

AC 2010-987: CDIO IN AEROSPACE ENGINEERING: THE NORTH AMERICA AEROSPACE PROJECT PROGRESS REPORT

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CDIO in Aerospace Engineering Education: North American Aerospace Project Progress Report

This paper provides an interim progress report for the North American Aerospace Project, an effort of the North American CDIO consortium. The project seeks to promote and facilitate the adoption of the CDIO (Conceive Design Implement Operate) model for engineering education in U.S. Aerospace programs. This paper reports the consortium's activities at the conclusion of the project's first year, highlighting the development of six project based learning modules, for which summaries are included. These modules are designed for ready adoption at other schools seeking to implement project based instruction.

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 Aeronautics Research Mission Directorate (ARMD) 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 (Science-Technology-Engineering-Mathematics) workforce is paramount to other organizations as well, including the NAE, the AIAA and the AIA.¹

There are a number of possible approaches to addressing this challenge. No single one will solve the problem – it is a systems problem, and the nation needs a systems approach, ranging from improving the STEM skills in K-12, to retaining workforce in the aeronautics industry. However all agree that a key aspect to the systems solution resides in engineering education in aeronautics and related fields.

Our consortium has proposed a solution that is designed to have widespread systemic influence on the university preparation of the aeronautics workforce in the US drawing on our participation in international engineering education reform. The goals of the immediate project include:

- Impacting the knowledge and skills of the graduating students, and their interest in aerospace
- Creating a sustainable impact to persist on its own merits after NASA sponsorship ends
- Involving many of the leading universities and aerospace companies

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. The project overview was previously presented to the aerospace education community;² this paper adapts and updates that prior report to document further progress.

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 goals of the CDIO approach are to educate students who are able to:

- Master a deeper working knowledge of the technical fundamentals
- Lead in the creation and operation of new products, processes, and systems
- Understand the importance and strategic impact of research and technological development on society

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 (PBL)). A key feature is the integrated use of PjBL in both the earlier and later years of the undergraduate education. Students work in learning laboratories and encounter repeated cycles of designing-building-operating systems. Such use of PjBL has been shown to increase the acquisition of deeper knowledge and develop in students desired product and team skills.^{4,5} 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.⁷

In the present effort, we're building upon the CDIO approach to engineering education, and developing educational approaches and tools to the education of the aerospace engineers. Specifically, we're developing modularized curricular materials around aeronautics PjBL. Our ultimate target audience is the students in undergraduate aerospace and related programs throughout the country. The more immediate audience is the instructors and planner in aeronautics programs in and closely related fields.

Pedagogic Foundation

The rationale for adopting the product, process, and system lifecycle (Conceive-Design-Implement-Operate) as the context for engineering education seeks more effective learning of

technical fundamentals, as well as the broader skills of product development. Learning is more effective when teaching and learning experiences are set within an environment or surroundings that help with understanding and interpretation. In education practice, this is called contextual learning.

Contextual learning is a proven concept that incorporates much of the most recent research in cognitive science.^{8,9,10} 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.¹¹

The evidence for adopting a contextual learning approach is compelling. This approach encourages students to choose specific careers and remain in their respective career preparation programs. Learning environments and experiences set in professional contexts open students' minds, enabling them to become more thoughtful, participative members of society and the workforce. Moreover, a contextual learning approach assists students in learning how to monitor their own learning so that they can become self-regulated learners.¹²

Project-based learning is an instance of contextual learning applied to design-implement experiences in engineering education. Project-based learning is a teaching method used in disciplines where students must learn to apply knowledge, not just acquire it. In these PjBL experiences, students identify problems of interest to them and experiment to find solutions, as well as design complex systems that integrate engineering fundamentals in a multidisciplinary approach. Project-based learning derives from the theory that learning is a process in which the learner actively constructs knowledge. Learning results from a learner's actions; instruction plays a role only to the extent that it enables and fosters constructive activities. Three major theoretical principles support the practice of PjBL:

- Learning is a constructive process. Learning occurs when students are able to make connections of new information with knowledge and experiences they have already assimilated.¹³ Not only is this active learning more interesting and engaging for students, it also develops a greater understanding of the material since students find the information for themselves and then actively use the information and their skills to complete the project.
- Knowing about knowing (metacognition) affects learning. Students can detect when they understand, or do not understand, new information, and know when to use different strategies to decipher new knowledge and experiences. Project-based learning gives students opportunities to monitor their own learning and assess their own progress.
- Social and cultural factors affect learning. Effective instruction is placed in the context of complex and meaningful social and cultural problem-solving situations. Project-based learning deals with problems that are as close to real-life situations as possible.¹⁴

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. Second, the project-based materials generally entail a modest non-recurring cost, and low yearly recurring cost, allowing them to be usable within the budgets of most institutions. Third, 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, and at January's AIAA Aerospace sciences meeting. It's also being conducted at this summer's ASEE conference. In the early phase of development, we're accumulating evidence in support of the approach. We are developing a Master Teacher Seminar to train further instructors in the Faculty Development Workshop, which will be piloted at the CDIO international conference in June, 2010. Hence, we intend to develop a sustainable engine for our future workforce by lowering the development time to the faculty member, by reducing the recurring cost, and by engaging industry as a source of projects.

