
AC 2011-47: USING SOFTWARE DEFINED RADIO FOR MULTIDISCIPLINARY SENIOR DESIGN PROJECTS

James Flynn, California State University, Northridge

James Flynn is a part time faculty member in the Department of Electrical and Computer Engineering at California State University, Northridge (CSUN). He holds a B.S. (1977) degree in Electrical Engineering from the Illinois Institute of Technology and a Master of Fine Arts (1981) degree from Northwestern University. He is a partner in a consulting firm specializing in electronics for television and film production. Currently he is developing education tools involving software defined radio (SDR).

Sharlene Katz, California State University, Northridge

Sharlene Katz is a Professor in the Department of Electrical and Computer Engineering at California State University, Northridge (CSUN) where she has been for over 25 years. She graduated from the University of California, Los Angeles with B.S. (1975), M.S. (1976), and Ph.D. (1986) degrees in Electrical Engineering. Recently, her areas of research interest have been in engineering education techniques, software defined radio, and neural networks. Dr. Katz is a licensed professional engineer in the state of California.

Using Software Defined Radio in Multidisciplinary Senior Design Projects

Abstract

In this past year's senior design program at California State University, Northridge (CSUN), faculty assigned two six-person teams with year-long design projects utilizing software defined radio (SDR). The course structure emulated a real world design project. Faculty acted as customers and management, presenting students with a list of requirements and constraints. Students were required to present weekly status updates on their designs, write specifications, documentation and test procedures. Students gained invaluable and in-demand expertise in this emerging technology, while fulfilling the criteria required by the Accreditation Board for Engineering and Technology (ABET). This paper focuses on the advantages to both faculty and students particular to using SDR in a senior design program.

Over the last four years the authors have been developing expertise and supervising student projects in SDR. While many schools offer study in SDR for graduate students, the authors felt that SDR was coming into such widespread use that undergraduates would benefit from exposure to the technology. In addition, upper division communications theory courses combined with the required foundations in programming made the transition to SDR a logical and inevitable step in undergraduate electrical engineering education.

I. Introduction

Most electrical engineering programs require a culminating senior design project to demonstrate a student's mastery of engineering concepts and electrical theory. Furthermore, these projects are essential in fulfilling the required engineering program accreditation criteria. Colleges and universities use a variety of approaches to assign projects to students. At CSUN, faculty often sponsor projects in their own field of expertise.

This past year's senior design program incorporated SDR into projects assigned to two teams. The first project was the design of a data link capable of transferring images and telemetry from an unmanned air vehicle (UAV) to a ground station with SDR being used both aboard the aircraft and on the ground. The link was to be semi-intelligent and adaptive to changing propagation and noise. The UAV and project funding were provided by Edwards Air Force Base. The second project was the design of an amateur radio high frequency transceiver. The transceiver was to include state of the art features found on high end non-SDR models.

In addition to their design work, students were required to report to faculty sponsors acting as the "customer", giving students additional exposure to real world engineering tasks such as writing specifications, documentation, written and oral presentations, team design and management. This experience parallels the Accreditation Board for Engineering and Technology (ABET) requirements that engineering programs demonstrate that their students attain outcomes, including: designing a system or process within realistic constraints, functioning on

multidisciplinary teams, communicating effectively, and identifying, formulating and solving engineering problems¹.

Multidisciplinary projects are often difficult to develop. SDR has proven to be an excellent basis for projects because of the wide spectrum of areas it encompasses. SDR provided the students the flexibility to rapidly explore different designs and features while challenging their mastery of concepts in communications, electronics and programming.

II. Senior Design at California State University, Northridge

At CSUN, the senior design project is implemented as a one year course in which students are assigned to work on a group project with three to five other students. This group project is to be completed in two semesters. Additionally, each student enrolled in senior design is assigned an individual project. This paper focuses on the group project.

