SPECTRE - An Extended Interdisciplinary Senior Design Problem

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Abstract

SPECTRE - the Student-run Program for Exoatmospheric Collecting Technologies and Rocket Experiment, is a sounding rocket experiment in NASA's Student Launch Program. Electrical and computer engineering seniors have worked on the flight hardware as a continuing capstone design project for five semesters, as part of an interdisciplinary student project team. Students have faced rich technical problems and unique project management challenges arising from the multi-team, multi-semester nature of this senior design effort. The need to interface regularly with other students, multiple faculty, staff engineers, and NASA review teams injected real-world pressures into the design course. This paper discusses the structure of the capstone course, the SPECTRE technical goals, and team experiences managing this complex evolutionary design problem. Substantial extended design can be successfully attempted within a capstone course if management continuity is maintained and if student teams develop effective communications and provide good engineering documentation for their successors.

Introduction

Senior Design in the Electrical & Computer Engineering (ECE) Department is a four credit required course that stresses open-ended problem solving, team dynamics, written and oral communication, and project planning and management. Annual enrollment is about 90 students, and the course is offered both semesters and during summer session. All projects are done by teams of two to four students, usually organized to have a mix of electrical and computer engineering majors. At the first meeting, teams generate preferences for their project from a list of candidate problems solicited from "customers" - local companies, government, public and non-profit groups, faculty and individuals. Final assignments are made by the professor to balance preferences, team and individual skills, and problem requirements.[1]

In one semester students are expected to develop a proposal, design a solution, fabricate a prototype, test their product, and document their efforts. This is an ambitious schedule considering that most projects arise from the real problems of real customers. Often teams have only partial success during their one semester effort, leading to some problems being attacked again by a new team in the next semester. These reworked projects are different from a few extended or "legacy" projects, e.g. the IEEE micromouse, that are deliberately maintained over several semesters. In legacy projects new teams are expected to improve incrementally on the prior design. Legacy teams are not allowed to scrap the previous work and start over, just as a business would not abandon previous development while seeking improvements.

The course operates as a virtual company, with team leaders reporting vertically to the professor. There is considerable and regular internal communication by members of the same team. Communication among different teams is minimal since projects are generally uncoupled, but some customers have defined problems requiring multiple teams, and here the students are expected to coordinate team efforts. This paper concerns a multiple team legacy project.

Figure 1 NASA's Nike-Orion.

NASA's Student Launch Program (SLP)[2] supports student space science experiments with flights on scientific balloons and suborbital sounding rockets (Fig. 1). SLP provides practical experience in every aspect of planning, building, and launching a space science experiment. Four SLP sounding rockets have been launched from Wallops Island, VA, since 1993, by several different university consortia, involving nearly two hundred students. Four more flights are upcoming, including Boston University's, now scheduled for a late spring 1999 launch. Each experiment has typically involved interdisciplinary student teams to provide project management, design and fabrication, testing, and flight support.

The SPECTRE project originated in a proposal to NASA prepared as an interdisciplinary student project in an undergraduate astronomy course. SPECTRE - the Student-run Program for Exoatmospheric Collecting Technologies and Rocket Experiment, has scientific, technical, educational, and public relations objectives. The scientific focus is on measuring the high-energy solar emissions of the electromagnetic spectrum and observing how different portions of the spectrum are absorbed by the earth's atmosphere. The technical objective is to use commercial off-the-shelf technology to develop compact, lightweight, solid state, and reliable instrumentation for multispectral imaging of the sun during the flight. Educationally, the project provides multi-tiered opportunities. Boston University undergraduates are managing the project and designing and fabricating the instrumentation payload; undergraduates from Wellesley College are calibrating the instruments and planning post-flight data analysis; and teachers from the local Chelsea schools are using the project in science curriculum development. Finally, the project provides public relations visibility for the College of Engineering, the Astronomy Department and the Center for Space Physics.

