An Interdisciplinary Field Robotics Program for Undergraduate Computer Science and Engineering Education

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Santa Clara University's Robotic Systems Laboratory conducts an aggressive robotic development and operations program in which interdisciplinary teams of undergraduate students build and deploy a wide range of robotic systems, ranging from underwater vehicles to spacecraft. These year-long projects expose students to the breadth of and interdependence among engineering disciplines, the span of processes in a system development lifecycle, and the challenges of managing a development process. Over the past five years, this program has provided more than 150 students with exposure to computer science and engineering topics, including software engineering, algorithm development, human-computer interface design, and artificial intelligence. This program provides exciting and compelling educational opportunities for students, offers real-world applications that naturally motivate the need for specific computing technologies, and serves a broader research and development program that utilizes the functional robotic systems to support externally-funded science and technology demonstration missions. The experience of the authors, as well as formal program assessment data, show that this program provides strong student motivation for learning, offers comprehensive and

valuable educational experiences, and enhances student performance. This article reviews the Santa Clara robotics program, highlights the role of computer science and engineering in several projects, and presents the assessment data showing the positive results of this program.

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1. THE SANTA CLARA UNIVERSITY ROBOTICS PROGRAM

Santa Clara University's (SCU's) Robotic Systems Laboratory (RSL) conducts a low-cost, aggressive, integrative educational program focused on the development of intelligent robotic systems [Kitts 2003a]. The centerpiece of this program is a set of yearly undergraduate design projects in which teams of senior students completely design, fabricate, test, operate, and manage high-quality robotic systems, including spacecraft, underwater vehicles, terrestrial rovers, airships, telescopes, and industrial robots. Figure 1 shows several of the robotic systems developed over the past five years.

Once operational, these robotic systems are used by undergraduates, graduate students, and professional researchers to perform compelling science missions and to demonstrate advanced technology. Specific missions include studies relating to marine

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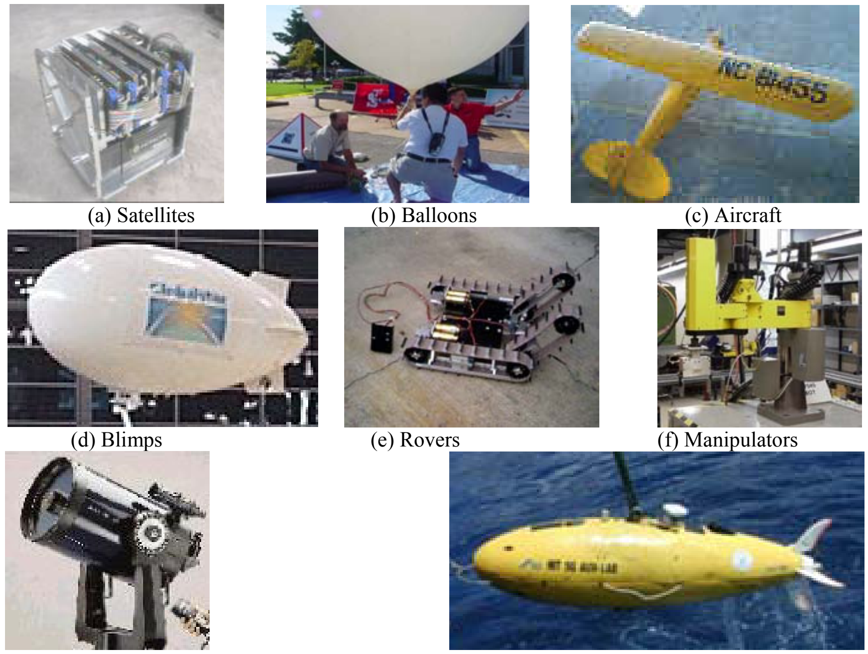

(a) Satellites (b) Balloons (c) Aircraft (d) Blimps (e) Rovers (f) Manipulators (g) Telescopes (h) Underwater Robots

Fig. 1. A sample of SCU robotic projects.

archeology, coastal ecological studies, space-based photography, space environment characterization, satellite formation-flying and constellation control, and autonomous operations. Collaborators and sponsors for these missions include a variety of government agencies (NSF, NOAA, NASA, DARPA, the U.S. Air Force); corporations (Lockheed Martin Corp., Globalstar, Highships LLC); academic institutions (Stanford University, MIT, University of Texas at Austin); and nonprofit entities (Monterey Bay Aquarium Research Institute, California Space Grant Consortium, Global Space League). During the past five years, the development and use of the Lab's robotic systems to support the requirements of these collaborators has resulted in nearly \$2 million of external funding; this financial support plays a crucial role in providing comprehensive educational resources, addressing extensive logistics needs, and the level of robust engineering required for a program that includes significant field operations.

The development and use of these robotic systems serves as the keystone for the integrative nature of the SCU program. Overall, the mixing of engineers and scientists across a variety of educational levels and from a multitude of organizations creates a particularly stimulating environment for technical education, engineering innovation, and scientific discovery. Furthermore, the availability of multiple operational robots in several domains offers unprecedented opportunities for low-cost experimental research exploring issues in multirobot-system control and teleoperation.

2. EDUCATIONAL COMPONENTS

The development and operation of the RSL robotic systems provides a wide range of educational opportunities for students, ranging from freshmen to graduate students. At the undergraduate level, the most widespread and academically formalized use of these systems takes place as part of SCU's engineering senior design program. As part of this

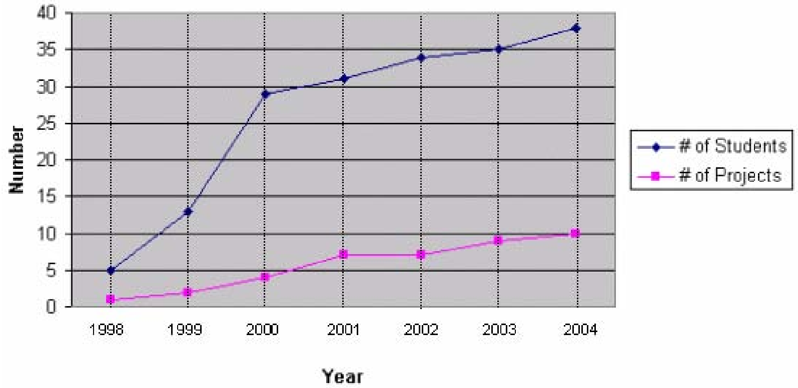

Fig. 2. Growth of the robotics education program.

program, all engineering students participate in a year-long sequence of courses through which they develop an engineering system in a way that draws upon and applies the knowledge and skills they have acquired during their undergraduate program.