Engineering programs are designed to demonstrate the outcomes required by ABET, the accrediting agency for engineering and other technology programs in the U.S. While many of the required outcomes are demonstrated in the course of standard engineering coursework, the following outcomes are best demonstrated in the context of a culminating experience such as the senior design project:

- an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- an ability to function on multidisciplinary teams
- an understanding of professional and ethical responsibility
- an ability to communicate effectively

III. Advantages of SDR in Education

Many of the aspects that make SDR attractive to the military and industry also make it ideal as a learning and teaching tool. Recently, the authors experimented with using SDR in classroom demonstrations for an upper division communications course. It is widely known that communications theory can be especially abstract and math intensive^{2,3}. The authors felt that students would be motivated and their learning would be enhanced by relating abstract communications concepts to tangible examples students were already familiar with. Using SDR, the authors developed a series of demonstrations centering on the basic principles of the time domain – frequency domain relationship, filtering, AM and SSB modulation and demodulation, and FM modulation and demodulation⁴. The use of real world signals, such as AM/FM broadcast and SSB communications, made these demonstrations particularly effective in motivating students to continue study in communications.

One advantage of using SDR in this way stood out almost immediately: SDR allows the rapid implementation of even complex receiver or transmitter systems. Using such readily available tools as GNU Radio and GNU Radio Companion (GRC), and MATLAB's Simulink⁵, a complete SSB receiver can be programmed in less than an hour⁶. Similarly, AM and FM receivers and transmitters for all modes can be created in a single sitting. Modification and improvement are equally easy.

The fundamental blocksets in both GRC and Simulink allow the direct implementation of the complex formulas found in signal processing and communications theory. This provides an essential and direct tie between the lecture and practical application. Students can explore how these formulas work and experience their function in a tangible way.

The SDR development platform that was used for these projects was very affordable. It consisted of the Ettus Universal Software Peripheral (USRP)⁷ connected to a PC. The USRP provides up/down conversion, and A/D and D/A converters. The signal processing is performed on a PC using the software described above.

Perhaps as obvious as it is important is the fact that using SDR in senior design, either as a centerpiece of the project or simply as an implementation tool, exposes the students to an emerging technology that will have an increasing role in communications and signal processing.

Finally, using SDR brings together students from various disciplines within electrical engineering, including electronics, radio frequency design, communications theory, signal processing, computer engineering, and programming. Students within the groups were assigned tasks within their sub-disciplines. This provided students an opportunity to work in a multidisciplinary team within the disciplines of electrical engineering.

Previous senior design projects have had difficulty moving from concept to design to implementation in the two semester time limit. Senior students, already strapped for time with course work, find it difficult to even prototype a complex system, much less go through design iterations and improvements. SDR speeds this process by an order of magnitude. This will be discussed later in this paper.

IV. UAV Senior Design Project

A team of six students was given the task of designing and implementing a telemetry link for a small unmanned air vehicle (UAV) that was provided by Edwards Air Force Base, who funded the project. The constraints on the implementation were that the link had to be in the 70 cm UHF Amateur Radio Band, comply with FCC regulations for a data link in that band, be under three pounds in weight, fit inside the UAV (which has a wingspan over slightly more than 9 feet), and use SDR with the Ettus USRP⁷. A PC-104 provided the small form factor and light weight needed for this project. The system was required to downlink, on command, image data from an on board camera, GPS data, battery voltage, vehicle temperature and a snap shot of the received radio spectrum as seen from the vehicle.

This last feature was included to deal with potential interference problems and lay the groundwork for future work in cognitive radio. A further foundation for this work was the requirement that the system be agile in frequency, mode and data rate. Additionally, the link health would be measured and the results presented to the ground controller. For this year, decisions on the link parameters would be made by the ground controller and the vehicle would change them only on command. However, the vehicle would automatically return to a default “phone home” frequency and mode in the event of loss of link.

The overall system would be controlled from a GUI at the ground station, which would display all data and images, while allowing the input and queuing of commands to the vehicle. A screenshot of the ground control screen is in figure 1.

