Vertically Integrated Research Experiences

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Abstract – The Center for Subsurface Sensing & Imaging Systems (CenSSIS) is using a curricular thread that is vertically integrated across the undergraduate curriculum to provide multiple entryways into research. Undergraduates mature in their research thinking at different rates, and need appropriate opportunities to become involved. A vertically integrated structure allows motivated individuals to advance through increasingly challenging research experiences. Key elements include CenSSIS Scholar awards to interest and enable freshmen, a freshman introductory course in the CenSSIS High Tech Tools & Toys Lab, undergraduate research assistant support, Research Experiences for Undergraduates summer awards, Undergraduate Research Opportunity Program awards, an applications-focused senior CenSSIS elective and team-based capstone project opportunities addressing CenSSIS applications. This paper reports the evolution and impacts of this integrated effort, gives case studies of several individual students, and explains how these programs are achieving sustainability.

Index Terms – Engineering Research Centers, undergraduate research, subsurface imaging, sensing.

INTRODUCTION

An undergraduate research experience is generally a positive learning experience, offering many benefits to engineering students. A research experience can develop new technical skills, reinforce the application of classroom principles, teach professional work habits, improve professional communications, and clarify career plans. Undergraduates can learn the excitement and importance of research, and build their professional portfolio for their eventual job search or graduate school applications.

The benefits accrued in an undergraduate research experience depend on matching well the student’s preparation, their commitment, the definition of an appropriate research problem, and the support given the student while they are working. A weakly designed research match can discourage a student, and make them reluctant to continue with research or even with engineering. A successful research assignment often leaves the student wanting to continue their research on more challenging problems. Having learned their field better, some will want to try another area of research.

With so many interacting elements, it is challenging to structure a broadly accessible program to encourage undergraduate research. First the program must create student awareness of and interest in research. Most engineering undergraduates, pursuing a busy and demanding program, have limited time for additional responsibilities in the academic year. Even in summers, few seek research as a critical part of their undergraduate engineering experience. Others, while acknowledging the broad importance of research, are not confident that they can compete with their limited skills and experience. As an extra-curricular activity, research competes with student employment, campus organizations, social activities, study abroad, and internships.

Undergraduate research programs next must match the interested students with research opportunities in faculty labs, centers, and possibly with external collaborators. Finding willing faculty mentors can be difficult. Faculty researchers often prefer to mentor the most advanced and experienced students, since they are most likely to produce useful results, support graduate student efforts and possibly generate publications. This pragmatic mentor bias toward immediate productivity can lead to undergraduate research programs that mostly support seniors or rising juniors. Such programs see undergraduate researchers as junior members of an otherwise graduate research team. Research is not primarily viewed as an educational experience for the student’s benefit. Such programs can be excellent for seniors, especially those already committed to graduate study. They tend to under serve more novice students, and miss the opportunity to shape the thinking and interests of those students early in their education. Senior-focused programs also have limited opportunities for a student to progress to more challenging research assignments. Participants are often just starting their research as decisions on work and graduate school must be made.

Finally undergraduate researchers must be supported as they learn the skills needed for research. This primarily occurs in the research setting, as the faculty supervisor (or an interested graduate student) provides specific training. When natural groups of undergraduate research students can be identified, shared skill development through seminars or training is effective. Direct financial support for research supplies, travel, and publication also makes undergraduate research more productive, and can be an incentive for faculty participation.

CenSSIS UNDERGRADUATE RESEARCH

This paper reports on undergraduate research programs at Boston University, one partner in The Center for Subsurface Sensing and Imaging Systems (CenSSIS), an NSF
Engineering Research Center. CenSSIS comprises four academic partners: Northeastern University, Rensselaer Polytechnic Institute, University of Puerto Rico Mayaguez, and Boston University, affiliates (Woods Hole Oceanographic Institute, Massachusetts General Hospital, Lawrence Livermore Laboratories, Idaho National Engineering Laboratory and Memorial Sloan-Kettering Cancer Center), and numerous industrial partners. Funded in August 2000, CenSSIS addresses a class of diverse problems related to subsurface imaging and sensing, and seeks similar solutions across these disciplines and applications. CenSSIS research addresses fundamental physical mechanisms involved in subsurface sensing and imaging, physics-based signal processing and image understanding, and image and data information management. Research is usually conducted at one of the partner universities, but can also occur at one of our affiliates or industrial partners. CenSSIS, like all Engineering Research Centers, has a significant education component. CenSSIS views the development of future researchers in subsurface sensing and imaging systems as a central goal of its education mission, and supports these activities with faculty time and funding.

Each CenSSIS university partner has unique local resources for research and training, and blends these with common educational infrastructure within CenSSIS. Shared efforts are supported by CenSSIS staff, such as the CenSSIS Research Experiences for Undergraduates site award from NSF, and a Northeastern University Research Experiences for Teachers award. Participating laboratories at each partner university welcome CenSSIS students as part of what is called the “distributed university”, implemented by simple course cross-registration, web-enabled seminars, and summer housing exchanges.