The formation of RSL in 1999 introduced a natural opportunity for senior design projects to involve the development of robotic systems. Offering such projects as part of the senior design program prompted the formal establishment of interdisciplinary projects, allowing students from multiple departments to work on the same project as part of their independently-administered, department-level senior design courses. This was largely motivated by the widespread student interest in these projects across multiple departments (primarily mechanical, electrical, and computer engineering) and by the projects' need for a development team with a range of engineering skills. Figure 2 shows the increase in the number of robotics projects and students involved in them each year for the past five years.

2.1 Computer Science and Engineering Educational Objectives

Customer-driven system requirements naturally motivate the need for a wide range of functionality that draws upon the fundamentals from standard computer science and engineering curricula. Many of the robots use embedded microcontrollers for on-board subsystem processing and PC workstations for off-board user interfaces. Many of the robots have autonomous modes that execute real-time dynamic control loops, procedural command plans, state machines, reactive sensor-actuator behaviors, and/or deliberative knowledge-based estimators and controllers. Other systems are designed for real-time human piloting with advanced graphical user interfaces, haptic peripherals, or Internet-based remote control architectures.

Implementing this range of capabilities requires students to routinely draw upon their knowledge of core computer science/engineering competencies spanning hardware, software, and the mathematical foundations of computing. Specific topics include programming (in a variety of languages), software engineering, operating systems, computer architecture and networking, databases, algorithm theory, embedded systems, and so on.

2.2 Additional Educational Objectives

The nature of these robotic-development projects allows a number of additional educational objectives to be met, beyond those directly related to the application of computer science/engineering fundamentals, including a number of learning objectives specifically required for ABET certified programs. SCU formally incorporates many of these objectives into its senior design program. A few noteworthy examples are described here (as follows).

Ability to design system, components, or process to meet needs. Executing a formalized and controlled design process is essential to complete these projects successfully. Because the exposure level to design techniques varies dramatically across departments, most students attend a set of lectures and complete several exercises relevant to the design process. This includes topics such as the typical flow of a design process, the use of systems engineering techniques (specifying requirements, composing subsystems, generating alternatives, performing a trade-off analysis, etc.), and the value of concurrent design issues (design for manufacturability, testability, and operability). A new initiative along these lines involves the development of curricula that specifically address interdisciplinary overlaps and challenges in the system design process. New course content focuses on "butterfly effects" (how design choices in one discipline/subsystem affect the performance and choices in other disciplines/subsystems), how subsystem interfaces can be defined and simulated to permit parallel development, and so on.

Ability to function on multidisciplinary teams. Due to the need for a wide range of engineering experience in order to ensure success, the majority of robotic development teams include students from multiple departments. While the ability to function in such teams is vital to success in many engineering careers, these senior design projects are often the first chance students have to work on projects with such a high level of sophistication. To prepare students for this experience, lecture content includes a review of project management techniques and techniques for working effectively in a team. Several group exercises are used to reinforce many of these issues. Finally, weekly meetings with a project advisor ensure effective team interaction.

Ability to communicate effectively. In these projects, students gain considerable opportunities to develop both their verbal and written communication skills. Effective system development demands quality face-to-face interaction on a day-to-day basis as well as the formalization of specifications, designs, and interfaces in the form of written documentation. Major communication requirements include a Fall quarter written conceptual design report, a Winter quarter formal design review (with industry reviewers), and a Winter quarter review of written technical work (e.g., requirements specification, design report, test plans, and detailed design documentation such as flowcharts, dataflow diagrams, functional block diagrams, schematics, mechanical layouts, etc.). In the Spring quarter, each team submits a formal comprehensive project report (thesis) and presents its project at the formal half-day School of Engineering Senior Design Conference, which is judged by industry engineers from the entire Silicon Valley region.

Understanding of professional, ethical, and societal issues. The SCU core curriculum places a heavy emphasis on these areas; for example, every student is required to take a course in ethics as part of their undergraduate program. Within the School of Engineering, the School's Engineering Handbook [Healy 2003] summarized the conceptual foundations for a wide range of topics relating to these issues. Each student team is required to reflect on the impact of each of these topics as part of their end-of-year written thesis.

Ability to use techniques, skills, and modern engineering tools necessary for engineering practice. Because all of these projects result in the development of a complex functional device, students are required to apply a wide range of analysis, fabrication, test, and field operation techniques and tools during the development process. Relevant to computing-related skills, these often include the use of integrated development environments, a wide range of programming languages, UML program specification tools, realtime operating systems, a range of PC/Unix-based/microcontroller hardware platforms, and board design/layout/fabrication tools.

2.3 Project-Based Learning

In conducting these projects, Project-Based Learning (PBL) methodologies are applied in order to provide a rich, well-motivated, exciting, and rewarding learning environment [Kitts 2003]. PBL techniques promote learning through the creation of a functional artifact that embodies the knowledge learned [Leifer 1995]. Through experiential creation, students are able to reinforce their engineering knowledge, improve their competence in the application of this knowledge, develop problem formulation/solving capabilities, expand their implementation skills, and improve their self-directed learning talents [Bridges and Hallinger 1995]. For assessment, PBL approaches provide ample opportunity to observe project processes and evaluate the work products generated by the learning activities (and are a natural source of data for program review [Leifer 1995; Brereton 1995]). Such products include the quality and features of functional systems, design documentation that captures the state and rationale of the design, and the demonstrated application of engineering knowledge.

3. PROJECT CASE STUDIES

To illustrate how the development and operation of SCU's robotic systems offer compelling opportunities and enable superior learning outcomes, several projects are described here in more detail. These examples highlight samples of RSL's range of mobile and immobile robots that have significant on-board and off-board computing elements and operate across the domains of land, sea, air, and space.