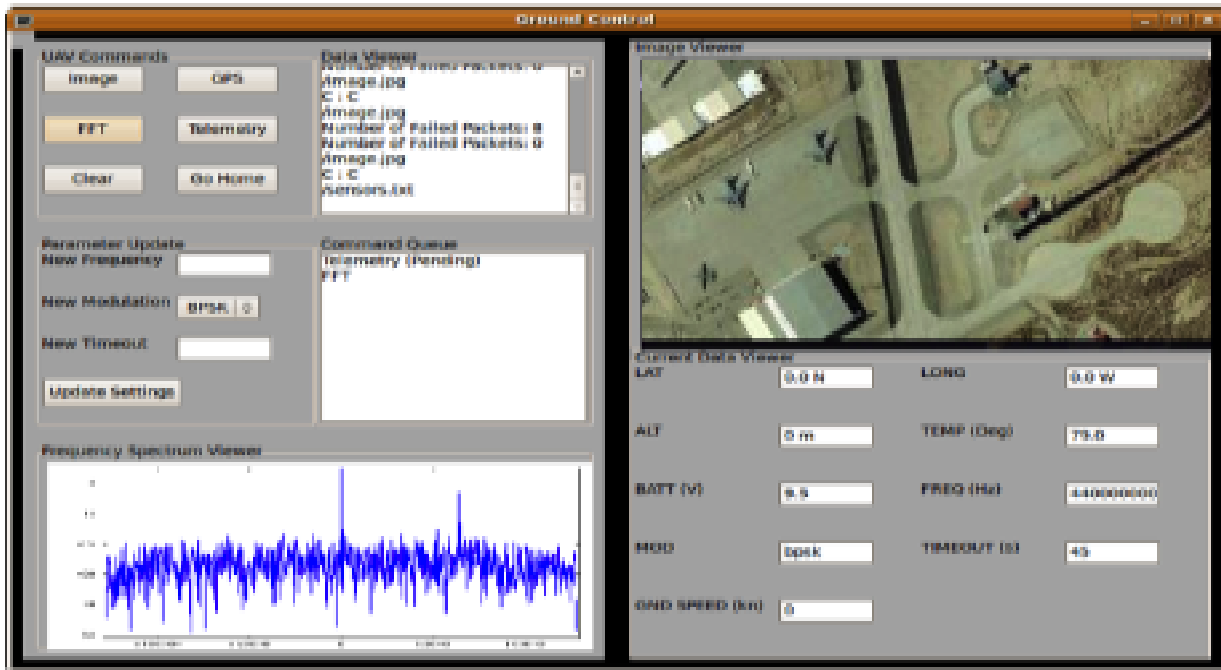


Figure 1. UAV Ground Control GUI

The students began their work with GNU Radio and GRC as a basis for their initial experiments with the data link. While the GNU Radio software worked well initially, the UAV team rapidly found it to be limiting and created their own blocks. They used the GNU Radio blocks as a starting point and integrated them into a master controller process both for the UAV and the ground station. In addition, the students developed their own packet protocol for the bi-directional data link, a process that was greatly facilitated by using SDR.

The engineering performance is impressive. The UAV Team has perfected a communications link using the USRP and their own software based on the GNU Radio code. They have demonstrated reliable data communications with images and test data being sent a distance of one half mile using the 20 milliwatt output of the USRP to a quarter wave antenna. The mode is BPSK at a data rate of 90 Kbits per second. The vehicle system has successfully downloaded images on command from the ground station. The UAV Team has developed their ground station GUI and successfully overcame interface difficulties and integrated all the command and receive tasks. Since the actual flight vehicle (not part of the project) was not ready, the UAV Team did not physically install the UAV side of the communications link or flight test it.

V. Amateur Radio Design Project

The second group of six students was given the task of designing an all mode, high frequency amateur radio transceiver. The requirements were that the transceiver operate on the amateur

bands from 1.8 to 30 MHz in the CW (Morse Code), SSB, AM, FM and two digital modes. The transceiver would use SDR and the Ettus USRP, but interface with a receive pre-amp and a 100 watt transmitting amplifier provided by the senior design faculty. The project was constrained mainly by the Part 97 FCC rules for bandwidth, spectral purity and mode parameters.