Multi-team design of the payload has presented special challenges and opportunities within Senior Design. Fabrication of the payload electronics and integration of commercial off-the-shelf instruments were started in summer 1997. Subsequent teams have continued to develop and test the major subsystems each semester. Fifty-three ECE students on fifteen teams have participated, and several alumni continue to be involved as volunteers. Boston University mechanical engineering students, computer science students from Wellesley, and student managers have also played a part in the design projects. Faculty and staff from engineering, astronomy, and computer science have participated as consultants, while engineers from NASA and the instrument vendors have been available for design reviews and technical advice.

This paper provides an overview of the SPECTRE payload and science in the next section, followed by a section discussing the organization of specific capstone design teams to develop the payload. The next section considers the special management problems and opportunities in such an extended multidisciplinary effort. Specific communications and record keeping activities that have proven important to making progress in SPECTRE are discussed. The paper concludes with recommendations for other large-scale extended senior capstone projects.

SPECTRE Overview

The major scientific payload comprises an Ocean Optics S2000 UV spectrometer, an Amptek MD501 channel electron multiplier, and an Amptek XR100T X-ray detector. Accelerometer and temperature data, system status data, and NASA flight data will also be collected. The payload will be launched from Wallops Island aboard a Nike-Orion sounding rocket to an apogee of approximately 135 km, with a flight time of about 400 s. Observations, when correlated with flight altitude data, will determine how the atmosphere from 60 km to 130 km scatters and absorbs shorter wavelengths of the solar electromagnetic spectrum.

The payload and its power supply must be entirely self-contained within a cylinder of diameter 14 in and length 26 in, directly behind the nose cone (Fig. 2). All instruments must be opened to space during UV data collection. Both the XR100T and the MD501 are behind a motor-driven Thermionics gate valve (Fig. 3) on the payload bulkhead, where the S2000 has an optical fiber feed. The gate valve opens after nose cone release, and later closes to keep the payload waterproof for recovery.

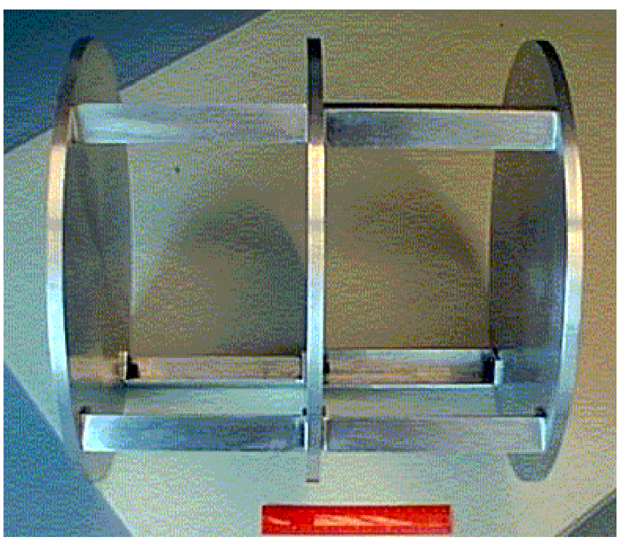

Figure 2 Payload bulkhead structure, on which electronics are mounted. Ruler is 15 cm.

Data is collected on board in flash memory and also transmitted over NASA telemetry during flight, in case recovery from the Atlantic Ocean is unsuccessful. Telemetry data is framed and Manchester encoded to be compatible with standard NASA receivers. Instrument signal conditioning and asynchronous data acquisition rates are managed by an interface scheme that buffers data during observation windows for scheduled polling. Power is supplied from NiCd batteries during flight and over an umbilical on the launch pad.

Comprehensive mission success is defined by correct gate valve operation, operation of the three instruments for at least 150s above 60 km, storage of data in flash memory and successful downlink transmission of the redundant data, and recovery of the payload.

Testing requirements are significant. Because flight conditions include greater than 20g acceleration, exposure to space vacuum and potentially wide temperature variations, NASA must test the assembled payload for shock, vibration and temperature extremes prior to launch. Provisions are also necessary for pre-flight benchtop testing and umbilical testing.