Here we report primarily CenSSIS program efforts at Boston University to create vertically integrated undergraduate research experiences. Elements of vertical integration include:

- **Multiple entry points:** The program presents students with repeated opportunities to become involved with research. These begin in the first semester of freshman year, and continue until graduation.
- **Pathways to increasingly challenging research:** The program encourages students to pursue more advanced research roles, commensurate with their academic progress and reflecting their maturing research experience.
- **Coordination with existing research programs:** The program advises CenSSIS research students to compete for summer and academic year research placements to develop their research skills further.
- **Support for advanced coursework:** The program offers advanced undergraduate electives that focus on CenSSIS research problems, and targeted capstone design experiences that address research problems.
- **Creation of an undergraduate research community:** The program encourages the formation of peer groups among undergraduate researchers, and the connection of these groups to existing graduate student groups in CenSSIS.

CENSSIS SCHOLARS - FRESHMEN

CenSSIS Scholars are freshmen engineering students selected based on their incoming academic record, an application statement of interest in CenSSIS topics, and their willingness to commit to several CenSSIS activities during their first year. Each CenSSIS Scholar receives a $500 book award, and a $500 credit to pay them to work in a CenSSIS-related laboratory some time during their first two years. These awards are funded by the College, and by discretionary industrial CenSSIS funds.

CenSSIS activities include taking an introductory freshman course in the CenSSIS teaching lab, attending several CenSSIS web seminars, participating in the CenSSIS Student Leadership program, attending the CenSSIS Research and Industrial Collaboration Conference, attending CenSSIS field trips to industrial sponsors and affiliates, or helping with CenSSIS outreach to K-12 students. Of course, CenSSIS research is expected, using the $500 award.

CenSSIS Scholars are selected by mid-October of their freshman year, and are immediately invited to hear CenSSIS faculty presentations about research opportunities. They are added to our e-mail newsletter list, and receive all notices about CenSSIS research, job opportunities, and Center events. They receive card access to the CenSSIS teaching lab, to facilitate meeting other Scholars, and are introduced to their predecessors. We have awarded 34 CenSSIS Scholars in four years. The first three cohorts received a $1000 book award, but no incentive to work in a research lab.

The opportunity to become a CenSSIS Scholar is explained to the assembled freshman engineering class, usually at their second or third class meeting in the fall. This is the first specific encouragement freshmen receive to consider research. Most are cautious and do not want to make an early research commitment. The result is that most CenSSIS Scholars are from a self-selected motivated group.

HIGH TECH TOOLS & TOYS LABORATORY – UNDERGRADS

All freshmen must take two Introduction to Engineering modules—half-semester courses that together fulfill one semester course requirement. Generally each of our four departments offers several modules that reflect their engineering discipline. CenSSIS offers a module on imaging and sensing, taught entirely in a dedicated teaching lab called the High Tech Tools & Toys Laboratory (HTTTL). The module is a hands-on, discovery based laboratory experience, modeled on a research environment. Students start each class with an engineering problem or application, and immediately must work on a software or hardware aspect of the problem.

As students develop basic skills in imaging and sensing, they advance to systems-level problems, where they investigate and operate “stations” implementing machine vision, pattern recognition, image guided control, image filtering, acoustic sensing, thermal imaging, etc. These high tech “toys” involve both real toys (e.g. slot and radio...
Students receive a $4000 stipend for their summer grant. Mentors are encouraged to match a $2000 partial grant from UROP so more students can be funded. Most grants are awarded to rising seniors or juniors, but a few rising sophomores get summer support. Students can propose follow-on grants for their work. Every grant recipient must prepare a conference poster on their work, and a symposium is held each fall during parents’ weekend, highlighting undergraduate research, and providing excellent practice for presentation skills. UROP also requires participation in a non-credit seminar on research skills, presentation skills, research ethics, and similar topics.

Our program in CenSSIS uses UROP as a continuation of the student’s research maturation. Initially in the HTTTL, or in a faculty lab as a CenSSIS Scholar, students are working on problems identified by others. Since they are novices these problems are often tightly constrained and the solution path is clear. To win a UROP grant, students must plan and write a proposal (with their mentor’s assistance), that identifies a worthwhile problem and develops a solution approach. Even if their proposal is not funded, UROP students benefit from the effort, and often work on the problem with other support, or at a reduced level on faculty funds. Successful UROP students receive considerable campus recognition, and their research posters become good assets for winning further support or as materials for job and grad school interviews.