One of the chief requirements for this project was that the end product be a radio that would be familiar to most radio amateurs and easy to use by someone with limited technical experience. The transceiver would incorporate displays and controls found on most high end hardware transceivers, such as signal strength meter, large frequency display, spectral display of the band in use, variable bandwidth filters, squelch and half-duplex operation. The group was challenged to make the operation of the radio as intuitive as possible.

As with the UAV group, the Amateur Radio group used GNU Radio and GRC as the basis for their work in developing modulators and demodulators for various modes. While the existing software provides a modulator and demodulator for FM, the group was required to develop their own FM system. They tried various methods for modulation, including indirect FM (Armstrong's method). These did not provide satisfactory results. They settled on a CORDIC modulator which was simple to implement. For detection, they developed an instantaneous frequency detector, directly applying equations and theory from their analog communications coursework. Both schemes are similar to the existing blocks in GNU Radio. For SSB and CW, they designed a system using Weaver's method for reception. For transmission, the USRP's frequency shifting function makes the operation trivial. AM was a direct implementation of the AM equation for transmit and a magnitude detector for receive.

Again, like the UAV group, the Amateur Radio team faced a number of problems with integration, including managing processor load and the more mundane issue of interfacing with the receive and transmit amplifiers. A screen shot of their GUI is in figure 2.

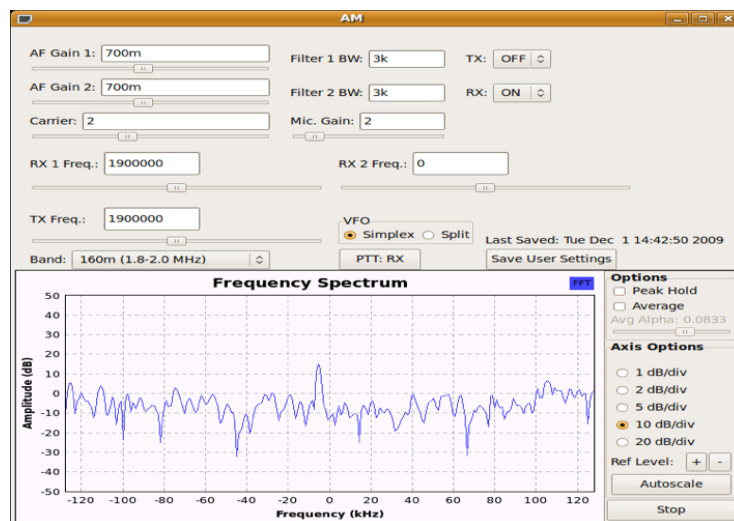


Figure 2. HF Transceiver GUI

The Amateur Radio Team has successfully demonstrated transmit and receive capabilities on AM, FM, CW, and SSB. Contacts were made and recorded with stations as far away as Fairbanks, Alaska and Mexico City. The finished transceiver met or exceeded specifications commensurate with high-end hardware transceivers in the \$2,000 to \$3,000 class. Because of the constraints of time and resources, the team made the decision to abandon work on the digital modes. The team made a compelling argument that continued work on these modes would jeopardize the success of the entire project and they were allowed to drop the capability from the design. The Amateur Radio Team conquered the daunting task of improving the throughput efficiency of their software to minimize the processor load on integration.

VI. Incorporating Real World Skills

One of the key goals of Senior Design at CSUN is to begin the transition from students as learners to productive engineers. Real world skills are often forsaken due to time constraints in courses concentrating on theory. Crucial among these skills is design experience. This creative aspect of engineering is personal and experiential; something a student must practice to learn. SDR offers an essential vehicle for design practice. With SDR, senior design students can rapidly create and test various approaches to solving the problem and receive feedback from faculty and peers. Allowing them to focus on the design process enables students to develop and refine their creative skills within the time constraints of the senior design course.

In addition to design skills, Senior Design requires students to develop oral and written communication skills. Students must present oral weekly status reports and document their work. Both teams presented their status reports at the same session and this had the benefit of the teams sharing information and discoveries. This occurred often enough that it greatly accelerated development on both projects, with teams avoiding mistakes already made and dead ends already explored.