3.1 Land: Omnidirectional Land Rovers

During the 2003-2004 academic year, an interdisciplinary team of four students developed, from scratch, two identical "omnidrive" robots capable of independent translation and rotation [Barycza 2004]. The intent is for these robots to ultimately serve as a Lab testbed for graduate-level research in multirobot collaboration and formation control. Using commercially available "omniwheels," shown in Figure 3, the team developed a chassis and a complete set of motion-control electronics that support open-loop externally-provided drive commands as well as both closed-loop velocity control and closed-loop position control. The vehicle configuration and its interior electronics are shown in Figures 4 and 5, respectively.

Fig. 3. Omniwheel

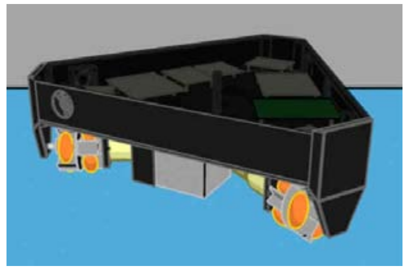

Fig. 4. Omnibot configuration.

Fig. 5. Omnibot electronics.

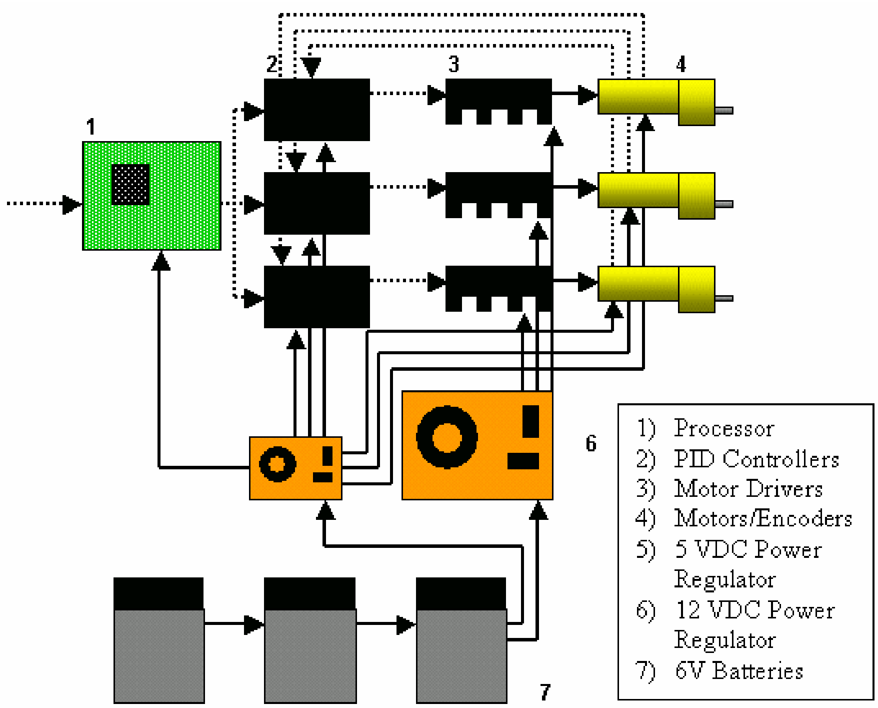

Fig. 6. Omnibot component architecture.

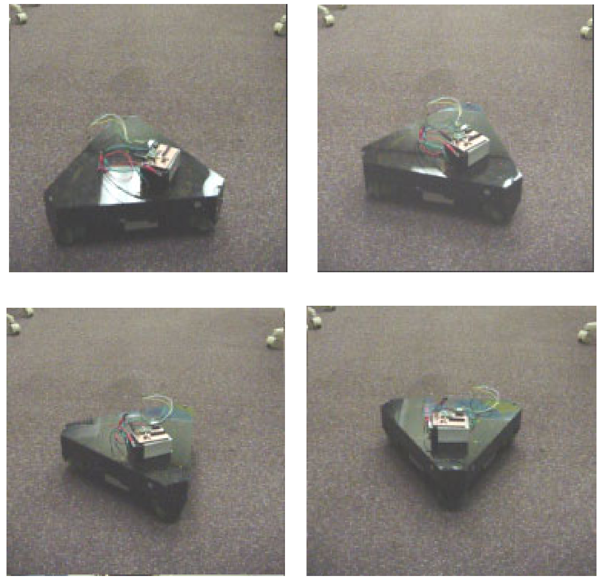

Fig. 7. Omnibot "frisbee" maneuver.

The computational control architecture for these robots is shown in Figure 6. Vehicle-level commands (e.g., translation and rotation) can be specified with respect to either the robot body or the fixed environment. An Atmel-based microcontroller is used to convert these commands to instantaneous wheel speeds through a combination of inverse kinematic and frame-transformation calculations. The instantaneous wheel-speed specifications are then provided to industrial-control components that implement a wheel-level proportional-derivative-integral (PID) control strategy. Figure 6 also shows the integration of other functional electronics such as the motor drivers and power subsystem components. In developing this system, the team had to address a number of design trade-offs, such as whether or not to implement wheel-level control in the microcontroller or with external PID controllers. In addition, the team had to implement a number of advanced computing features such as integrating several concurrent real-time feedback control loops, using integer math for advanced mathematical computations in order to dramatically improve performance, and incorporating a state-machine to administer the numerous control modes within the system.

Figure 7 shows the successful demonstration of a robot's ability to drive a straight line while independently spinning (e.g., the frisbee maneuver), which was set as the team's ultimate goal a the beginning of the project. The results were dramatic; the team was awarded the Best Interdisciplinary Project for the academic year at the School's annual Senior Design Conference, and achieved the highest set of ratings in school history, given by a panel of industry judges. In addition, the team won a design award in the national Lincoln Arc Welding Foundation competition. The success of this team has resulted in two immediate follow-on projects that will extend the capabilities of these robots and use them in several experimental graduate research studies.

3.2 Sea: Triton Underwater Robot Digital Control System

The Triton undersea robot, shown in Figure 8, was developed in 1999 by an interdisciplinary team of seven undergraduates. Developed for shallow water (less than

1000 feet) tethered operations, Triton is a 270-pound vehicle powered by two ½ hp horizontal thrusters (for horizontal plane motion) and two ¼ hp “vertrans” thrusters (for vertical and lateral motion). The vehicle includes a camera and lights to support both piloting and video-based science operations; in addition, the vehicle is able to support modular instrumentation for specific scientific objectives. An armored tether provides power to the robot and communication between the robot and a human pilot located on the deck of the boat. The pilot controls the robot through a “pilot box” consisting of joysticks and switches while watching the video and sensor telemetry feed from the vehicle [Weast 1999a].