A broad-based approach with national impact

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 are working 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, either formally as partners or contributors, or informally as constituents of our products. With over forty universities and 70 programs now involved in the international CDIO Collaborative spanning all fields of engineering, this goal is hardly unreasonable.

Technical Approach

Our conceptual approach has been to:

- Form an alliance of leading aeronautics programs, industry, and leading educational researchers
- Develop project-based learning approaches to aeronautics, along with aligned student learning assessment methods, within the CDIO framework
- Develop dissemination and faculty development support materials, and disseminate them widely through an open courseware model, and through Faculty Development Workshops

Developing aeronautical project-based learning and assessment materials

Our approach is to build upon the 12 CDIO Standards, as outlined in Reference 3, a model of effective practice developed by the CDIO collaborative, and specializing this model to aerospace engineering. Specifically we are:

- Working with our collaborating programs, aided by industry, to establish and accept the principle that conceiving – designing – implementing and operating aerospace products, systems and services should be the context of the undergraduate education. [CDIO Standard 1]
- Working with our integrated project team to refine the definition of the critical aeronautical knowledge and product skills most needed for America’s aerospace workforce [CDIO Standard 2]
- Developing laboratory and design-implement projects that help aerospace engineering programs integrate learning laboratory and project-based experiences throughout the undergraduate program, focusing on first-year and multidisciplinary capstone design-implement experiences. [CDIO Standards 4, 5, and 6]^{15,16}
- Developing a rigorous approach to assessing student learning and skills development, based on objective measures, and surveys of student self-confidence in learning. [CDIO Standard 11]

System development as the context for aeronautical engineering education

Context is the surroundings and environment that contribute to understanding. It is appropriate to set aeronautical education in the context of aerospace product development for several reasons. First, it is what our graduates will do when they graduate. It culturally prepares them for the activities of engineering, and excites them by satisfying their desire to perform the roles of an engineer. Secondly, it aids in teaching the skills that they will need in the workplace. If we are to teach students to communicate and work in teams, and especially to act ethically and creatively, it is far easier to impart this understanding while working on authentic engineering activities. Finally, and most subtly, learning in context better supports the learning of the critical aeronautics core competencies.

Engaging stakeholders to refine expectations and models

The Aerospace workforce has diverse stakeholders: the universities, the students, the industry, the government, the professional and trade associations, and the customers and consumers of aerospace services (effectively our entire civilization). The CDIO consortium has found broader agreement among these groups as to the desired outcomes than might be expected. Each of our CDIO programs has engaged with our respective program stakeholders to define knowledge and skills expectations of graduating students, and to refine outcomes and approaches for our project.

The framework for expected learning outcomes is the CDIO Syllabus, a rational and peer reviewed set of the broad outcomes for technical learning, as well as personal, interpersonal and system building skills (Table 1). Inclusive of other frameworks such as ABET, it is more complete and more detailed. Extensive studies have already been done by the USNA and MIT for US aerospace industry expectations for student learning. We are using these surveys as a baseline, and refine the outcomes and expectations. This has formed the basis of rational design of curriculum and aligned student learning assessment. Release of the first major revision of the CDIO syllabus is expected in the coming year.

Table 1. The knowledge, skills and attitudes of engineering graduates, from the CDIO Syllabus

- 1 Technical Knowledge And Reasoning
 - 1.1 Knowledge Of Underlying Science
 - 1.2 Core Engineering Fundamental Knowledge
 - 1.3 Advanced Engineering Fundamental Knowledge

- 2 Personal and Professional Skills and Attributes
 - 2.1 Engineering Reasoning and Problem Solving
 - 2.2 Experimentation and Knowledge Discovery
 - 2.3 System Thinking
 - 2.4 Personal Skills and Attitudes
 - 2.5 Professional Skills and Attitudes

- 3 Interpersonal Skills
 - 3.1 Teamwork
 - 3.2 Communications
 - 3.3 Communications In Foreign Languages

- 4 Conceiving, Designing, Implementing, and Operating Systems in the Enterprise and Societal Context
 - 4.1 External and Societal Context
 - 4.2 Enterprise and Business Context
 - 4.3 Conceiving and Engineering Systems
 - 4.4 Designing
 - 4.5 Implementing
 - 4.6 Operating

Developing project-based learning materials

The main goal of PjBL within CIDO is to provide students with opportunities to apply knowledge contextually. PjBL focuses on problem formulation as well as problem solution. It seeks to simulate real-world engineering research and development. The main features are:

- Learning is student centered, i.e., students make choices about how and what they want to learn
- Learning occurs in small student groups and promotes collaborative learning
- Teachers are facilitators or guides or coaches
- Problems, projects, or processes form the organizing focus and stimulus for learning
- Projects are a vehicle for the development of authentic engineering skills
- New information is acquired through self-directed learning

We have been successfully implementing project-based learning in CDIO programs for more than eight years. Examples of these PjBL experiences and courses are documented in various sources.^{17,18,19,20}

As an initial effort, we're conducting a survey of the conceive-design-implement-operate projects that are currently being used in CDIO programs worldwide. Our intent is to catalog and compare projects, analyze features that lead to success for students, and disseminate this

information widely for adoption by aeronautics engineering programs across the United States. This survey builds on the work of Malmqvist and other CDIO collaborators.²¹ Appendix A is the template we've developed to characterize and disseminate projects across universities and programs. It includes:

