Carleton University Simulator Project (CUSP)

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This paper presents novel aspects of CUSP, an industrially relevant 4th year design project, and its pedagogical paradigm in the framework of Capstone Design Projects in the Department of Mechanical and Aerospace Engineering at Carleton University. There are currently six projects involving 28 faculty members, 6 graduate students, 200 4th year students, and a significant number of 3rd year student volunteers. CUSP will be presented as a case study. This project is by nature multidisciplinary and includes participation of the Department of Systems and Computer Engineering, the Centre for Applied Cognitive Research, and the Eric Sprott School of Business. Given its industrial relevance, proposals have been made for industrial sponsorship of graduate students and post-doctoral fellows to lead basic research and development aspects, thereby evolving the project into a vertically integrated research programme. A similar thrust is being made by the five other multidisciplinary projects.

1 INTRODUCTION

In February 2003, the CSME and the Department of Mechanical and Industrial Engineering at Concordia University in Montréal co-hosted the International Conference on the Future of Engineering Education (CSME-ICFEE 2003). The objective was to create an opportunity for frank discussion between engineers in academia and those in industry. Topics ranged from issues facing women in engineering to a panel discussion on Interdisciplinary Engineering Programmes and another on Re-Engineering the Aerospace Curriculum. All of the sessions were productive, but the two panel discussions were particularly so. Moreover, the resulting conclusions and recommendations from the two panel sessions meshed very nicely with the evolution of 4th year capstone design projects in the Department of Mechanical and Aerospace Engineering at Carleton University.

Filippo Salustri, from the Department of Mechanical, Aerospace, and Industrial Engineering at Ryerson University, led the discussion on interdisciplinary engineering programmes [2]. The panel members were all academics and the discussion focused on how such programmes can be developed at Canadian universities. The most generally accepted idea was that modern engineering design challenges require a multidisciplinary paradigm, rather than an interdisciplinary team approach. That is, in the paradigm of 4th year capstone design projects it is not enough to enable interaction between different engineering disciplines. What is required is the enablement of interaction between different disciplines. For example, a design team examining issues associated with *human factors* in the design of a human-machine interface must include not only mechanical, electrical, and systems engineers, but also requires input from psychologists, cognitive scientists, industrial designers, physiologists, etc..

The panel on re-engineering the aerospace curriculum was chaired by Hany Moustapha from Pratt & Whitney Canada. The majority of panel members were from the aerospace corporations in the Montréal area, including CAE, Bell Helicopter, and Bombardier. There was general agreement that mechanical and aerospace engineering students graduate with sufficient technical skills, but lack key *soft skills*. The outcome of the discussion was a wish list of soft skills the aerospace industry members wanted the aerospace, and by extension the mechanical engineering, curriculum to impart to new graduates. This wish list was nicely summarized by Gerhard Serapins [3], Manager of Research and Development, Operations, CAE Inc.:

> "There is a need for students to experience working in a virtual enterprise environment. Among other soft skills, they need to experience a design project matrix: experience having to prioritise among multiple supervisors and multiple tasks; communicating in a large multidisciplinary team; develop verbal and written communication skills, but also develop the capacity for unbiased listening."

For the last ten years the paradigm for the 4th year capstone design projects in the Department of Mechanical and Aerospace Engineering at Carleton University has evolved such that it satisfies the major requirements agreed upon by both panel discussions [1]. That is, a compromise has been found that meets the academic requirements for accreditation, while focusing on industrially relevant design issues.

While the projects are *resource intensive* both in terms of funding, time, and space, the end result is very well justified. Moreover, the return on the investment is irresistible. It includes good will and cooperation from industry and government institutions, research opportunity, potential graduate students, and graduating students well prepared to make a strong contribution to any modern design project. One very tangible benefit for our 4^{th} year students that stems from the relationship between industry and university fostered by the capstone design projects is a job. The final design reviews are well attended by relevant industry representatives. Frequently students are invited to interviews, or even offered an entry level position during the banquet following the design review.

In the next section we shall give a brief history of the evolution of the 4^{th} year capstone design project paradigm, present an overview of management and operational practices, and briefly describe each of the current six projects. The subsequent section will illustrate the concepts using CUSP as a case study, wherein we shall describe the objectives of CUSP in greater detail, discuss the management and organization of the *matrix* format, and outline the technical aspects.