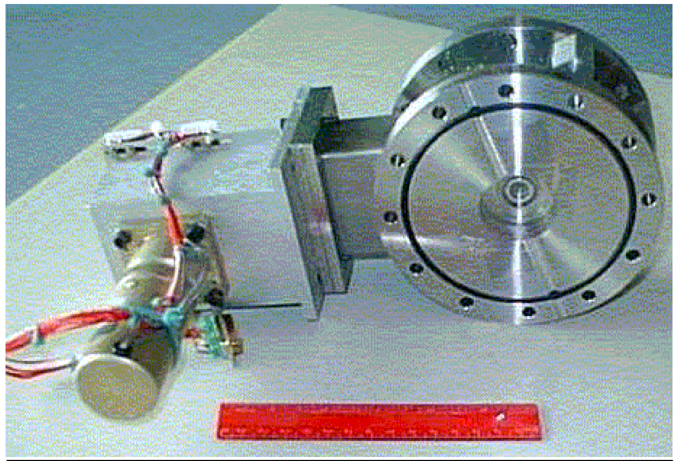

Figure 3 Gate valve and drive unit. Note the small aperture in middle, through which all sensing is done.

ECE Design Projects within SPECTRE

During the first summer, two ECE Senior Design teams started with the successful NASA project proposal and developed an overall system design concentrating on the flight controller and the instrument interfacing. These components evolved into four distinct subsystems with the addition of the on-board power supply and the redundant telemetry downlink. The mechanical designers developed a mounting scheme that calls for five stacked 8in x 8in boards dedicated to flight control, instrument interface (2), telemetry, and power, with flight cable harnesses for communication among the boards and instruments. Subsequent SPECTRE projects addressed detailed design, fabrication, and testing of individual boards, and, more recently, integration testing of the subsystems.

All hardware must be flight certified. Consequently, design teams have to plan beyond preparing wire-wrapped prototypes (frequently the end point for our one-semester projects) to developing reliable PCB layouts using CAD software and working with commercial board fabricators to manufacture and stuff the boards. IVEX WinDraft and WinBoard [3] were used for PC-based schematic capture and board layout and conversion to Gerber files. Boards were two-layer or four-layer, with as many as 750 pins. Figure 4 shows the board-level interfacing.

The flight controller board (Fig. 5), based on a Motorola MC68HC11E9 microcontroller, manages the on-board clock and initiates gate valve operation, instrument power-up and shut-down, data polling, and storage to 2 MB of flash memory. The flash chips reside on this board.

Scientific instrument interfacing occurs on the two interface boards. The first board samples and buffers the electron arrival counts from the MD501, thresholds the X-ray pulse outputs from the XR100 and stores the threshold counts. It also buffers the temperature and accelerometer signals. The second interface board, built around an FPGA, operates the S2000 spectrometer, controlling the integration clock and all triggering, and performing A/D conversion on the 2048 CCD outputs. It adds every four adjacent cells to reduce the data, and buffers the data until polled by the flight controller.