- The intended learning outcome, and relation to CDIO syllabus
- A description of the project and tasks and their complexity level
- How this project typically integrates into a curriculum, and the core aeronautical knowledge it introduces or utilizes
- The learning activities
- How the project is described to the students
- The deliverables or outcomes of the student project
- The materials necessary, how much of it is supplied vs. left to the students to find or innovate
- The team structure recommended (size, leadership and organizational model)
- The involvement of industry, and contacts who might facilitate further industry participation
- Approaches to student assessment (individual and team)
- Evaluation of the experience
- The non-recurring and recurring costs and other resources needed
- Description of where the project has been used: university, program, course title, credits, hours, documentation, number and gender mix of students, staff etc.

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 project's second year. Other universities are invited to aid in development, and beta test the project experiences in their programs, before wide scale dissemination.

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 preliminary 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 each of these cases, students emerge with clearer conceptions of the messy work of engineers—that there are commonly no ‘right’ answers, that small weaknesses in one product attribute can outshine excellent work in other features, that team dynamics can make or break a product.

In the second freshman/sophomore model, a laboratory project is 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 of a radiator for the thermal control system of a satellite

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.

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 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.

Four summary product descriptions are included: MIT’s Lighter-than-Air project (Appendix B), USNA’s Dragonfly (Appendix B), Colorado’s composite lay-up and test (Appendix D), and MIT’s Skyscraper (Appendix E). The summary descriptions are the front end of multi-file packages that faculty can download for review, adoption or adaptation to their project context. Three additional underclass project files will be built during 2010-2011 in preparation for dissemination in summer 2011.

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
- A hybrid diesel-electric unmanned aerial vehicle designed in collaboration with three teams from different universities.
- A solar unmanned aerial vehicle

- Flight testing of piloted aircraft

As an example, an extended capstone experience at MIT spanned 3 semesters and involved 70 students in design, fabrication and demonstration of a lunar/Mars rover. The project expended \$30,000, and required considerable project management skills on the part of the involved student leadership. The project package includes the materials a faculty member would need to adapt this effort to another similar project. The project summary is found in Appendix F.

As a second example, a project on flight test engineering emphasizes the Operations in CDIO. About a half-dozen 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 project summary is found in Appendix G.

Three upper-class projects are being readied for publication and will be available in early 2010. The project teams will then move to documenting 3 additional projects by the summer of 2011.

Developing integrated learning experiences

CDIO standard 3 speaks to the development of an integrated curriculum, and standard 7 addresses integrated learning experiences. The project plan for the Aerospace Project has not included any explicit development work addressing these standards, but feedback from colleagues has indicated that many of their questions touch these standards. Project based learning is frequently viewed with suspicion if it appears to erode students' time on task with foundational engineering science. Others worry that extensive team activities likewise uncut individual student accountability. An "integrated learning experience" means that common engineering science goals are targeted in an integrated exercise along with the personal/ interpersonal/ systems-build objectives. Those exercises may be either team or individual. Resources detailing such questions may be found on the CDIO knowledge library (www.cdio.org), and the Aerospace project intends to detail some examples in the second project year.

Developing a rigorous approach to student learning assessment

The development of a rigorous approach to student learning assessment is being guided by the student learning assessment process described in Reference 2, namely: specify learning

outcomes; align assessment methods with outcomes; use multiple methods to collect and analyze data; and use results to improve teaching and learning. Student learning assessment will focus on examining students' deep understanding of the technical fundamentals; systematic understanding of personal, interpersonal and product development skills necessary to translate technical knowledge into competitive products; and self confidence in learning (self-efficacy).

We've introduced the innovative adaptation of new tools for student learning assessment to aeronautics education. Assessment of self-confidence in learning will be used both as an important educational outcome and as a means to better understand the dynamics of career development. There is a rich literature that has addressed the importance of having self-confidence that one can successfully perform the tasks necessary to achieve larger goals. This form of self-confidence, called self-efficacy,²² is not a general personality trait like self-esteem, but instead varies from one domain to another as individuals gain experience and self-awareness of their areas of relative competence. Where the individual has higher self-efficacy shapes career interest, and then becomes a major determinant of whether students will persistently pursue their career goals.

Members of this integrated project team have been studying self-efficacy for math,²³ teaming, technology, venturing and organizational innovation,²⁴ and have scales in hand (with coefficients of reliability that generally range from .80 to .92) that have been used in research to understand what forms of pedagogy strengthen different types of self-efficacy. For example, our research has shown that freshmen who participate in project-centered learning experience with certain characteristics causes an increase in student technology and teaming self-efficacy and that this increase is associated with increased retention of students in engineering majors. Just as math self-efficacy is known to predict whether students follow science and engineering careers,²⁵ we will evaluate whether self efficacy in aeronautical skills predicts the pursuit of careers in aeronautics.

This effort has led to a set of tools for learning assessment of aeronautical technical knowledge, personal and interpersonal skills, and self-confidence in learning (self-efficacy). The tools are presently being piloted with the freshman/sophomore and junior/senior level projects, and will be available for adoption and adaptation by other programs around the country as they implement and assess the projects.

