a paper study only, we will consider developing a build-test component of this project.

Composite materials are becoming more important in aircraft technologies. In the composite truss design and experiment, students have to design the lay-out of the epoxy glass fiber composite to sustain a defined load. They have the choice of 3 different diameter glass fibers. They have to calculate the modulus of elasticity and define a factor of safety for their design. The students receive a mold with minimal accessories; they are expected to design a feature to straighten the fibers, make the mold leak proof. Preparing the mold, fibers and two-component epoxy, and filling the mold exposes them to subtle differences between theory and manufacturing practice. Testing their designed strut to failure and evaluation the failure exposes them to testing methods, strength of fiber reinforced composites, and conveys an appreciation of Hooke's diagram.

We view the early use of system-level PjBL as an important innovation. Traditional engineering pedagogy holds that students cannot effectively design and build anything until they reach the "capstone", and can build upon layers of engineering theory. We have found that for the reasons discussed above that it is highly advantageous to introduce project-based learning in the first years of engineering education. In addition, the specific innovations that will be introduced include:

- The closer coupling of the engineering science fundamentals into the development of the project. Many early year design-build projects appear to give the students outlets for creativity, but do not couple well to the actual theory also being taught. This reduces the value as an introduction and motivation for deep disciplinary learning. We have explicitly sought to make the disciplinary coupling to the projects more explicit and real—such as the use of modern CFD codes such as X-Foils in the design of the wing of the RC aircraft.
- The integration of teamwork skills into the design-build experiences. Engineering education commonly asks our students to work in teams, yet often does not support this skills learning. We are developing a modular approach to supporting team formulation and operations.
- The integration of basic project management skills into the design-build experiences of modules. Like teamwork, we expect our students to acquire these skills, and must develop a scalable modular approach to delivery.
- Utilization of novel Web 2.0 methods that are intensively used by today's young adults, to develop projects by remote teams. These methods include among others wikis, blogs, and server-based file sharing such as Google Docs, Office Live, or SharePoint.

B. Third and fourth year project-based experiences

Third and fourth year project-based experiences reinforce learning, and develop student awareness and empowerment of newfound knowledge. We are developing third and fourth year experiences of two types. In one, the entire class work as one team in the execution of the project. In the second, smaller groups work in teams of 6-10 on the project. In most cases, the projects have a real customer, and deliverable "flying" article. Projects are interdisciplinary spanning modern aerospace disciplines (aeronautics, propulsion and structures, avionics, software, control and autonomy). The projects build awareness of other issues, including financial, regulatory, environmental and public policy, although this broader interdisciplinary

scope may not be a primary focus of every project. Example of laboratories and projects that are being developed or have been developed include:

- Development of UAV aircraft for tactical situation, including development of risk mitigation and safety planning for testing of student built UAVs
- Design, test and construct a hybrid propulsion system with the purpose of reducing fossil fuel dependency and increasing flight endurance for a baseline aircraft. This project is a collaboration of 2 Universities (Colorado and Daniel Webster College) where the aircraft frame is designed by one College (DWC) and the propulsion system by the other partner (CU)
- A solar unmanned aerial vehicle. Students modify a high performance sailplane by adding batteries and by integrating photovoltaics in the wings
- Flight testing of piloted aircraft
- Design a quad rotor vertical ascent and landing aircraft to carry dedicated payload
- Design of a flying wing aircraft with high aerodynamic efficiency. This project is an international collaboration with the Universities of Stuttgart and Sydney where the work "follows the sun"

As an example, at the University of Colorado, Boulder, students design, develop, and test a small unmanned aircraft powered by solar energy, with the goal to understand possible opportunities for solar powered flight. The military is interested in sustaining flight indefinitely through multiple solar periods. Perpetually flying aircraft have very significant applications, whether to serve as communications relays, earth imaging, or a science platform. High altitude solar aircraft are seen as low cost satellite replacements that can be easily refurbished with new sensor packages. The goal of this project was to modify an R/C sailplane by adding a structurally integrated PV energy harvesting system in order to increase the standard endurance of the aircraft to 250% from COTS value. This aircraft will be launched by hand by a single operator, while under the manual control of an r/c pilot operator. The aircraft will then be brought to altitude and then switched to an autonomous mode, where it will remain for the majority of the flight until it is switched out of autonomous mode and landed manually. In order to achieve this proof of concept, the aircraft will need to fulfill a number of secondary objectives. A robust communications system will be required in order to verify energy harvesting capabilities, control the aircraft and ensure that maximum endurance is attained. In-flight strain data will be gathered to verify that a sensitive photovoltaic system will be capable of enduring the stresses and strains exerted during flight. Finally, thin-film batteries will be integrated into the composite structure of the aircraft to demonstrate the weight and volume saving concept of integrated battery composites.