Triton was used to support geologic studies of Lake Tahoe by the Scripps Institution of Oceanography and the U.S. Geologic Survey (as shown in Figure 9); ecological surveys of the Channel Islands region for the National Marine Sanctuary; and marine biology studies for the National Undersea Research Program. Triton has also been used as a technology testbed for undersea manipulators and stereo-vision applications [Yoshida 2000; Weast 1999b].

Several undergraduate-student projects on the implementation of computer engineering systems have involved extensions to the Triton system over the past five years. One such project is the development of a digital multi-microprocessor controller to interface to the pre-existing Triton analog piloting system [Francis 2002]. The need for this digital control layer was motivated by the desire to incorporate automated piloting functions and to implement an extended remote-control system for scientists on shore. Four microcontrollers were used to implement this design, with individual processors used to (a) collect pilot commands, (b) read/display sensor data and execute simple autopilot control laws, (c) drive hardware outputs to the analog control system, and (d) act as a communication hub between these processors. Figure 11 shows a block diagram of the digital-control layer; Figure 10 shows the vehicle response for the implemented automated depth-control system.

The performance of the digital-control layer is outstanding, and has been adopted as a standard element in the Triton deployment system. In addition to enabling previously nonexistent autopilot functions, this system allows simple customization of pilot-specific joystick mappings (e.g., dual vs. single joystick, vehicle or video referencing, proportional gains, etc.). In addition, it supports the interfacing of extended computer-based controllers that can bypass the simple functionality embedded in the digital layer. This extended capability has been used for a number of more advanced tests, all performed with the participation of undergraduates, to implement an Internet-based pilot interface and to characterize the impact of communication delay on piloting performance [Kitts 2003b; Bulich 2004].

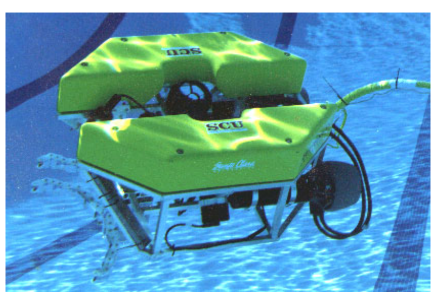

Fig. 8. The Triton robot.

Fig. 9. Deploying Triton in Lake Tahoe.

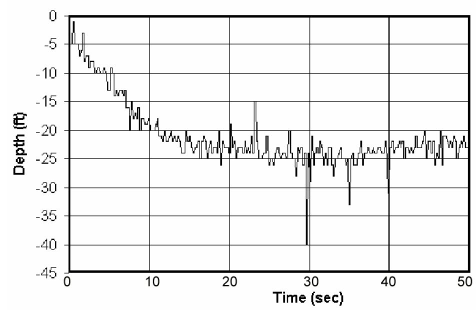

Fig. 10. Time response of Triton's automated dept controller.

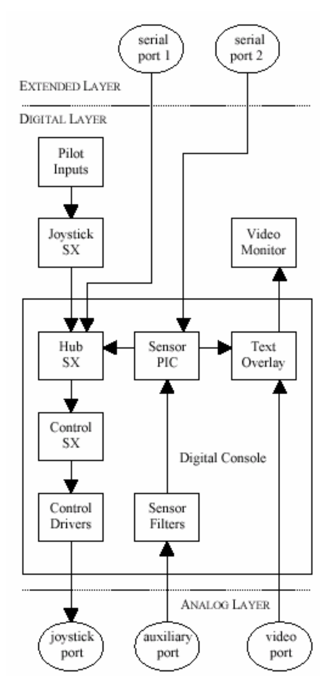

Fig. 11. Component block diagram of Triton's digital-control layer.

3.3 Air: Formation-Flying Aircraft

During the 2003-2004 academic year, a team of three computer engineers developed an outstanding project involving the development of several radio-controlled aircraft and the implementation of basic, automated follow-the-leader formation flying [Becker 2004a; 2004b]. Shown in Figure 12, these aircraft are hobby-class planes with 80-inch wingspans and 2-stroke engines. The team developed an embedded avionics suite consisting of a GPS receiver and other sensors, a microcontroller to collect and format this data, and a digital wireless communications link in order to broadcast flight data during operations. The team also implemented real-time video broadcasting through the incorporation of an on-board camera with servo-based tilt control and a separate long-range wireless video transmission system; Figure 13 shows a picture recorded on the ground during a flight.

As part of this team's participation in the annual unmanned aerial vehicle (UAV) competition, sponsored by the Association for Unmanned Vehicle Systems International, this team was given a Micropilot MP2028g autopilot system for one plane. This component was first used to successfully develop the required capabilities to become competitive in this event, including the ability to autonomously take-off and fly a predetermined waypoint-defined route in order to image an unknown ground target. This team ultimately achieved a third-place finish in this international event, competing against several teams with established graduate programs in UAV systems.

This team, however, was motivated to go well beyond this level of capability. Intrigued by RSL's research program in multirobot formations, the team exploited the capabilities of their autopilot in order to implement an automated follow-the-leader capability. With a human pilot flying a lead plane, position data from this plane would be sensed continuously and broadcast to the ground. A ground station application, developed by the students, filtered this data and generated the target waypoints for the chase plane. These waypoints were then transmitted to the chase plane's autopilot for execution. The chase plane's position was also sensed and broadcast to the ground for subsequent analysis and display. Figure 14 depicts the dataflow for this demonstration; Figure 15 shows a screen-shot of the graphical interface for the ground station program. Figure 16 shows flight data from an experiment and indicates the outstanding results achieved by this team.

Fig. 12. Two of the UAV aircraft.

Fig. 13. Real-time aerial video feed.

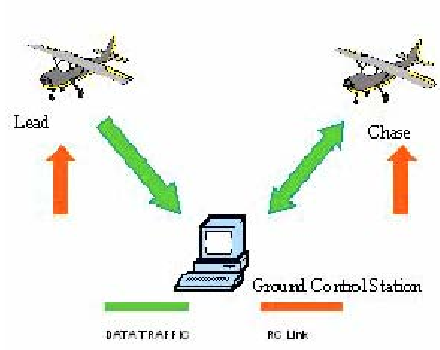

Fig. 14. Follow-the-leader data flow architecture.