2 EVOLUTION

Carleton University began offering Masters and Doctoral degrees in aeronautical engineering in the early 1960s. By the 1970s there were several faculty members who had spent some time in the United Kingdom and were well aware of the design project that was a major part of the educational activities at The College of Aeronautics, Cranfield, England (now Cranfield University). The Cranfield project involved a design team of about 20 students, guided by several faculty members. Over a period of a year or more the team would typically develop, to quite a high level of detail, the design of an aircraft for some specified mission.

In 1986 a proposal to offer an undergraduate degree program in aerospace engineering was being prepared for Carleton University's Senate and there was a consensus that a team design project similar to that at Cranfield should be included in the final year of the new program. The intent was to simulate insofar as possible the team-design environment typically found in the aerospace industry. It was felt that such a team project would not only provide students with substantial first-hand design experience but would also provide a vehicle for attaining other educational objectives, including making students aware of the importance of collaborative effort, communications, documentation and configuration control and for giving them opportunities to improve their presentation and report-writing skills. The proposal was accepted by Carleton's Senate and both an aircraft and a satellite design project, each with about 20 students, were implemented in 1991-92, the final year of the first Aerospace Engineering graduating class.

Representatives of industry were involved in the projects from the beginning, both as lead engineers in the project work itself and as evaluators in the formal design reviews at the end of each academic year, see [4], for example. The feedback from industry representatives was very positive, so much so that in 2001-02 the same team project format was adopted in the mechanical engineering degree program. At present there are six ongoing projects.

3 OVERVIEW

The current success and popularity of the capstone design projects largely can be attributed to three main factors: challenge, industrial relevance, and continuity. Experience has demonstrated that the more challenging the task faced by students, the greater the accomplishment that can be expected. To foster this, project managers and lead engineers (faculty members and consultants) are finding that technical and management support rather than direction is an effective operating model for the projects. Each project is technically challenging and generally based on ambitious end objectives. All the projects have multi-year time lines, typically five years, carried out in yearly phases.

Projects are industrially relevant in two senses - technically and administratively. The technical relevance of projects facilitates obtaining financial support and interaction between students and engineers in industry. Currently there are more than 50 industrial participants supporting in cash, and in kind, the six projects. The combined industrial and educational environment exposes students to industrial project management, but with greater tolerance for mistakes along the learning curve. The support provided by industry is partly due to the fact that these projects provide a pool of highly qualified personnel who are already familiar with technical and interpersonal aspects of large projects, and with potential technical solutions to difficult problems. Publicity with students and the public at large, and an opportunity to contribute to engineering education are additional factors. Continuity results from both the size of project teams and the multi-year nature of the projects.

A typical project now involves in excess of 25 students, five lead engineers, and a project manager, each contributing a minimum of 200 hours (sometimes much more) to the project each year. In addition, one graduate student and numerous 3rd year student volunteers participate in each of the projects. This results in a project budget in excess of 35,000 engineering hours over five years - representative of a large engineering project. The large number of participants and long duration allow for efficient parallel developments as well as long serial developments such as design iteration. While annual student turn-over necessitates more annual lead time than would otherwise be required, it provides many new perspectives and a continuous evaluation of previous design decisions. One result is that the projects are currently strong and are also evolving - quality is improving, student involvement at the graduate level and from programs external to Mechanical and Aerospace Engineering is growing, industrial interest and participation is increasing, and greater financial resources are becoming available.

At present, projects are proposed and selected by departmental faculty members. As industry fully appreciates the potential of these projects for tackling challenging problems that can more easily be undertaken in a university environment due to greater academic resources, greater cost effectiveness, and reduced requirements for guaranteed success or immediate results, it is likely that projects will be selected and coordinated collaboratively with the research and development activities of industrial and government partners.