Such design would be extremely sensitive to subtle design changes, leading each design team member to maintain a thorough systems engineering perspective and keep their systems within the system design constraints. The members of this team need to understand that every subsystem can significantly affect other systems, and will need to account for all of the potential problems a design change can create. The technical activities include: ensuring that the wings and other structural components can withstand the forces exerted during flight; designing the control system to fly autonomously to predetermined locations; and creating an electric system design for the processors, motors, and servos. Embedding the batteries in a composite structure is a manufacturing challenge. This team's deliverables include an aircraft with the capabilities described above, as well as a means of preparing and launching that aircraft. The team also provides a portable ground station and telemetry system. The innovation in this project is to expand the understanding of the students of the sensitivity of design to in the introduction of new technologies (e.g. batteries and power conditioning).

A second project at the University of Colorado, HELIOS, was the design of a hybrid propulsion system for aircraft. This project was developed as a multi-university project to expose the students to delocalized design engineering as often used in industry practice. The senior student team at the University of Colorado designed a hybrid gas-electric propulsion system which combines the torque from a gas-engine and an electric motor at the propeller. This design led to the submission of a patent on the gearbox. A senior team from the Daniel Webster College designed the airframe after the requirements and constraints defined by the engine manufacturers at Colorado. The team of 4 students at Daniel Webster collaborated with two students at the University of Massachusetts at Lowell to manufacture the 13 ft wingspan airframe. They did preliminary testing of their airframe with an electric motor. Then the airframe was shipped to the University of Colorado and the dual torque propulsion system designed by the 7 students from Colorado was integrated and flight tested. The major successful learning experience in this project was the delocalized design effort and its related communication practices.

A current follow-on project to HELIOS¹⁴ is the project HYPERION¹⁵. This project is also a delocalized design project with teams on three continents: 1) A team of 11 graduate students at the University of Colorado, 2) a team of 7 undergraduate senior students, 3) a team of 4 graduate students at the University of Stuttgart, and 4) a team of one graduate and 5 undergraduate students at the University of Sydney. The project is about designing a blended wing body aircraft powered by a second generation of the hybrid propulsion system which is designed and developed by the Colorado undergraduate team. The project is partially funded by the Boeing Company, eSpace Inc. and the German DAAD. The structural and aerodynamic studies were done by the three universities and select elements were selected to be developed under a “follow-the-sun” design effort where the work was transferred to the next continent at the end of the day.

As a fourth example, a project on flight test engineering emphasizes the Operations in CDIO. Few US universities have formal courses in Flight Test Engineering, and these are commonly led by faculty members who have had direct experience as test pilots or test engineers. We have developed and refined a program that has learning outcomes that span foundational test processes: test planning, safety planning and risk mitigation, air data, instrumentation, flight conduct, data reduction and referral, specification compliance, and test reporting. Topics including performance, propulsion, structures, stability & control, and avionics are profoundly reinforced. Hence, even those schools without direct ties to the flight test industry can benefit from including such a project in their offerings. A related task yet to be done is to catalog best practices from among those schools actively conducting flight test engineering courses with manned airplanes and simulators, and development of new flight test exercises. The innovation in this project is developing approaches to teaching Flight Test Engineering in universities without experienced test pilots. We have enabled this by producing syllabi, procedural guidance, instrumentation requirements, budget and faculty competencies (and qualifications), and implementation issues.

The underlying innovation in these projects is the incorporation into the mainstream curriculum of the design, building and testing of realistic, in fact in some cases real, aerospace vehicles and systems and in one case a “global” design project. These are no paper study capstone projects, but drag the students through the stimulating experience of having to implement, operate, and deliver to the specification of a customer. This builds skills, reinforces knowledge and creates excitement. The additional innovations that would be introduced into these design-implement-operate experiences would include:

- Closer interaction with industry customers who define the needs and specification of the system, and the success of the system. Our industry-university steering group will identify a set of topics for each school year. The topics will be concept studies, exploratory studies, or alternative design studies, and should not be in the critical path of the customer. Students have the opportunity to interact with the sponsoring customer at several occasions.
- More “vertical integration” of the project between seniors, juniors, sophomores and alumni. This involves sophomores and juniors in tasks commensurate with their skills. They benefit from the excitement of the senior students, and they understand what issues the seniors face with their projects. Seniors are exposed to more explicit leadership and management issues. We have also demonstrated Web 2.0 technologies for engaging alumni in teams.
- Enhanced emphasis on operations, operational environments and risk assessment. Many design-implement programs involve flight test of UAVs, which should include mission requirements and plans for risk mitigation and safety. We are cataloging and refining best flight test practices from among schools actively conducting design-build courses with UAVs, so that students learn professional practice, while life and property are not put at risk.