Fig. 15. Ground station graphical user interface.

3.4 Space: Avionics and Mission-Control Systems for Spacecraft

RSL undergraduate students participated in the development of more than ten satellite development projects during the past five years. As part of this program, undergraduate computer engineering students made significant contributions to the development of the Lab's distributed spacecraft avionics system and its satellite mission control network.

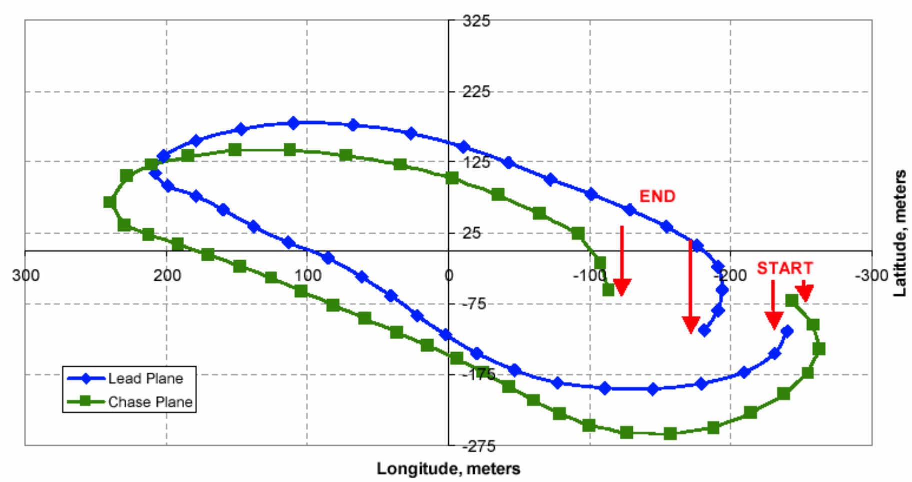

Fig. 16. Results from a follow-the-leader flight test.

The distributed avionics system project involves the development of a robust command and data-handling architecture suitable for modular system development and distributed operation within a satellite, between satellites, and between spacecraft and ground communication stations. Undergraduate contributions to this project include the use of one of the system's standard microcontroller motherboards, shown in Figure 17, in order to develop a telemetry-sensing system for the NASA/USAF-sponsored Emerald spacecraft, shown in Figure 18. This project encompasses the development of a file system, the implementation of an advanced production rule system for automated monitoring and control, and the implementation of extensions to the system's Dallas 1-wire micro LAN and Phillips Inter-IC (I^2C) bus communications interfaces [Watson 2003; Lee 2004]. In addition to supporting the Emerald project, this system was adopted by several other funded satellite-development programs at partner institutions such as U.T. Austin and Washington University in St. Louis.

SCU undergraduate students also designed and implemented an NSF-sponsored ground communications network suitable for controlling university-class spacecraft. The core of this network is a centralized mission control center, shown in Figure 19, which is used to remotely control and monitor satellites when they are in orbit. Software running in this center includes more than $1 million of professional satellite control and analysis software; in addition, a number of undergraduate-designed applications play a crucial role in controlling remote communication stations, processing satellite command and telemetry, and implementing advanced analysis algorithms. Students using this center log into remote ground communication stations in order to transmit and receive data to/from spacecraft.

Figure 20 shows the student-developed software architecture that allows remote communication stations to operate unattended. A ring-buffered network bus (RBNB) data server is used to stream independent data streams between specific applications. Applications at the station directly control the equipment in the communication station, while operator-side applications are used to (a) configure the station in preparation for contact with a satellite; and then (b) directly exchange commands and data with the satellite. Overall, this software architecture allows a student operator to log into a remote station, turn on equipment, set appropriate communication frequencies, point the antenna in the proper direction, and control other configuration parameters, as required. This system is currently used to support the on-orbit Sapphire microsatellite (built by Stanford and being used by the U.S. Naval Academy), as well as a to test a number of ground-based satellites in their integration and test phases. The network is also being prepared to control several spacecraft, currently planned for launch in 2005 and 2006, to include the NASA GeneSat biological test spacecraft, the University of Texas at Austin's two FASTRAC navigation test satellites, and the Washington University in St. Louis Akoya-Bandit vehicles.

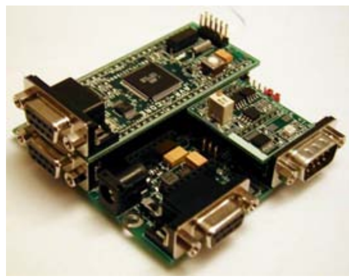

Fig. 17. Avionics motherboard.

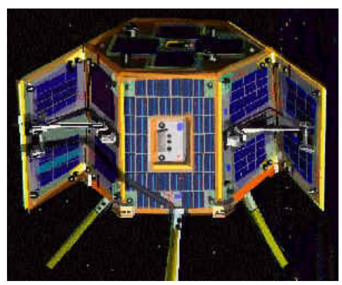

Fig. 18. Emerald satellite.

Fig. 19. Mission control center.

4. THE PATH TO SUCCESS

The projects highlighted in Section 3 are indicative of the level of success that is routinely achieved in SCU robotics projects. This section reviews several critical aspects of the projects that significantly influence project success.

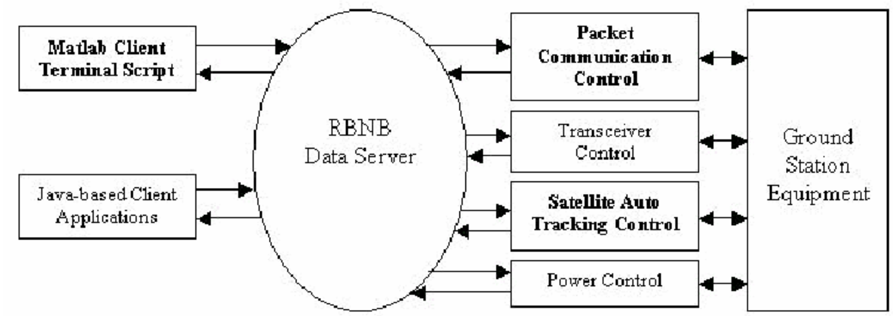

Fig. 20. Communication station data architecture.