Finally, it should not be overlooked that SDR itself is a real world skill. The students put directly into practice theories encountered in class. They also developed a vital, new mind set for communications, not based on compromise and bound in hardware, but adaptive to conditions at the time a message is sent or the immediate user requirements.

This brings up a problem often encountered by faculty: dealing with students who are still learning the very principles that they need to apply to the project. This situation presents opportunities and challenges for students and faculty. Faculty must provide the students with the necessary knowledge to move forward, carrying the students over the hurdle at first. However, as the students complete their classroom studies, they benefit immediately from being able to apply and solidify their newfound understanding of the theories involved. SDR allows them to quickly backtrack and implement their own design based on the concepts fresh from the classroom. Students are presented with a problem, for which their class work provides the key. They can experience that moment of revelation when concepts fall into place and make sense because there is an immediate need for them.

VII. Project Results and Assessment

The students began work on the projects at the beginning of the Spring 2009 semester. At the end of the semester, both teams made an interim presentation of their work in progress to faculty and representatives from industry. Over the Summer 2009, both groups finalized their designs and began the process of integration, which proved to be a surprise for both groups. Both the UAV Team and the Amateur Radio Team had divided up the design workload among the team members. Both groups received a valid and painful lesson in what often frustrates an engineering project: getting everything to work together. Neither group had budgeted time for this phase of the project, despite the gentle urgings of faculty. Both groups had to rapidly reassign resources to overcome the problem.

In the Fall 2009 Semester, both groups froze their designs, albeit reluctantly, and began the test phase. Both projects found deficiencies in their systems and modifications were made. This exposed the students to a second lesson in the problem of system integration: incorporating modifications and the attendant ripple effects of changes. The students wrestled with these realistic problems right up to their final presentations to faculty and industry at Edwards Air Force Base and at the CSUN campus at the end of the Fall 2009 semester.

In addition to providing final documentation, both teams presented papers at the ASEE Zone IV Conference in March 2010 in Reno, Nevada.

The objective of this project was to increase the benefits that ECE seniors derive from the one-year senior design experience. Table 1 below describes the desired outcomes for this course along with the informal assessment of the project. ECE faculty continue to work to formalize the assessment of senior design.

Table 1a. Project Assessment Table

Desired Outcomes	Assessment Method	Preliminary Observations
Improve the written communications skills of ECE graduates	Compare papers submitted to campus IEEE paper contest	The quality of the papers submitted by our student participants considerably exceeded that of other papers.
Improve the completion rate of senior design projects	Use grade rosters to compare the completion rate of senior design projects by students within and outside of our projects	Over the past two years, only 20% - 60% of ECE students actually complete their group projects by the end of the academic year. Our groups completed their projects before the end of the academic year.

Table 1b. Project Assessment Table (continued)

Desired Outcomes	Assessment Method	Preliminary Observations
<p>Improve the oral communications skills of ECE graduates</p>	<p>Comparison of video tapes of past senior design final presentations to the final presentations of current students</p>	<p>Faculty evaluators observed a notable improvement in the presentation skills of participating students over those of past students and current students on other projects</p>
	<p>Compare CSUN faculty assessment of student IEEE paper presentations</p>	
	<p>Students presented their work at the ASEE 2010 Zone IV Conference to an audience of faculty from many schools. Informal comments were collected at the end of the event</p>	<p>Comments received informally were favorable. Faculty were impressed at the high level that our undergraduate students had reached.</p>
	<p>Students present a final design review and project demonstration to a group of 20 industry members. Informal comments were collected at the end of the event.</p>	<p>Industry members commented that the quality of the presentation was superior to that normally observed in undergraduate students or first year engineers.</p>
<p>Raise the quality of senior design projects including the ability to include concurrent coursework</p>	<p>Students present a final design review and project demonstration to a group of 20 industry members. Informal comments were collected at the end of the event.</p>	<p>Industry members commented that the level of presentation was much higher than normally observed in undergraduate students</p>
	<p>Evaluations by CSUN faculty based on their informal observations of senior design projects over the past few years</p>	<p>Faculty found that the SDR projects stood out among other projects because students were able to complete a complex design project in the allotted time.</p>
	<p>Students presented their work at the ASEE 2010 Zone IV Conference to an audience of faculty from many schools. Informal comments were collected.</p>	<p>Many faculty attending were impressed at the technical level and proficiency of the student work. They were surprised that these were not graduate students.</p>