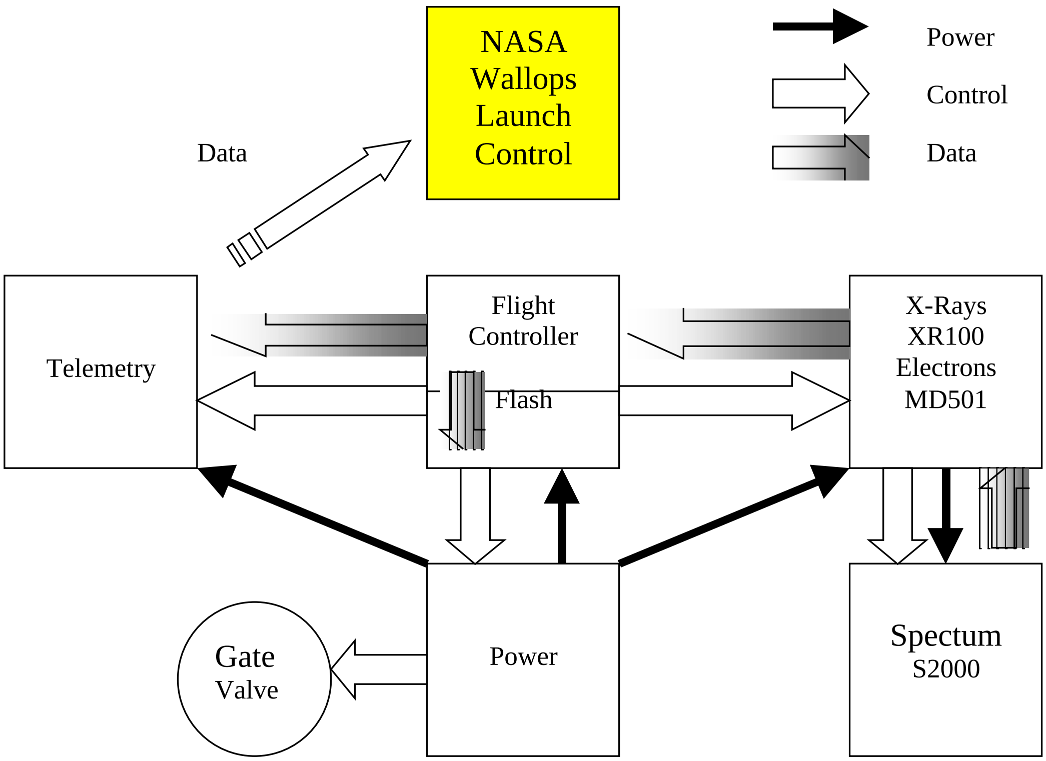

Figure 4 System boards, data and control flows.

The telemetry board provides the buffering and framing needed to operate over the NASA 200 kb/s S-band telemetry link. The transfer of data into flash memory is bursty, and has little framing information. The telemetry board uses its own MC68HC09 microcontroller to collect data from the flash lines, frame it and clock it to a Manchester encoder and then to the S-band transmitter.

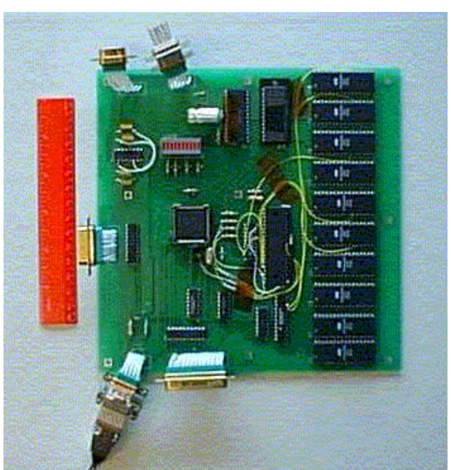

Figure 5 Microcontroller board and flash. Note modifications to the board.

All power is supplied from a 28V NiCd battery pack during flight. The power board (Fig. 6 and 7) handles battery charging and monitoring, umbilical switchover, gate valve control, circuit protection and voltage monitoring, DC-DC conversion to required output levels, and instrument relaying (on commands from the flight controller).

Each of the boards proved to be a challenging legacy senior design project in itself. Students were often dealing with (for them) new technologies (e.g. DC-DC converters, data encoder chips) and designing within stringent specifications on space, power, timing, data rates and reliability. Often requirements were influenced by other teams, by NASA engineers, or by students in the mechanical group.

Specifications changed often as other teams better understood their own boards' requirements and exploited system level tradeoffs.