All projects include prototype fabrication and testing of the entire design or major subassemblies. In the time frame of one academic year moving from concept to prototype is an immense challenge for any design team. To achieve this objective requires strict adherence to schedules and budgets, but imparts in students an appreciation that while “paper” is patient, moving to physical reality through a prototype is not. The requirement for prototype fabrication and testing means that design “timecompression” technologies must be developed and utilized, including concurrent engineering, CAD/CAM, virtual solid modelling/visualisation, computer aided analysis, numerical analyses, tradeoff and sensitivity studies, and rapid prototyping. As importantly, students must be innovative and efficient in their communication, time management and interaction with industry and external participants.

Three hour project general meetings are held every week to co-ordinate progress. Two formal design reviews are held - one each term. Industry representatives familiar with the design objective participate in the final formal design review and offer suggestions on design strategy, technical feasibility and potential improvements. Projects include visits to industrial facilities of relevance to the design objective. This collaboration and interaction with industry enhances the skills imparted to students, enabling them to be more productive when they embark on their careers following graduation.

To support these projects the Department maintains Design Laboratories equipped with networked computers, the necessary CAD software, and specialized design and analysis software for each project. In addition a wide range of prototype fabrication, development and testing facilities are available so that students can manage the transition of their designs from “paper” to physical reality.

The spectrum the projects cover is broad and address virtually all aspects of mechanical and aerospace engineering. It is evident that industrially-motivated needs provide challenging capstone design projects, and result in lasting benefits both in terms of student development, as well as potential employees and products.

The six current design projects are:

1. Carleton University Simulator Project (CUSP);
2. Air-launched Earth-observing Ground Information System (AEGIS);
3. Zero-emission micro turbine engine;
4. Autonomous Underground Mining Vehicle (AUMV);
5. Formula SAE vehicle;
6. Unmanned Air Vehicle (UAV).

4 CUSP

CUSP is the newest of the capstone design projects and was introduced in the 2002-2003 academic year. The decision to develop a simulation project was based on growing prevalence of simulation throughout vehicle and process design cycles and for subsequent uses ranging from simulation-based acquisition through operator training. The concept of a simulator project has received strong support from the Canadian simulation community as it is projected that demand will exceed supply of recent graduates with the skill set required to integrate seamlessly in this industry over the next decade. Further, due to the strong support, significant opportunity exists for students to interact with counterparts in industry and government during their involvement with CUSP, and this interaction will further hone the important soft skills identified and highlighted by the panel discussions.

Vehicle simulation in various forms has been applied to all types of vehicles including fixed- and rotary-wing aircraft, surface and subsurface marine vehicles, on- and off-road ground vehicles, and rail vehicles as well as many process-related environments such as power station operation and air-traffic control. Simulator objectives, structures, and specifications for each vehicle or process and application can be quite different. The overall technical objective of the CUSP design project is to develop a set of requirements for a multi-functional vehicle simulator and motion platform that can be applied to a range of vehicle types, and subsequently design the corresponding multi-functional simulation facility exploiting, within financial constraints, new technologies. The project is both complex and ambitious and is therefore expected to span multiple years and correspondingly, multiple groups of students. The CUSP objectives can be categorized into both short- and long-term. Short-term objectives are defined based on a one year time line appropriate for a single class of students whereas long-term objectives are based on a five-year time line.

The long-term objectives of the project are to develop a complete and flexible simulation facility located at Carleton University including a variety of mathematical models, a multi-functional motion platform, a general vision system, and a reconfigurable user interface all interoperating based on high-level architecture (HLA). This research and simulation facility will be used to support simulation education as well as specific research objectives motivated by industry and government. Evidence suggests that such a facility can eventually become economically self-supporting.

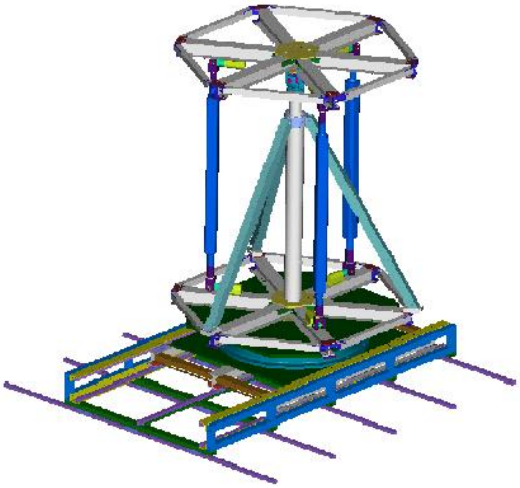

Figure 1: NASP conceptual design.