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.²⁶ We're following 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.

We're taking a two-level approach to faculty competence. We have developed a Faculty Development Workshop to be conducted on the campus of interested schools. This workshop is maturing nicely, having delivered this workshop on several campuses and during several conferences during 2009 and 2010. We will then "train the trainers" for further dissemination of

the faculty development workshop by Master Teacher Seminar currently in development that includes a rigorous approach to program evaluation and student learning outcomes assessment. The Master Teacher Seminar will be delivered and refined at regional and national meetings in June 2011, allowing the master teachers to return to their universities and conduct the Faculty Development Workshop.

The Master Teacher Seminar and related Faculty Development Workshop is being designed, developed, and implemented following the model for using data to inform project planning and implementation.²⁷ The purpose is to familiarize aerospace educators with current approaches to education that will support learning in aeronautics core competencies and product development. The 20-hour workshop will be presented in a project-based/active learning format with the focus on first/second year and multidisciplinary third/fourth year design-implement experiences. The Faculty Development Workshop includes: project-based learning, project-based syllabus development, and assessment tools for benchmarking success. The Master Teacher Seminar entails an introduction to topics that provide the necessary general background for conducting Faculty Development Workshops as well as first-hand experience with the actual faculty workshop topics/modules listed above.

Conclusion: Summary of Program Progress to Date

The project's purpose is the deployment of the CDIO pedagogy to other North American institutions. The project's eight specific tasks, products and progress are summarized below.

1. *A refined and stakeholder-validated description of the knowledge and skills desired in graduating students by the US aerospace industry.* This task is complete with a report in work. In a related effort, the international CDIO consortium is currently weighing a draft of the 2.0 version of the CDIO syllabus. Proposed changes reflect both 8 years of experience working with the syllabus, and shifts in industry's emphases. Action on proposed changes is expected in 2010.
2. *The documentation of six freshman/sophomore and six junior/senior level projects that suitable for adoption and adaptation by other programs around the country are the responsibilities of a team of professors, supported by educational specialists, from the three core universities.* During the project's first year, each of the three lead schools has prepared both one underclass and one upper-class projects. Those six projects are in the format of Appendix A and will be available on-line in early 2010 for use, comment, adoption or adaptation. Their summary pages are found in appendices B-G.
3. *A set of tools for learning assessment of aeronautical technical knowledge, personal and interpersonal skills, and system building skills.* The self-efficacy instrument has been reviewed and currently being piloted at several institutions.
4. *A set of data on student learning that indicates the effectiveness of the proposed project-based approach.* This is a second year task. Data from the effort above will feed this task.
5. *A Faculty Development Workshop with exportable format and materials that will enable adoption at other universities conducted by local educational leaders.* The Faculty Development Workshop has been conducted at MIT, USNA and CU in 2009 with participants from several dozen schools. Abbreviated formats are scheduled for several venues in 2010, including AIAA and ASEE meetings.
6. *A developed and refined format and materials for the Master Teacher Seminar, as well as*

delivery of the seminar at least four times over the course of the program. This seminar is in development and will be piloted during the project's second year at the June 2010 CDIO Conference in Montreal, and the January 2011 AIAA Aerospace Sciences meeting.

7. *A web site for the dissemination of the materials developed by the project. The website has been developed and should be live for open use in early 2010.*
8. *A final written report on the effectiveness of the program, based on the program assessment heuristic.*

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Appendices

A. Template for Documenting Design/Build/Operate Projects for Export and Dissemination

Note: The Project Overview and Learning Objectives descriptions should fit on 2 sides of 1 sheet of paper. These two items become the extractable short-form which can then be easily cataloged with other projects for review by instructors looking for a suitable project activity for their class.

1. Project Overview (1 page)
 - 1.1. Overall goal or purpose
 - 1.2. Societal context and relevance
 - 1.3. Integration (e.g., where project fits in a course, program, or curriculum)
 - 1.4. Description (e.g., complexity, duration, group size and number, budget)
 - 1.5. Learning activities and tasks (brief summary)
2. Learning Objectives (1 page)
 - 2.1. Technical objectives (e.g., basic math, science and engineering knowledge, skills, processes and procedures)
 - 2.2. CDIO outcomes (e.g., personal and professional skills and attributes teamwork, communication, conceiving, designing, implementing and operating skills)
3. Student Instructions
 - 3.1. Project description (e.g., brief description of project purpose and context)
 - 3.2. Learning objectives
 - 3.3. Learning activities including specific procedures, tasks, etc.
 - 3.4. Assessment criteria and standards
 - 3.5. Equipment, tools, supplies and/or materials
 - 3.6. Safety and risk mitigation procedures
 - 3.7. Deliverables (e.g., products, oral and written reports, and/or reflective journals)
4. Instructor Guide
 - 4.1. Commentary on conducting the project keyed to the Student Instructions
 - 4.2. Team Organization and Management suggestions (e.g., number of groups and group size, initial organization, and ongoing management)
 - 4.3. Assessment
 - 4.3.1. Criteria (e.g., to judge the quality of student products, processes, or performances relative to the learning outcomes and activities)