Sampling rate design is the best example of an inter-team problem. The major instruments sample at different rates and generate different volumes of data. Data from the S2000 in particular overwhelms all other instruments if the sampling rate and cell binning are not

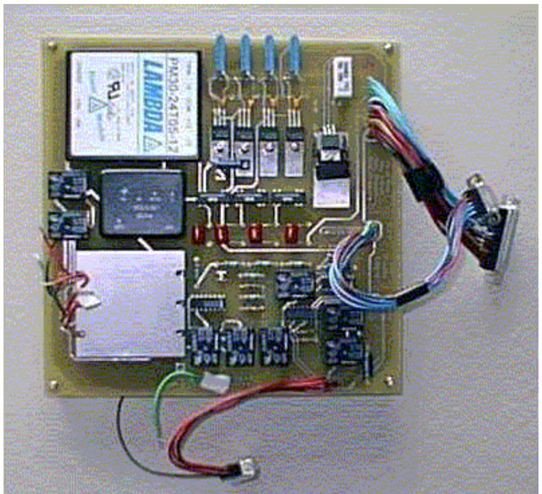

Figure 6 Version 1 PCB for power board.

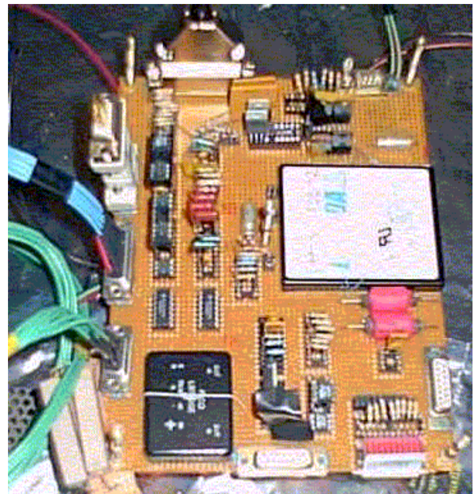

Figure 7 Prototype for Version 2 power board.

carefully controlled. NASA's 200 kb/s telemetry constraint sets one data rate ceiling, as does the flash memory capacity. Science discussions identified when the most useful observations could be made during the flight. Students resolved their polling scheme from this information.

Fabrication of flight quality boards presented another challenge for inter-team cooperation. Some teams began board layout earlier, and developed considerable expertise with the software tools, vendor contacts, and various design tricks. This knowledge needed to be shared with other teams using the same tools. Then the expertise needed to be migrated to new teams picking up a legacy design in the next semester.

Managing the SPECTRE Projects

An undergraduate project leader manages the project, working closely with the faculty and staff advisors. The student manager helps coordinate the multiple ECE design, fabrication, and testing efforts, provides liaison with the mechanical team building the payload hardware, and with instrument calibration and data analysis efforts at Wellesley College. He has no design role.

SPECTRE's scale and duration accentuate many aspects of teaming and project management that are less critical in smaller student design groups working for only one semester. Students are often not well prepared for such team skills by prior coursework.[4] SPECTRE's management problems resemble the challenges faced by any small business in effecting technology development across an organization. In the instructional context of Senior Design, these teaming and management problems can be both excellent learning opportunities, and possible obstacles to a successful project. Some of these problems appear in any legacy design project, but managing multiple interrelated legacy teams is especially challenging.

Interesting learning opportunities arise in this extended project because of SPECTRE's broader scope and the entry situations it creates for new participants. SPECTRE students practice incremental design in an existing complex system, rather than starting with a clean design slate. The day-to-day level of complexity is greater than most student projects can address. Testing also becomes more sophisticated and deals with more subtle measurements and interpretations than in shorter smaller efforts. Upon entering a legacy project the new team must master quickly their predecessors' technical plans and implementations before they can start their own work. This must be done critically, and may involve immediate testing, because the preceding designs cannot always be trusted. Fresh perspectives reveal new problems or new approaches that can be explored. Students are required to make important engineering judgments sooner in a legacy situation than in a completely novel design.

Recurring management questions included:

1. allocation of technical responsibility. Which team or individual should assume direct responsibility for completing a specific task on deadline?
2. scheduling of interdependent tasks. How do we identify tasks that impact multiple teams? Who enforces a schedule across multiple teams?
3. resolving conflicting specifications. How do we identify overlapping specifications? Who has final say in setting performance targets?
4. maintaining design records. How can we ensure that all modifications are recorded? In what form should records be maintained?
5. accelerating the learning curve. How can new teams be helped to learn about their specific technical problem and the details of any prior work.
6. supporting student morale. What can be done to avoid discouragement among students facing substantial design questions? How can we motivate students when a clear deliverable (e.g. launch) appears unlikely during their project?