A Compelling Application. Focusing projects on compelling applications serves several purposes, ranging from motivating students to ensuring the availability of resources necessary for project success.

For example, the authors believe that student motivation to achieve excellence is dramatically influenced by the significance of the contribution they feel they can make. With only a few exceptions, SCU's robotics projects generally support very specific field missions and/or the development of key systems crucial to long-term programmatic objectives in conducting operations or supporting experimental research. Beyond simply providing an opportunity to be involved in a hands-on interdisciplinary engineering project, emphasis on the future use of a compelling application provides students with a sense of value that fuels their passion for the work. In the most successful projects, this level of motivation elevates student commitment to the project beyond the level normally expected as part of an academic course. Indeed, students on these projects elect to use their project as a tangible and impressive demonstration of their skill and dedication as young engineers, with their work featured in interviews and design portfolios given to industry recruiters and graduate schools.

For educators, this means that effort must be expended to identify project opportunities with motivating themes and solid chances of continuity after any particular student group concludes its work. It also requires great care in putting the project in context for the students so that they understand the value of their work. At SCU, many of the projects contribute to a well-defined capability/technology roadmap for the field robotics program. This roadmap points to future capabilities that are easily understood and appreciated, and provides a very clear explanation of how any particular student project contributes to the overall effort.

Investment of Resources. Compelling applications, and the participation of end-users invested in these applications, also play an important role in ensuring the availability of resources to successfully support the project. These resources include the availability of student and faculty/staff time, funds for component acquisition and other expenses, accessibility to required equipment, and so on. Without question, SCU's Silicon Valley location and strong established ties with local industry provide a rich environment for establishing access to such resources.

A compelling application with interested users, almost by definition, dramatically improves the odds of motivating resources to aid project success. While a compelling application certainly opens the door to financial sponsorship, it may also generate more value via in-kind donations (e.g., the use of special analysis, fabrication or test equipment, the use of deployment platforms) and the interaction of knowledgeable mentors. In the SCU robotics program, significant portions of the aforementioned roadmap are externally funded, which, of course, makes the search for resources easy. However, it should be stressed that a significant fraction of the roadmap is not explicitly funded, and outstanding results can occur in new areas with little to no support. The authors have found no strong correlation between the level of project funding and team success, although nearly every robotics project requires at least several hundreds of dollars to implement (some have annual budgets of several tens of thousands of dollars). For example, the Triton control system project had no explicit funding when it was initiated, and the entire design was delivered for approximately $500 (given student emphasis on a low-cost design, on seeking educational donations/discounts, and on re-using spare material and components in the robotics laboratory). In general, educators must be careful to scope projects within the level of available resources.

A key issue related to project resources is the amount of time and attention the faculty advisor can give to the project. In many schools (including SCU), advising is often considered an additional duty for faculty members, a duty that ultimately takes time away from scholarly activities. For this reason, considerable effort has been invested at SCU in attempting to align design team activity with the need for research equipment. The success of this strategy allows faculty time spent on advising to also serve as an investment in the long-term development of the program's experimental infrastructure --a topic that, for a field robotics laboratory, requires significant attention. As project advisors, the authors typically spend one to two dedicated hours each week with each design team (in addition to time spent with all students in a weekly lecture format). About half of this time consists of weekly team meetings, with the balance spent on providing detailed engineering assistance, helping with project logistics, and so on.

The strategy of using undergraduate design teams to develop robotic systems, components, and instruments suitable for the research program has other benefits as well. In addition to justifying increased faculty attention to the student design teams, it provides a natural impetus for exposing undergraduates to a research environment and stimulating interaction between the undergraduate teams and graduate students who work on the same research issues. The graduate students often serve a dual-role as mentors to the team as well as tangible "voices of the customer," available to the team on a daily basis. At SCU, the graduate students are often previous SCU undergraduates who participated in the senior design program, thereby increasing the quality of the interaction between graduates and undergraduates. Over the past two years, the SCU program has reached a level where graduate and undergraduate student interaction of this type is common in about 30% of the robotics projects.

Design or Research. At times, the integration of SCU robotic design projects with the school's research program in field robotics blurs the line between design and research. However, while these undergraduate projects often produce functional systems and experimental testbeds crucial to the research program, the clear demarcation of requirements in these projects allow the development process to be managed as a design process.

For example, Section 3.4 highlights recent undergraduate work on the development of on-board avionics and ground-based operational control systems for SCU's spacecraft projects. This work represents a small fraction of the deliverables for significant spacecraft-related research projects sponsored by agencies ranging from NSF to NASA. Undergraduate teams working in these broader research areas are given a very well-defined project scope with specific functional and interface requirements for their system. This allows projects to follow a typical development process that includes functional decomposition, alternatives generation and trade-offs, detailed analysis, prototyping, and so on. So, for example, the authors consider the senior project work on the implementation of the satellite communications station's command and data-handling infrastructure an outstanding example of software design with several innovative and creative features. The relevant research issues in this system (exploring suitable architectures and appropriate performance requirements for the implemented architecture, using the architecture to conduct research investigations with spacecraft.) were addressed by graduate students in the broader research program.

Making this distinction, however, does not mean that undergraduate research is not an option. Each year a small group of students (approximately 2-5 each year) achieve a level and quality of performance that allows them to use their senior project as a venue to explore relevant research issues; such activity is often accounted for via additional course credit and/or internships, and is typically managed by defining a set of goals that are distinct from the design activity. For example, the student who worked on the Emerald distributed avionics system ultimately joined a graduate student and two technical staff members in making research-level contributions to the design of the production-rule system. This dimension of his work was accounted for through a separate internship with SCU's robotics laboratory. Other examples of student research include using the completed project system for field work (e.g., using the Triton undersea robot on a very successful marine archaeology expedition [Ota 1999]) and developing an additional vehicle subsystem for a specific technology investigation (e.g., underwater vision systems for both 3-D scene mapping [Weast 1999a] and autonomous docking [Zabel 2001]).

Managing the Teams. Projects must be managed actively in order to promote team success and the utility of the engineered systems for supporting follow-on research.