The short-term objectives completed in Year 1 of the project (2002/2003) were to survey potential applications, requirements, existing shortcomings, and possible configurations for simulator motion platforms that are appropriate for a range of vehicle types, develop a preliminary design for a novel six-degree-of-freedom motion base (called NASP, for *not a Stewart platform*, and illustrated in Figure 1), and simultaneously design and build an HLA compliant simulation demonstrator (called SiDFreD, for *single degree-of-freedom demonstrator*, and illustrated in Fig-

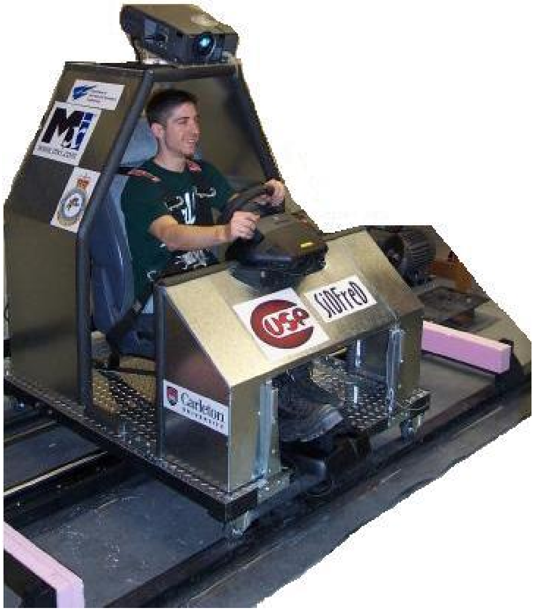

Figure 2: 4$^{\text{th}}$ year student Andrew Bruce in SiDFreD testbed.

ure 2) having a single-degree-of-freedom based on a road vehicle system that includes a mathematical model, user input, actuation, and graphical display. While initially a simple system, this model establishes an approach that can be applied for the implementation of the full motion simulator.

The short-term objectives for Year 2 of the project include developing SiDFreD into an effective multi-functional simulator having three degrees of freedom; refining and expanding the NASP platform and facility into a practical multi-functional design; and strengthening external ties through focussed research and effective communication relevant to the simulation industry.

5 ORGANIZATION

The current CUSP design team includes five faculty members, one graduate student, and twenty-eight final year undergraduate students from programs in Aerospace Engineering, Mechanical Engineering, Systems and Computer Engineering, Computer Science, Buiness, and Psychology at Carleton. In addition, the possibility exists for undergraduate student volunteers and graduate students to become involved with the project. In the past academic year, five third-year engineering student volunteers were directly involved with CUSP. Note that the multi-disciplinary team offers the varied set of analytical skills and perspectives necessary to effectively advance a project of this scope.

The organizational structure of the project is based closely on an industrial model where a faculty member serves as the Project Manager, while faculty members and graduate students serve as Lead Engineers responsible for leading functional teams. The students and lead engineers are organized into teams according to area of expertise (Integration-INT, Actuation-ACT, Kinematics and Dynamics-DYN, Structures-STR, and Systems-SYS) and task-oriented groups (Business Development-BUS, SiDFreD Demonstrator-SID, NASP Platform-NSP, Safety Systems-SAF, Human Factors-HMF, and Vehicle Simulation-VS). Each team includes approximately 6 students and each group is staffed as appropriate for the anticipated group activities. Table 1 illustrates the matrix concept. To facilitate communication and integration within the project, each team has an appointed Integration Team liaison person and the group leaders are the members of the Integration Team. Lead engineers are also associated as technical advisors to the groups. Using this matrix structure, a functional and industry-relevant management structure is created.

The project has a weekly general staff meeting attended by all participants. These meetings provide an opportunity to discuss technical aspects and progress of the overall project, listen to presentations by invited speakers relevant to the project, and present data and results that are of common interest to project members. The format of weekly staff meetings includes opening remarks by the project manager and lead engineers, status reports from the project teams and groups, general discussion, and individual group and/or team meetings. In the event of guest speakers or facility tours, the format is altered as necessary. In addition to the common meeting, lead engineers generally meet with team members at another convenient time as well. Student groups meet on their own as necessary.