4.3.2. Methods and materials (e.g., rubrics for oral/written reflection methods, peer/team self-evaluation, assignments, lab reports, and standard quizzes embedded in the learning activities)

4.4. Resources

4.4.1. Budget (e.g., recurring and non-recurring expenses)

4.4.2. Equipment and tools

4.4.3. Materials and supplies (e.g., reusable and consumable including hazardous materials)

4.4.4. Staffing (e.g., describe particular skills and scope of commitment of instructors, technical staff, and others with additional expertise or licensure)

4.4.5. Spaces (e.g., minimum feasible space requirements per student or per student team, whether space is dedicated or used only during student activity, and use of space for design, build, operate, and storage)

4.4.6. Other resources (e.g., computer hardware and software)

4.5. Safety and Risk Mitigation

4.5.1. Operational safety

4.5.2. Governing policies and regulations (e.g., governmental and institutional)

4.6. Other information, for example:

4.6.1. Possible variations in the project

4.6.2. Supplementary multi-media and other resources

4.6.3. Sample student products from previous iterations of the project

B. Lighter than Air (LTA) Freshman summary project description

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1 Project Overview (1 page)

1.1 Overall goal or purpose

As a team, design and construct a lighter-than-air (LTA) vehicle, often referred to as a "blimp". This project is used as a microcosm to represent many aspects of real world project design, construction, test and operation in the real world. The goals are both technical and societal. Most first-year engineering students nowadays have never built a major hands-on project, so it is an excellent introduction to aerospace engineering, especially since a lighter-than-air vehicle is much easier to control than an airplane, given that its lift does not depend on its velocity.

1.2 Societal context and relevance

Aerospace projects are almost always team efforts, and this project is an excellent introduction to teamwork. It also duplicates many aspects of the design/build process used in industry and government: preliminary and critical design reviews, opportunities for test flights and evaluations, and a competitive "fly-off".

1.3 Integration (e.g., where project fits in a course, program, or curriculum)

The project is the final experience in a freshman-level class that introduces the students to aeronautics. It also provides preparation in communication for their future classes: The preliminary and critical design reviews give the students experience in oral presentations, and the students also prepare two written reports.

1.4 Description (e.g., complexity, duration, group size and number, budget)

Participate in a lighter-than-air race, and as a team design and construct vehicle that is:

- Stable
- Controllable
- Reliable
- Able to carry a payload
- Fast
- Aesthetically pleasing and an elegant design

1.5 Learning activities and tasks (brief summary)

Preliminary Design Review (PDR)

Objectives

Describe the design process to arrive at proposed vehicle layout

Provide justification for the selected design

Preliminary analysis of selected design's performance

Roadmap to arrive at finished product

Convey technical ability and confidence that you will get the job done e.g., to justify funding from a supporter

Completed Design Review (CDR)

Objectives

Describe the detailed design of the vehicle

Layout and analysis

Major modifications since PDR

Present and discuss at least one built prototype component or subsystem

Convey that you can overcome any issues that remain and will have a working vehicle on trial day

2 Learning Objectives

2.1. Technical objectives (e.g., basic math, science and engineering knowledge, skills, processes and procedures)

Design, Build, Test and Operate a lighter-than-air vehicle.

Calculate lift and drag for blimps to evaluate aerodynamic designs.

Design a radio-control system

Evaluate the tradeoff between maneuverability and stability in aerospace systems

2.2. CDIO outcomes (e.g., personal and professional skills and attributes teamwork, communication, conceiving, designing, implementing and operating skills)

2.1.5 Solution and Recommendation

2.3.4 Trade-offs, Judgment and Balance in Resolution

2.4.7 Time and Resource Management

3.1.x Teamwork Skills

4.3.2 Defining Function, Goals, and Architecture

4.4.1 The Design Process

4.5.5 Test, Verification, Validation and Certification

4.6.2 Training and Operations

C. Dragonfly summary project description

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1. Project Overview

- 1.1. Overall goal or purpose. This lab is part of an introductory course in aeronautics for the freshman/sophomore aerospace engineering student. This student has typically been highly interested in airplanes, space, and typical applications of aerospace engineering from an early age. The course and lab represents the first connection of physics and mathematics to an airplane. The airplane is a very light radio controlled airplane which the student is required to assemble, modify, fly, and most importantly, predict its performance using the theoretical tools developed in the course. Quantitative performance is measured from flight test, and the student asked to compare the results to theory. The lab not only provides practice in the application of the theoretical tools introduced in the class, but also provides a context to explore higher level concepts such as the limitations of the theory applied, experimental measurements with error analysis, as well as team and project management fundamentals.
- 1.2. Societal context and relevance. If engineering is defined as the practical application of a discipline to industry, then this lab provides an introductory experience for the sophomore engineering student in that context. In addition to the proper application of the equations regarding aeronautics in general and aircraft performance in particular introduced in the classroom, the engineering student is required to build and demonstrate a mechanical machine (airplane) which is then flown in a public venue (sports field house). In this way, the student sees that engineering is both a science and a practice.
- 1.3. Integration (e.g., where project fits in a course, program, or curriculum). The DragonFly Lab is conducted during the fall semester of the sophomore year as part of an introductory course in aeronautics. Laboratory time is interspersed with construction and testing of the airplane and with development of computational methods (spreadsheets) to predict the airplane performance.
- 1.4. Description. Scope of effort is three weeks. One airplane kit is provided to each group of 5 to 6 students. At the Naval Academy, this equates to three teams per section/class. The total cost is \$500 in expendable supplies and \$400 in non-recurring equipment.
- 1.5. Learning activities and tasks (brief summary). A radio controlled park flyer (very light weight) airplane kit is distributed to a group of students. The students must apply fundamental principles of aircraft performance from their recitations in order to predict one or more performance characteristics of the r/c airplane. For example, they could be asked to predict the total energy required for the airplane to fly a predefined circuit. As another example, they could be asked to predict the maximum payload that the airplane could carry around a circuit. The airplanes are then built and the performance metric is measured from a flight test. Students are asked to compare and contrast results in the form of an oral presentation and written report.