Project management begins with a clear statement of expectations in the form of a project milestone schedule, as shown in Table I. As can be seen, the Fall quarter emphasizes the conceptual design and systems engineering of the system, and includes a crucial proof-of-concept functional demo to highlight the feasibility of some key technical aspect of the project. The majority of detailed design, implementation, and integration occurs in the Winter quarter, with a key demonstration of basic end-to-end system functionality due at the end of this period. The Spring quarter emphasizes project completion and presentation in the form of a written thesis and several oral presentations. One of the most important events in the Spring quarter is a formal presentation to industry reviewers at the SCU School of Engineering's annual senior design conference. In addition to serving as a showcase of the team's accomplishments, this event plays a significant role in project assessment, as described in Section 5. Student workload varies over this timeline. Analysis of self-reported student "timesheets" shows that students typically invest 10-25 hours weekly during the period that spans (approx.) week 3 in the Winter quarter and the senior design conference; commitments of 5-10 hours per week are common during the rest of the year.

Another crucial aspect of these projects is specifying the scope of each project given the selected topic, the interests/capabilities of the students, the available financial/equipment resources, and the needs of the robotics program. This process is typically done in an interactive manner with the student team. It is common to specify two levels of functional goals, one "baseline" goal, upon which grading is based, and a "showcase" goal that represents a truly outstanding level of accomplishment. The majority of teams plan their projects with the hope of achieving the showcase goal, with the idea that they can ultimately de-scope their projects to the baseline goal if the

Table I. Summary of Major Milestones for Interdisciplinary Senior Design Projects

Fall Quarter		Winter Quarter		Spring Quarter	
Week	Item Due	Week	Item Due	Week	Item Due
3	Project Selection	3	Revised Conceptual Design Report	6	Senior Design Conference
5	Initial Project Description	6	Component-level functional demos	8	Thesis Draft
10	Conceptual Design Report	10	Basic end-to-end functional demo	10	Final Thesis
10	Design Review	10	Detailed design documentation	10	Final end-to-end demonstration
10	Proof-of-Concept Demo			10	Public Open House

showcase goal proves too demanding, given the resources required (a major influence is often the amount of personal time students wish to dedicate to the project during the last part of their senior year). For example, the formation-flying aircraft team originally set out with a baseline goal of building a competitive system for the AUVSI UAV competition; their showcase goal was to achieve follow-the-leader formation flying; as discussed in Section 3.3. The team met both goals. De-scoping from the showcase to thebaseline goal typically occurs around week 5 of the Winter quarter if it becomes apparent that detailed design and implementation work is not developed enough to support the showcase goals. On occasion, reducing the scope below the baseline is required when the performance of the design team becomes inadequate; this reduction is an attempt to get some fraction of the project fully functional, rather than the entire project remaining only partially functional (history has shown that these projects are usually scrapped and started anew the following year, if at all).

Throughout the year, teams meet with their advisors on a weekly basis for 30 to 45 minutes. During these meetings, action items are reviewed and set, managerial issues are discussed, and plans for detailed engineering work are made. The teams meet and work on their own in order to accomplish weekly tasks. Over the past 5 years, teams have varied in size from 2 to15 students. Large teams are always broken into groups of no more than 3 to 4 students, with the focus of each group generally aligned with the functional subsystems of the system being developed. For example, the Triton project had 7 students broken into 2 groups, one focusing on development of the structural elements of the system, and the other on the development of the functional avionics/electronics. Of course, the challenge is in conducting a controlled systems engineering process that defines and actively manages the subsystem interfaces such that the work can be conveniently divided, while ensuring that it can be efficiently integrated. Students are integrally involved in managing these processes. In order to support these efforts, projects often employ mass/power/volume budgets, simple interface control documents, and detailed component block diagrams.

Design Education. Without question, educating successful design engineers requires more than simply equipping students with the appropriate analytic capabilities.

Understanding the conceptual foundations of design and gaining experience in its practice are crucial elements of a complete engineering education. In the SCU program, seniors in most of the departments participate in a design class that teaches concepts such as the design process, systems engineering methodologies, concurrent design practices, project management techniques, and so on. In many cases, the specific topics are timed to support the scheduled project work, as outlined in Table I.

Improving the manner in which this is accomplished, however, is one of the crucial remaining challenges in the SCU robotics program. By its nature, these projects are highly interdisciplinary, with considerable demand for students from the computer engineering, mechanical engineering, and electrical engineering departments. The program is fortunate in that it is now routine for students from different departments to work together on a common project with a single advisor (it took four years to achieve this at SCU; in many schools, due to curricular or cultural barriers, this is simply not possible). However, many significant differences remain, ranging from the level of credit received by students in different departments to the amount of design education students have had prior to their senior year. Regarding the latter issue, SCU computer engineering students, as it turns out, have the least amount of design experience compared to students in other departments (SCU's mechanical engineering program has an extensive formalized design element in the junior and senior years; the electrical engineering department's design curriculum is moderate, but is being expanded due to feedback from the senior design program). Furthermore, the department's educational requirements for the senior year design program are the least rigorous. This, combined with other departmental differences, prompted a new initiative within SCU's School of Engineering to improve the consistency of the senior design program across departments, at least for students in interdisciplinary projects. For computer engineering students, this may lead to an expanded senior year academic experience that reinforces the essential elements of design education. Furthermore, the authors hope that this initiative leads to an expansion of interdisciplinary themes (such as the butterfly effect discussed in Section 2.2) for students in all departments prior to the senior year.

Pipelining underclassmen is one specific strategy employed in the robotics program in order to provide freshmen, sophomores, and juniors with formative hands-on design experience. Several one-unit introductory project-based courses exist (as electives that do not satisfy upper-division engineering course requirements) for freshmen and sophomores who show an interest in robotics. For example, a student may start out working alone in order to complete several tutorials on the use of a simple embedded controller. In the next quarter, the student could be teamed with others in order to design a simple mobile robot. Students who continue in this discipline often elect to expand their involvement during their junior year by taking an independent study course in which they create a more detailed design of a robotic subsystem, often as "junior interns" in an on-going senior design project. Each year 5 to 10 students are involved in experiences like this, which provide motivated students with additional design experience. These students often become the leaders of their respective senior design teams. Students in two of the four projects outlined in Section 3 (two of the four students on the omni-directional land rover team and all three students on the formation-flying aircraft team) had previous experience with robotics projects like those described above. It should be noted that while some of the students may work on projects that are similar to those they will ultimately work on as seniors, these preparatory underclassman experiences are distinct. In general, work performed by the senior design teams is done exclusively during the senior academic year.