With the number of project members involved and the number of tasks undertaken concurrently and the many associated interdependencies, communication between individuals, teams, groups, and the project management are vitally important. In addition to verbal communication during the weekly meetings, project information is documented and transferred using a combination of brief technical memos to convey information to other team members, design reports to docu-

Table 1: CUSP organizational structure

group \ team	INT	ACT	DYN	STR	SYS
Business	student 1	student 2	$\cdots$		
SIDFreD	student 3	student 4	$\cdots$		
NASP	$\vdots$	$\vdots$	$\ddots$		
Safety					
Human Factors					
Vehicle Simulation					

ment significant accomplishments, and a comprehensive final report summarizing the contribution to the project by entire classes of students. The objective is to have concise effective communication. A project web site is used as a central means of communication and serves as a repository for all 'published' information such that it is available to all project members at all times. The web site has both public and private components as the public portion of the web site is used to keep project sponsors and potential industrial receptors of the developed technology aware of progress to date.

5.1 Groups

The task-oriented groups involved with CUSP are formed and staffed consistently with current project objectives and can vary from year to year. As an example, the groups appropriate for Year 2 of CUSP are reflected in Table 1. Functions of individual groups are described briefly below.

5.1.1 Business Development

The two primary functions of the Business Development Group are sponsorship and external communication. The funding for CUSP relies heavily on sponsorship provided from various sources within Carleton University, Industrial and Government contributions, discounts offered by suppliers, and in-kind support provided by industry, government, and individuals. In this regard, the business group identifies potential support and prepares the appropriate sponsorship packages and applications. In the second capacity, the business group prepares project brochures, develops and maintains the project web site, and interfaces with the media.

5.1.2 SIDFreD

The several integrated degree-of-freedom demonstrator (SIDFreD) Group is responsible for all aspects of designing, integrating, and testing the SIDFreD technology demonstrator. The range of tasks includes design and manufacture, mechanical maintenance, software development and testing, and operation. Further, since SIDFreD is intended in part to be a technology demonstrator for the NASP design, the SIDFreD Group is responsible for customizing SIDFreD as appropriate for performing new technology evaluation.

5.1.3 NASP

The acronym NASP stands for *not a Stewart Platform*, which reflects the strong emphasis on innovation within the projects. The NASP Group is responsible for developing concepts and advancing the design of the conceptual NASP platform. Unlike SIDFreD, that involves physical hardware, the NASP Group is focussed on an initially paper design that will necessarily require the collaboration of industry and government partners for its ultimate fabrication and evaluation.

5.1.4 Safety Systems

The Safety Systems Group ensures that safety-related issues are addressed completely within the project. Activities include ensuring that CUSP meets or exceeds departmental, university, and provincial health and safety guidelines and ensures safety aspects are included in both the mechanical and software aspects of both the SIDFreD facility and the NASP design. Safety is highlighted throughout CUSP and innovative approaches for improving simulator safety systems are investigated.

5.1.5 Human Factors

The Human Factors Group is focussed on two primary issues. First, the cognitive science aspects of simulation are addressed in determining limits of human perception such that they can be incorporated into the platform washout algorithms thereby ensuring high fidelity of the developed systems. Second, ergonomics aspects of the simulators are addressed by this group.

5.1.6 Vehicle Simulation

The Vehicle Simulation Group is responsible for the mathematical modelling and simulation of the vehicle systems that will be simulated using the SIDFreD and NASP platforms. As the overall objective is to develop reconfigurable platforms, special attention is required to ensure that the ranges of motion of the platforms are appropriate for a range of vehicle types. This activity of simulating various vehicles is performed by the vehicle simulation group. Further, the developed vehicle models are integrated into the SIDFreD demonstrator and provide the core mathematical models and simulation software driving the developed simulators.

5.2 Teams

As mentioned earlier, the students and lead engineers are organized into teams according to area of expertise. Each team includes approximately 6 students and each student is cross appointed to one group so that each team has a representative of each group, and vice versa. The scope and technical objectives of the five teams are summarized below.