2. Learning Objectives

- 2.1. Technical objectives (e.g., basic math, science and engineering knowledge, skills, processes and procedures). This lab requires the student to apply basic principles of aircraft performance taught in class to a small radio-controlled airplane. The
- 2.2. CDIO outcomes (e.g., personal and professional skills and attributes teamwork, communication, conceiving, designing, implementing and operating skills).
 - 1.2.4 *Computational Techniques*
Demonstrate basic spread-sheet skills for reduction of test data.
 - 2.1.1 *Problem Identification and Formulation (4)*
Translate between diverse systems of units.
 - 2.1.2 *Modeling (3)*
 - 2.1.3 *Estimation and Qualitative Analysis (4)*
 - 2.1.5 *Solution and Recommendation (4)*
 - 2.2.2 *Survey of Print and Electronic Literature (3)*
 - 2.3.1 *Thinking Holistically (3)*
Identify and define a system, its behavior, and its elements
Describe what is meant by a “system of systems”
 - 2.4.2 *Perseverance and Flexibility (3)*
 - 2.4.3 *Creative Thinking (3)*
 - 2.4.4. *Critical Thinking (4)*
 - 3.2.5 *Graphical Communication (3)*
Demonstrate basic plotting skills to include proper annotation/labeling
 - 3.2.6 *Oral Presentation and Inter-Personal Communications (4)*
 - 3.2.2. *Communications Structure*
Construct logical, persuasive arguments
Construct the appropriate structure and relationship amongst ideas
Choose relevant, credible, accurate supporting evidence
Practice conciseness, crispness, precision and clarity of language
 - 3.2.3. *Written Communications*
Demonstrate writing with coherence and flow
Practice writing with correct spelling, punctuation and grammar
Demonstrate formatting the document
Demonstrate technical writing
 - 3.2.4. *Electronic/Multimedia Communications*
Apply various electronic styles (charts, web, etc)
Apply various written styles (informal, formal memos, reports, etc)
 - 3.2.5. *Graphical Communications*
Demonstrate sketching and drawing
Demonstrate construction of tables, graphs and charts

D. Composite truss member lay-up, summary project description

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1. Overview

1.1. Overall goal

Manufacture a unidirectional glass fiber-reinforced epoxy matrix strut with round cross-section that can sustain a theoretical load of 3500 lbs without failing.

1.2. Societal context/relevance

In the quest for increased performance and fuel savings of all kinds of vehicles, which includes reduced weight and lower cost, current metallic alloys frequently have reached their limits. Composites, which are made of two or more constituents, proved promise to fulfill these requirements without jeopardizing safety.

1.3. Program integration

The project is integrated into an introductory course on materials science which includes a few weeks of studies on composite materials. The strut design and manufacture may take 6 hours of laboratory and two hours of testing. Limitations may occur due to availability of tensile testing equipment.

1.4. Project description and scope

The objectives of this lab were to design and fabricate (cast) a fiber reinforced strut, perform a tensile stress test, and obtain stress/strain data from the sample. The groups were expected to understand the effect of the number of fibers within the strut, the effect of cross sectional area ratios on the strength of the strut, and identify the challenges and difficulties in manufacturing a composite material.

1.5. Learning activities and tasks

1.5.1. Model the Modulus of elasticity of composites

1.5.2. Manufacture a composite strut

1.5.3. Prepare a strut for tensile testing

1.5.4. Operate tensile testing equipment

1.5.5. Analyze data

2. Learning Objectives

2.1. Technical Objectives

2.1.1. Concepts

- Fiber reinforced composites combine the strength of strong and brittle fibers with the ductility of a matrix material. The fibers carry the bulk of the load.
- The reinforcement must have higher elastic modulus than does the matrix.
- Fiber composites provide exceptional strength and strength-to-weight ratio.