5. EDUCATIONAL RESULTS

In assessing the benefit of robotics-based educational opportunities, the authors rely on a collection of formal programmatic assessments based on an evaluation of the work (as prescribed by PBL theory [Becker et al. 2004b; Bridges and Hallinger 1995]) and feedback from students, advisors, and external evaluators.

Design Review Evaluation. Two formal quantitative assessments are performed each year by a panel of industry engineers: the first is a conceptual design review held at the end of the Fall quarter; the second is during the School of Engineering's Senior Design Conference in the middle of the Spring quarter (see Table I). The panel of industry engineers scores the teams on a variety of categories that include the quality of technical work, the ability to perform a rigorous design process, the level of teamwork, and the ability to communicate effectively. The judges are local engineers from the Silicon Valley region; it is typical for the panel to include anywhere from 5 to 12 judges for each project group. This Senior Design Conference event includes the work of approximately 150 students (who are typically organized into about 50 teams) in the mechanical, electrical, computer, and civil engineering departments.

Table II. Summary of Project Evaluations for 2003-2004

Max Score = 50	**Summary of All Projects**		
	Mean	**Median**	**Std Dev**
All Projects (51)	39.5	39.2	4.3
- Robotics Projects (9)	43.6	43.6	4.5
- Non-robotics Projects (42)	38.7	39.1	3.8
	Summary of Interdisciplinary Projects		
	Mean	**Median**	**Std Dev**
All Interdisciplinary Projects (10)	42.1	43.0	5.1
- Robotic Interdisciplinary Projects (8)	43.6	43.6	4.5
- Non-robotic Interdisciplinary Projects (2)	36	36	0.6

The best of show award (for the top project in the entire school) was presented to a robotics project each year of its existence during the most recent five years. In addition, there is a clearly elevated level of performance for robotics-oriented projects. Table II shows a summary of the judges' evaluations for the 2003 to 2004 academic year. The top part of the table shows a significantly higher mean score for the robotics projects: out of a total of 50 points, robotics projects averaged a score of 43.6, compared to an average score of 38.7 for all other projects. A one-sided test using this data shows that the hypothesis that robotics projects performed better than other projects is supported with a confidence level of better than 99%. In an attempt to determine if this performance was due to the opportunities for learning motivated by robotics-oriented projects, or was simply due to the general interdisciplinary nature of the projects, the projects categorized as "interdisciplinary" during the 2003 to 2004 year are compared in the bottom portion of the table. Although the number of projects is quite small, a one-sided hypothesis test of this data shows that the hypothesis that robotics projects performed better than other interdisciplinary projects is supported with a confidence level greater than 80%.

These judges also rated team performance from the perspective of the School of Engineering's ABET-specific Program Outcomes, a crucial element in the school's accreditation program. In the SCU program, the senior project specifically addresses outcomes in multidisciplinary design, in the application of engineering knowledge to produce a functional system, in functioning well on teams, and in communicating effectively. Quantitative scores in these areas, as well as written qualitative feedback, indicates that students in robotics projects distinguished themselves through their demonstrated excellence in working in a multidisciplinary team and in applying engineering knowledge and skills to produce a functional system. Finally, SCU engineers as a group received "above average" ratings for their communication skills, their ability to work effectively on teams, and their appreciation for professional, ethical, and societal issues.

Student Feedback. Positive student feedback has also supported the claim that robotics-based projects provide positive learning experiences for undergraduate students. First, the level of student interest in these projects continues to grow, as indicated in Figure 2. Second, written student comments and the results of exit interviews clearly support the hypotheses that robotics projects (a) provide a highly motivational and hands-on learning environment; (b) improve student ability to work in teams and across disciplines; (c) require students to address the technical complexity of these systems through the use of methodical design processes; and (d) result in functional systems that provide direct benefits to external customers. Furthermore, results of formal externally-conducted exit questionnaires show that SCU students believe that they have higher than average abilities in working on interdisciplinary teams and in developing functional prototypes.

Advisor Feedback. Although the advisors of SCU's robotics projects (the authors) are potentially biased, their consensus is that robotics-oriented projects provide an outstanding platform from which to conduct engineering education. While other themes that provide similar benefits most certainly exist, the qualities of projects that involve the development and operation of a robot provide a wonderful blend of learning opportunities that are naturally motivated and that easily motivate student attention and participation. The computer-based control element of most modern robotic systems is relevant to computer science and engineering fundamentals, and provides a natural introduction to a myriad of computing-related topics.

It is also worth noting that the SCU program routinely manages to motivate teams to a level of performance that, at the undergraduate level, is truly astonishing. For example, the underwater robots produced as part of this program truly rival professionally-built robots in qualities and features. As another example, several robotics projects during 2003 to 2004 (such as the omni-directional land rover and the formation-flying aircraft projects) successfully designed and robustly implemented high-performance, closed-loop, hybrid control systems. Such accomplishments require a level of engineering maturity well beyond any standard expectation for undergraduates. Finally, the ability of students to both develop and then operate such a system in performing science and technology missions for world-class partners is, without question, one of the most satisfying educational experiences possible.

Other Indicators. A number of other benchmarks provide informal feedback on the quality of this program. For example, all SCU projects in which mechanical engineering students participate are entered each year in the national Lincoln Arc Welding Design

Competition. Over the past three years, nine of these projects have had a significant computer science or engineering component, and each one has won an award in this competition (three Silver, one Bronze, and five Merit Awards). In addition, the scope and quality of projects are often suitable for publication and presentation in industry conferences. During the past 6 years, more than 23 student papers have been published; 8 were refereed. Finally, student work has been featured in a wide variety of news reports and specials, with highlights that include two Discovery Channel specials, a National Geographic update, and a CNN.com feature article.

6. CONCLUSIONS

In summary, SCU has developed a highly successful robotics-based undergraduate education program that provides a wide range of learning experience relating to computer science and engineering fundamentals. In addition, these hands-on and highly interdisciplinary projects provide a comprehensive educational environment by exposing students to the breadth of engineering, all phases of a development cycle, and the challenges of managing a group enterprise. Assessment data shows that the performance of students in these projects is clearly superior to that of participants in nonrobotics projects. The authors of this article conclude that this is a result of the highly motivating nature of the projects, the comprehensive nature of the educational experiences, and the hands-on nature of the activities.

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