5.2.1 Integration (INT)

The focus of the integration team is primarily on project management. Tasks include establishing a project work breakdown, and critical time lines for deliverable deadlines to ensure all tasks will be completed on time; coordinating the efforts of all teams and groups; overseeing preparation of documentation and presentation templates. Integration team members are required to be familiar with all aspects of the project.

Integration team members get their share of experience with technical aspects of the design through their cross appointment to one of the groups. Moreover, the Integration team members must understand, at least superficially, all technical aspects of the project in order to be effective managers. The conceptual design of NASP requires significant research of the state of the art of simulators while the proof-of-concept demonstrator requires aspects of the simulator to move off the drawing board and become a working prototype. INT must oversee this transformation.

5.2.2 Actuation (ACT)

Initial effort in the Actuation (ACT) team was directed at understanding various techniques to achieve controlled motion including electromagnetic, ball screw, linear belt drives and related motors. Research included a physical description of the method of operation, its technical limitations, its cost and an estimate of the time to manufacture not-in-house components. Subsequent efforts were directed at understanding the relations between the structural constraints (placement on platform, force, torque), the envelope of motions that would be attempted (kinematics, velocities, accelerations) and the duel issues of human physiology (what motions feel real) and cognitive perception (what motions appear real). Research on these issues and their inter-relationships are ongoing through group discussions, etc. Preliminary results permitted ACT to initiate a process to implement a second degree of freedom on the existing SIDFreD platform.

The process to implement a second degree of freedom required additional team interaction with the Systems team (SYS) to insure a proper selection of actuator PC control card and compatibility with the system architecture. Thirty industries involved with actuator design and manufacture were identified and canvassed for product information including a product's operating characteristics, reliability, robustness, expansion flexibility, cost, product support, ease of implementation and integration with power supply, control card and a software interface. A point student was identified and placed in charge of coordinating and cataloging the team's efforts and accomplishments during this phase of the effort. A significant challenge was to optimize the information obtained and the industrial relationships over a relatively short period of time to achieve a good fit with the aims of the CUSP project. The next phase of the project will include extensive testing of the software controlled actuator to obtain load-frame information on the load-displacement, load-velocity and load-acceleration behaviour.

5.2.3 Kinematics and Dynamics (DYN)

The primary focus of the kinematics and dynamics team is on model development. These models are essential for platform analysis and control. Because the control system requires position, force and torque output in real time, the mathematical models must be computationally optimized. The equations of motion for the 3 DOF SIDFreD are reasonably straightforward, and employ the Newton-Euler formulation. But DYN is also responsible for washout algorithm development and implementation in the appropriate HLA Federate.

The kinematics and dynamics of 6 DOF motion platforms are non-trivial, and are still a hot topic in the research community. The DYN team will have to carefully examine traditional Cartesian techniques as well as more sophisticated methods (kinematic mapping, Study's soma, dual-quaternions, etc) to develop the kinematic model. For the dynamics the Newton-Euler, Lagrange, Kane, and possibly other formulations will be examined. The bottom line shall be computational efficiency.

Human factors and Washout represent a key point of intersection between the fields of human physiology, psychology, cognitive science, and engineering. The implementation of a convincing motion simulator starts by modelling how the proprioceptive, visual, and vestibular receptors respond to force and motion cues encountered during actual operation of the vehicle being simulated. The training simulator must provide cues that the human receptors interpret as real. Moreover, the simulator must not provide *negative* training. These motion cues must be provided by a combination of environmental prompts and movement of the simulator platform within its operational workspace envelope. They must be imparted such that the perception of the motion and associated forces are sustained while the platform returns, with movement below the perception threshold of the operator, to a neutral kinematic configuration to await the next command input. This is accomplished by a *motion cueing* algorithm, or *washout* filter.

To implement a washout filter the reachable and orientable workspace limits of the motion platform must be known. Workspace characterization of 6 DOF spatial parallel platforms is also a hot research topic among the kinematics community. Hence, there are no *off the shelf* solutions. The characterization will have to be developed by the DYN team in collaboration with industry and the research community.