2.1.2. Skills

- Model the modulus of elasticity of composites
- Manufacture a composite strut
- Prepare a strut for tensile testing
- Operate tensile testing equipment
- Analyze data

2.1.3. Processes

- Analytical design study
- Creativity in molding ancillaries
- Casting composite
- Removing casting from mold
- Preparing strut for testing
- Verify and validate testing data

2.1.4. Procedures

Procedure for Casting a Composite Strut.
 Preparing the Mold
 Making the Composite Mixture
Epoxy Strut Tensile Testing Procedure

E. Skyscraper summary project description

1. Project Overview

- 1.1. Overall purpose: The overall goal of this project-based learning experience is to promote students' ability to describe, anticipate, and plan for some of the realistic factors encountered in an engineering project.
- 1.2. Societal context and relevance: Students benefit from setting learning activities in realistic contexts. The exercise provides a context for introducing the need for good documentation, customer requirements and construction regulations, R&D, critical thinking, creativity and intuition, problem solving and experimentation, teamwork, competition, budget and schedule constraints, aesthetics, and the unusual requirement of safety. It also draws on engineering and scientific disciplinary knowledge
- 1.3. Integration: The project-based learning experience is targeted for first and second-year engineering students. With elaborations described below, it could be used with third-year students. The target audience is largely independent of engineering discipline, as the outcomes are focused on real-world factors likely to be present in any engineering project. For students who study structures, *e.g.*, aerospace, mechanical, civil, there is a bit more disciplinary relevance, but this is not the primary goal of the learning experience.
- 1.4. Complexity: This project is of moderate complexity since it primarily involves a set of structured design-implement-operate activities by a small team (5 – 8), within a half or full day (see below) regarding a problem with a somewhat open-ended solution set.
- 1.5. Brief Summary of Learning Activities and Tasks (the Student Instructions provide a detailed description of the learning tasks.) A typical timeline for the Skyscraper activities is:

	Full Day	Half Day	
Introduction by the instructor	15 minutes	15 minutes	15 minutes
The conceive phase	30 minutes	30 minutes	30 minutes
Journal completion	15 minutes	10 minutes	
The design phase	30 minutes	30 minutes	30 minutes
Journal completion/Building Inspector Review	15 minutes	10 minutes	15 minutes
Debrief conceive/design phases	30 minutes	20 minutes	15 minutes
Introduction to implementing PBL activities	30 minutes	10 minutes	15 minutes
The implement/operate phase	50 minutes	45 minutes	40 minutes
Journal completion	15 minutes	15 minutes	
Debrief implement/operate phases	30 minutes	15 minutes	15 minutes
Development of local PBL exercise	30 minutes		
Summary and discussion of experiences	20 minutes		
Workshop evaluation and debrief	20 minutes	10 minutes	5 minutes
Total	5.5 hours	3.5 hours	3.0 hours

2. Learning Objectives

- 2.1. Recognize when disciplinary knowledge can be applied to a design
- 2.2. Identify additional knowledge required to design and analyze a proposed structure
- 2.3. Anticipate and plan for factors encountered in an engineering project
- 2.4. Explain ways in which critical thinking, creativity, problems solving and experimentation are required in designing and building the proposed structure
- 2.5. Describe the importance of dividing tasks among team members aligned with their respective strengths (e.g., leadership, analysis, design, manufacturing) and the benefit of designating a team leader
- 2.6. Describe the need for good documentation of designs and implementation processes
- 2.7. Explain the challenge of and trade-offs necessary to meet the requirements and regulations within the fixed budget and timeline
- 2.8. Describe the benefits of conducting research and development testing without unduly delaying the manufacturing process
- 2.9. Realize the importance of designing structures with quality and the safety of the public in mind
- 2.10. Accept the need to be fair-minded in competitive situations

F. MoRETA summary project description

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1. Project Overview

1.1. Overall goal or purpose

The MoRETA project was established in order to develop and validate a modular rover design capable of conducting a wide range of high impact science operations in a variety of extreme terrains under both direct and remote human guidance in order to maximize the scientific return per cost of future Lunar and Martian rovers.

1.2. Societal context and relevance

The success of the Mars Exploration Rovers (MER) during their missions has demonstrated the importance these rovers have in the exploration of planetary surfaces. Future rovers bound for Martian and Lunar surfaces will need to be more autonomous, capable of assisting astronauts, and able to perform multiple tasks in order to truly return the highest value for the mission. Furthermore, the most interesting scientific samples are located in areas of extreme terrains. For example, meteorite impacts and erosion expose layered bedrock on steep slopes which contain material holding clues to Martian geological, hydrological, and biological history such as those seen in the inner wall of “Endurance Crater”. These terrains result in a need for a more mobile and versatile rover as such extreme terrains pose a high risk to the current rovers.

1.3. Integration

MoRETA ran as a three-semester capstone project as part of the MIT Aero-Astro course 16.83x.

1.4. Description

The MoRETA project spanned three semesters with nearly 70 students participating in the first semester. Due to the structure of the class, enrollment drops each semester; the second and third semesters had 65 and 23 students respectively. The materials budget for the project was approximately \$30,000.

1.5. Learning activities and tasks

High level tasks for the MoRETA Project organized by semester:

Semester 1 (12 Units): Informal Review, Engineering Analysis, Subsystem Requirements Finalized, Systems Requirement Review (SRR), First Iteration of Conceptual Designs, Informal Review, Engineering Analysis, Second Iteration of Conceptual Designs, Conceptual Design Review (CoDR), CoDR Design Document, Informal Review, Preliminary Design Finalized, Leg Prototyped, PDR Design Document, Preliminary Design Review (PDR), Prototype Styrofoam Model of Rover Finished.