The course emphasized shared decision making[5] by the team members themselves to resolve instances of the first four types of questions, which addressed technical issues that are part of the student design experience. The last two kinds of questions were considered more personal and pedagogical, and were addressed by faculty.

Communications and Documentation

SPECTRE participants need reliable information to support shared decision making. Effective communications and reliable, complete project documentation were keys to successful decision making and project management by the teams. It was repeatedly seen that the quality of documentation determined how fast students master the project learning curve, and that poor information and weak understanding lead to frustration, poor progress and low morale. Students working on SPECTRE are asked to provide a higher level of communication and documentation than our non-legacy Senior Design teams, to counteract these problems.

Senior Design teams prepare four formal major reports during the semester: a proposal, an interim progress report, a testing plan, and a user's manual. SPECTRE teams also must report on recent accomplishments and plans in an informal weekly memo to the project manager. E-mail is used extensively to discuss immediate problems and share decisions and data. The SPECTRE project[6] and some individual teams[7] set up web sites. Teams must organize all technical backup materials as an appendix to the user's manual. On an individual basis, students must maintain an engineer's log book of their work, which is reviewed during the semester and during weekly, in-lab team meetings with faculty. All logbooks are permanently kept in the Senior Design lab bookshelf, along with user manuals and appendices, as part of the final team record.

Oral communications are also emphasized. An oral interim progress report is required, during which students are videotaped. SPECTRE's oral presentations are given as a formal design review session before engineers from the faculty and staff from the Center for Space Physics. Each week each SPECTRE team must discuss team progress, individual problems and integration issues. The project manager chairs these meetings, which often include students from the mechanical team, from Wellesley, and staff from astronomy or space physics. At the end of the semester a formal seminar is held for all Senior Design teams, at which the SPECTRE team members make oral presentations on their team and individual design accomplishments. In spring 1998 team members and several alumni traveled to Wallops Island for a design review before the NASA flight operations team, in lieu of their on-campus final oral presentation.

Engineering records were maintained on a daily basis and then codified in the interim and final reports. As the boards evolved, the key elements of the design increasingly were embodied in the schematics, the board layouts, and the associated mechanical designs. Investment in software tools like WinDraft and WinBoard made it easier to create good documentation and share it among team members, faculty and staff. Students still must maintain log books and prepare written reports, but the legacy information is embodied in the design files. The physical evolution of the stuffed boards also became increasingly important as teams moved from rough subsystems to wire wrapped boards and eventually to full PCB implementations. Recent design efforts, for example, have involved adding signal conditioning and ground support interfaces to boards that were already functional.

Conclusions

Extended multi-team legacy projects like SPECTRE are more challenging for students, and provide a different kind of design experience compared to smaller, more controlled problems. Students can accomplish significant designs if provided with continuing project management and good communication of technical information. Record keeping is critical to successful legacy projects, both to accelerate the learning curve of teams at the start of each semester, and to maintain progress across multiple teams during the term. Student enthusiasm is high for real projects like SPECTRE, and the design experiences are valuable for novice engineers.

Substantial extended design can be successfully attempted within a capstone course if management continuity is maintained and if student teams develop effective communications and provide good engineering documentation for their successors.

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Biography

MICHAEL RUANE is Associate Professor of Electrical & Computer Engineering at Boston University. He received the B.E.E. from Villanova University in 1969, his S.M.E.E. from MIT in 1973, and the Ph.D. in Systems Engineering from MIT in 1980. He spent two years as a Peace Corps volunteer in Sierra Leone, was a staff member of the MIT Energy Laboratory from 1973 until 1977 and is a registered professional engineer (electrical). He joined Boston University in 1980 and is a member of the Boston University Photonics Center.