Table 1c. Project Assessment Table (continued)

Desired Outcomes	Assessment Method	Preliminary Observations
Improve the ability of ECE students to work on multidisciplinary teams	Create a rubric to evaluate student team work	This is a work in progress. A rubric is being created and will be tested on this semester's students.
	Evaluations by CSUN faculty based on their informal observations of senior design projects over the past few years	Many groups in the past have had difficulty working together leading to members dropping out of the group. Both of our groups completed their project, dividing the work between the members together.
Expand funding sources for senior design	Compare funding sources for student projects over past 3 years	Prior to this effort either the department or students paid for the parts required in the projects. Over the past 3 years our efforts have led to funding from both the Air Force and the Navy for senior design projects.

VIII. Conclusions and Plans for Future Work

Based on the results presented here, the authors conclude that the use of SDR in senior design provides many benefits. It provides a platform that allows students to complete complex and interesting communications projects within the constraints of a two-semester senior design project. The projects provide a vehicle in which students can demonstrate important ABET outcomes, including:

- an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
- an ability to function on multidisciplinary teams
- an understanding of professional and ethical responsibility
- an ability to communicate effectively

The use of SDR in Senior Design at CSUN is part of an overall effort to introduce SDR into the graduate and undergraduate courses of study. The authors intend to expand the use of SDR as a teaching tool and a subject of study. This work is primarily focused on increasing the exposure of SDR to undergraduates.

Immediate plans for the study of SDR itself are centered on the Senior Design Program. Many of the requirements for the UAV telemetry link were created with an eye toward building on

these features with future teams. Most of the operation of the ground control and vehicle SDRs are currently directly controlled by the ground controller. However, these same features, such as frequency and mode agility, can be implemented automatically, moving the project toward cognitive radio.

The projects outlined here in detail currently use a PC or an embedded PC to perform most of the signal processing functions. The authors intend to continue using PC based SDR as a development and research tool. Currently, graduate students are simulating complex spread spectrum communications systems in an effort to study interference models for this mode. However, the authors also have the goal to complete the design cycle with a realistic, usable system or device that could actually be manufactured in quantity. Undergraduate and graduate students are also working to carry SDR designs into a more practical implementation using field programmable gate arrays (FPGAs). This phase would expose students to all aspects of design engineering and greatly expand the possible applications that could be tackled in Senior Design.

The authors plan to expand on their success in achieving the goals of giving students communications and multidisciplinary design skills; outcomes demanded by accreditation and prized by industry. The authors will widen their partnership with local companies and provide employers with engineering graduates experienced in the emerging technology of SDR.

Bibliography

- [1] Accreditation Board for Engineering and Technology (ABET), <http://www.abet.org>.
- [2] Goodman, Peter, "A Software-Defined Radio Project for First Year ECET Students," Proceedings of the 2007 ASEE Annual Conference.
- [3] Goodman, Peter, "Geek Civilization: Amateur Radio and First Year Projects to Improve Recruitment and Retention in an ECET Program," Proceedings of the 2006 ASEE Annual Conference.
- [4] Katz, Sharlene; Flynn, James, "Using Software Defined Radio (SDR) to Demonstrate Concepts in Communications and Signal Processing Courses," Proceedings of the 2009 ASEE Annual Conference.
- [5] Mathworks, <http://www.mathworks.com/help/toolbox/commblocks/ref/a1083164701.html#fp263715>
- [6] GNU Radio, <http://gnuradio.org/trac>.
- [7] Ettus Research LLC, <http://www.ettus.com>.