Semester 2 (12 Units): Informal Review, Engineering Analysis, Second Prototyped Leg Finished, Flight Chassis Finished, Informal Review, Critical Design Review (CDR), Engineering Analysis, Informal Review, Flight Leg Finished, Bench Review (BR), One Full Hip-Leg Module Finished.

Semester 3 (6 Units): Rover Fully Assembled and Wired, Unloaded Leg Testing, Wheel Prototyped, Acceptance Review (AR), Hip-Wheel Design Finalized, Mechanical Light Weighting Finished, Preliminary Joystick Control Integrated with Rover, Flight Wheels Finished, Locomotion Module Begins Sending Gaits, MoRETA GUI Finished, Loaded Leg Testing, Final Design Document Finished.

2. Learning Objectives

2.1. Technical objectives

- Develop technical specification from detailed customer requirements
- Design and build a complex space-based system
- Analyze the performance of a complex space-based system
- Develop and implement a rigorous testing procedure

2.2. CDIO outcomes

2.3.4 Tradeoffs, Judgement and Balance in Resolution

2.4.7 Time and Resource Management

3.1.1 Forming Effective Teams

3.2.6 Oral Presentation and Interpersonal Communications

4.3.1 Setting System Goals and Requirements

4.3.2 Defining Function, Concept and Architecture

4.4.4 Disciplinary Design

4.5.2 Hardware Manufacturing Process

4.5.5 Test, Verification, Validation and Certification

G. Flight Test Engineering summary project description

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1. Project Overview

- 1.1. Overall goal or purpose. Fascination with flight draws most aerospace engineering students. Some may have considerable time in light airplanes; others await the day. Engineering flight tests provide profoundly powerful academic experiences in which can achieve and assess a broad range of aerospace engineering program objectives (technical and professional), while further capturing the hearts and imaginations of our students.
- 1.2. Societal context and relevance. Flight Test Engineering is a distinct technical discipline within our industry, with its own publications, professional societies, and graduate-level professional schools. Operational engineering necessarily requires unique planning and leadership, such as safety, risk management, and logistics. Flight experiences, with substantive quantitative analysis, operationalize their education.
- 1.3. Integration. The material below has been integrated into Aerospace Engineering programs in two distinct ways. Some programs with close industry affiliations offer a full course in Flight Test Engineering, the principal goal being to directly acquaint students for opportunities in active flight test enterprises. Other programs conduct flight test exercises as an extended lab exercise in support of other courses, such as Airplane Performance or Stability and Control. In both cases, these activities integrate a program's diverse disciplines and add exposure to test planning, safety planning and risk mitigation, flight conduct, data reduction and referral, specification compliance, and test reporting.
- 1.4. Description. Flight exercises introduce foundational flight test practices in the context of a limited scope quantitative evaluation of a light airplane's flying qualities and performance. For a full course format, teams of three students plan and execute four data flights per team. Specific tests include Pitot-static calibration, level flight performance, climb performance, static longitudinal stability, and dynamic stability. Students produce a 40-page report on the stability and performance of the subject airplane. For the limited format, any of the exercises in a full course can be adapted as stand-alone flight exercises. Individual flight experiences can be conducted for ~\$100 per student. Total costs strongly depend on pilot currency requirements apart from syllabus flying.
- 1.5. Learning activities and tasks (brief summary). Flight exercises measure the flying qualities and performance of a light airplane. Students are involved in planning and directing each test, as well as being responsible for data collection, reduction and reporting. The scope can range from a solitary stand-alone flight exercise, or a broad evaluation requiring thirty hours and two dozen flights.

4. Learning Objectives

- 4.1. Technical objectives. In a stand-alone flight test course, most technical content resides in pre-requisite subjects such as Airplane Performance, Applied Aerodynamics, and Stability and Control. Pitot-statics and Instrumentation must typically be treated at greater depth than typically found in such courses.
- 4.2. CDIO outcomes. Flight Test activities can be used to both utilize and teach a large range of CDIO outcomes. The following CDIO skills are commonly utilized:
 - 2.1.1 *Problem Identification and Formulation*
 - 2.1.2 *Modeling*
 - 2.1.3 *Estimation and Qualitative Analysis*
 - 2.1.5 *Solution and Recommendation*
 - 2.2.2 *Survey of Print and Electronic Literature*
 - 2.4.3 *Creative Thinking*
 - 2.4.4. *Critical Thinking*
 - 2.4.6 *Lifelong learning*
 - 3.2.4 *Written Communication*
 - 3.2.5 *Graphical Communication*
 - 3.2.6 *Oral Presentation and Inter-Personal Communications*
 - 4.4.3 *Utilization of Knowledge in Design*
 - 4.4.5 *Multi-disciplinary design*
 - 4.6.1 *Designing and Optimizing Mission Operations*

The following CDIO skills are explicitly taught:

- 2.5.3 *Career Planning* Flight test as a career opportunity
- 4.1.1. *Roles and Responsibilities of Engineers*- The test engineer's responsibility to the customer or certification authority.
- 4.6.2 *Training and Operations*- Operational Resource Management, risk assessment and mitigation
- 4.6.3 *Supporting the System Lifecycle*- the flight test community (Developmental Test and Operational Test)
- 4.6.4 *Systems Improvement and Evolution*- flight test's role in life cycle improvement of fielded systems.

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