C. Assessment

Besides being structured according to a common template all projects will be subjected to a common assessment template defined by CDIO outcomes. The first outcome in the template is linked to the technical discipline, in this pilot case aerospace engineering. Skills are for example: aircraft control, construction, propulsion, modeling and other analysis. For example Students in HELIOS, described above, will be required to develop and implement a wide variety of essential engineering project skills including: systems engineering, project management, design, manufacturing, analysis, testing, and more.

Assessment of team and individual student performance should emphasize the understanding of the fundamentals involved in a complex engineering project. Team performance metrics includes successful project management, effective systems engineering, good schedule maintenance and planning, safe fabrication and operation, useful testing and analysis, and overall project verification, validation, and success. Individual student performance metrics include student Peer Evaluations and overall contribution to the project as observed by close advisors. Success or failure is associated with overall project effort and analysis of results, and not dependent on meeting technical requirements.

In the fall semester, a PDD and CDD help to form the Project requirements, definitions, and overall scope. This is followed by a PDR and CDR to allow for advisory and/or professional review of the preliminary and critical designs accomplished by the team. The fall semester closes with an FFR to summarize all design work accomplished so far, and to detail the plans for the spring semester.

1. Project Definition Document (PDD)

The PDD is a written document detailing project objectives and scope. This document should help in developing top level requirements, concept of operation, and in identifying key technologies and required team skill sets.

2. Conceptual Design Document (CDD)

The CDD is a written document describing three concepts of system options. It should also detail the convergence on top-level system architecture and assess the feasibility of the project.

3. Preliminary/Critical Design Review (PDR/CDR)

The PDR and CDR are 20-25 minute oral team presentations to a panel of advisors or experts explaining requirements and preliminary baseline design with alternative options. This presentation also identifies and assesses project risks, prototyping, subsystem requirements, evidence of feasibility, and top level project plans with contingencies.

4. Team Managed Webpage

A team-managed website should be maintained to outline the details of the project and its team members and/or provide a central file management location.

5. Oral Assessment:

Interim Readiness Reviews 1 and 2 are two informal oral team presentations to an advisory board with the intention of providing updates on the project; Spring Project Review made during the 2nd semester is a final comprehensive oral team presentation.

6. Final and Interface Reports

Final reports at the end of each semester are designed to document all aspects of the project very carefully. They can serve in the evaluation of individual student performance if the assignment requires individual team members to assume select authorship on select chapters.¹⁶ Final reports are handed over to the project sponsor and owner to show validation of the initial project requirements. Interface documents are necessary when several teams collaborate on a project. For example delocalized teams need precise definitions of their charter. Collaborating local teams of e.g. graduate and undergraduate teams also need to define carefully their job charter.

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Biographies

Prof. Edward F. Crawley, crawley@MIT.EDU, is Ford Professor of Engineering and Professor of Aeronautics and Astronautics and of Engineering Systems at MIT. He is Co-Director of the CDIO Initiative, and co-author of *Rethinking Engineering Education: The CDIO Approach*. He currently directs the MIT-Bernard M. Gordon Engineering Leadership, and was awarded the 2011 Gordon Prize for Engineering Education by the National Academy of Engineers.

CAPT Rob Niewoehner, niewoehn@usna.edu

Robert J Niewoehner is the David F. Rogers Professor of Aeronautics at the United States Naval Academy. Dr. Niewoehner entered academia after a thirty-year career as a Navy pilot and experimental test pilot, including service as the US Government's Chief Test Pilot for the development of the F/A-18 E/F Super Hornet. He initiated the Naval Academy's involvement in CDIO in 2002 and has been an active collaborator since that date.

Prof. Peter J. Gray, pgray@usna.edu

Peter J. Gray is the Director of Academic Assessment at the United States Naval Academy. He serves as the assessment and evaluation expert on the North American Aerospace Project-Adaptable Design/Build Projects for Aerospace Education. He was been a member of the USNA CDIO team and the CDIO International Leadership Council since 2003.

Prof. Jean Koster, jean.koster@colorado.edu

Jean N. Koster is Professor of Aerospace Engineering Sciences at the University of Colorado, Boulder, Colorado and President of Tigon EnerTec, Inc., a start-up company for aerospace propulsion technologies. He is the CDIO representative from the University of Colorado and is the department course coordinator for the senior design projects courses.

Corresponding author:

Prof. Ed Crawley

Massachusetts Institute of Technology

77 Massachusetts Avenue 37-391

Cambridge, Massachusetts, USA 02139

crawley@MIT.EDU