5.2.4 Structures (STR)

In the first week of the Fall semester, the Structures team is assigned the task of drafting several designs of the motion platform that can potentially yield the range and the degrees of freedom required. The brainstorming of ideas typically involve students from other teams as well. When accomplished, these ideas are presented at the weekly general meeting of all the members of the project. The advantages and disadvantages of the different conceptual designs are discussed and one of them chosen for the detailed design for the year.

Students in the Structures team are then assigned separate tasks of determining the final detailed design of the different structural parts of the motion platform. This involves compiling the list of components and carrying out stress analysis to obtain the final physical dimensions to ensure their structural integrity. Where necessary, this may involve using commercial finite element software. Final design working drawings of the components and the final assembly are then created and documented. The design and manufacture of SIDFreD follows a similar process as described above, with a tighter deadline. This is feasible as the demonstrator must be completed before the final design review in March.

Once the design drawings of the components and the assembly have been approved by the lead engineer of the team, the students then proceed with sourcing and purchase of the materials required, followed by the manufacture in the departmental machine shop of the necessary parts that they have designed. Throughout this process, there is constant communication between the members of the Structures team and those of the Actuation and Dynamics teams in particular to ensure that all their engineering and safety concerns are duly considered in the structural design.

5.2.5 Systems (SYS)

The Systems Team (SYS) is responsible for the computing infrastructure associated with CUSP, and the Lead Engineer for the team (Dr. Trevor Pearce) was recruited from the Department of Systems and Computer Engineering. The team's responsibilities have expanded over the past two years, and SYS members are active in the complementary groups that deal with issues that span the project's team structure. Membership in the team is open to any interested student; however, the computing focus has resulted in the team being dominated by students from Computer Systems Engineering, Software Engineering, and Communications Engineering programs. With the current SYS team representing about one quarter of the total number of CUSP students, it represents a significant infusion of interdisciplinary participation.

The scope of the SYS team has evolved with the project. In the first year, the team focused on a computing architecture suitable for the short and long-term goals of CUSP. A central goal was to include the High Level Architecture (HLA) for simulation interoperability [5]. The HLA provides a framework for component-oriented distributed simulation, and was targeted as the underlying infrastructure to enable the run-time computing associated with CUSP platforms. Over the past two years, the team's scope has expanded to include various sensors, development environments, and business planning. SYS members also participate in broader cross-team activities associated with safety, human factors of display technology, psychology, washout algorithms, manufacturing, procurement, assembly, system integration and project management.

The use of the HLA is not entirely without drawbacks. The HLA has a comprehensive set of services designed to support a wide variety of simulation styles. The steep learning curve, and the lack of relevant and readily available examples, are limiting factors for deploying the HLA in an academic project with tight time constraints. To help offset this, the first year SYS Team developed PoolSim, a real-time simulation of a ball rolling on a pool table, as a learning exercise. The PoolSim approach to real-time was reused while developing the first year SIDFreD simulator, and thereby reduced the number of technical issues encountered. The second year SYS Team familiarized themselves with the HLA by extending PoolSim with additional functionality. Again, the learning experience greatly simplified their subsequent step into the SIDFreD environment.

6 CONCLUSIONS AND FUTURE WORK

In this paper we have described the development, or *design* if you will, and implementation of the 4^{th} year capstone design projects in the Department of Mechanical and Aerospace Engineering at Carleton University, citing CUSP as a specific example. The projects are broad in scope and multidisciplinary in nature. While they are resource intensive, experience has shown that, when carefully managed, the results are well worth the investment. A strong working relationship can be formed between industry, government, and university research and development programmes which can lead to opportunities for all involved. In the best case this means jobs for students; highly qualified personnel for industry; funding and collaborative research opportunities for faculty.

Much work remains to be done. To convince other departments in the Faculty of Engineering and Design, and in the university at large, to commit resources, faculty, and students requires careful planning. All participants require some tangible return on the investment. This clearly enlarges the scope of the virtual enterprise analogy. While we must be committed to maintaining the principles of collegiality, and be careful to not make decisions that could erode our academic and philosophical independence, we must strive to be relevant. We all think; may as well think big.

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