**Research Experiences for Undergraduates**

CenSSIS has a National Science Foundation site award for a Research Experiences for Undergraduates program supporting eight students to work in CenSSIS research areas. The award provides summer stipends and housing support for a ten week experience in a CenSSIS-related lab, or at a CenSSIS affiliate.

Additionally, CenSSIS and the Northeast Louis Stokes Alliance for Minority Participation support up to six more science or engineering undergraduate students from NE-LSAMP Universities including Northeastern University, Worcester Polytechnic Institute, University of Connecticut, University of Massachusetts at Amherst, and the University of Rhode Island to work at CenSSIS laboratories. The purpose of the NE-LSAMP program is to increase the participation of under-represented students who are Latino/Latina, African American, or Native American in Science Technology Engineering and Mathematics (STEM) undergraduate research.

About a third of the REU/LSAMP REU students come from within CenSSIS. CenSSIS faculty define research areas, and students are matched based on information in the application process. This provides another opportunity to advance an undergraduate research student who has succeeded as a CenSSIS Scholar or internal UROP student. A summer REU also provides additional training in research skills, and often introduces the student to a much larger research group. They also share some activities with high school science teachers in our summer Research Experiences for Teachers program. RET teachers and REU students sometimes work in the HTTTL for their assignment.
In some cases, students want to pursue summer REU positions outside CenSSIS. These may allow them to explore new interesting research areas, or to live at home or visit another university for the summer. Students who have had prior undergraduate research experience are more competitive in earning REU slots, and they generally return the next fall with increased research interest. Some reenter the CenSSIS research community, and others start working in new research groups.

**Undergraduate Research Assistants**

The College of Engineering has several programs for undergraduates who want to work as research assistants, whether associated with CenSSIS or not. Engineering Scholars are identified during the financial aid awards process, and get a research stipend for use in any faculty laboratory during their freshman or sophomore year (like CenSSIS Scholars). STARS (Summer Term Alumni Research Scholars) are identified by application, and by virtue of having a summer research position. A STARS award pays full on-campus housing costs to allow the student to live in Boston for the summer. The SURF (Supplemental Undergraduate Research Funds) program will provide matching funds to support undergraduates working in faculty projects, and funded by faculty or other sources. Each dollar of faculty support is matched with one dollar from the College of Engineering, and one dollar from the faculty member’s department.

Engineering currently has two other REU programs, one in biomedical engineering (21 students) and one in photonics (16 students). Both of these programs have overlapping research activities with CenSSIS. CenSSIS research students have proven to be strong candidates for the internal positions in these programs.

Undergraduate research assistants during the academic year spend about 5-10 hours/week in the research laboratory. During summer session, about 35 hours/week is typical. Day to day, mentoring is likely to be provided by a graduate student or post doc in the lab, although some faculty prefer to supervise directly their undergraduate researchers.

Summer training and presentation expectations vary more widely in individual undergraduate research assistant positions. One exception is safety training, which is required of all undergraduate research students. Training typically includes chemical/hazardous materials safety, laser safety, radiation safety, and machine shop safety, as appropriate.

**Senior Year Elective Courses**

Students who have developed research interests in CenSSIS can pursue those interests by enrolling in a CenSSIS technical elective, Introduction to Subsurface Imaging, during senior year. This course covers using electromagnetic, optical, X-ray, and acoustic waves for transverse and axial imaging (confocal scanning, time of flight, and interferometric techniques), multiview tomographic imaging (computed axial tomography, diffraction tomography, diffuse optical tomography, electrical impedance tomography, and magnetic resonance imaging), image reconstruction and inverse problems, and hyperspectral and multisensor imaging.

Students are expected to work on several real-world data sets as they learn the science and technology of subsurface imaging. These assignments are based on data from faculty research settings, CenSSIS test beds, or the repository of images available at the CenSSIS web site (http://censsis-db1.ece.neu.edu/index.jsp and www.censsis.neu.edu).

Students can also enroll in CenSSIS electives originating at our partner universities through the “distributed university”. This allows research students (both undergraduate and graduate) to take courses with the CenSSIS research leaders in their areas of interest. These courses have been offered in several formats. The most common is attending a course on another campus (two partners are in Boston). Courses originating at or being taken at RPI and UPRM have been distributed through video web streaming and by on-line voice-annotated PowerPoint lectures, supplemented by telephone office hours and telephone conferencing.

Administratively, the Provosts at the partner universities allow CenSSIS students enroll for a special study course with a CenSSIS faculty member at their home institution (avoiding the complications of formal cross-registration). After a student completes a distributed university course, their grades are conveyed to their home CenSSIS faculty member, who records the grade for the special study registration. Cross registrations have been small (a few a semester at each university), and fairly balanced, such that no single school has experienced substantial tuition losses for courses delivered.

**Capstone Design Team Experience**

CenSSIS sponsors several team-based senior capstone projects each year. These typically involve designing instrumentation or software related to imaging and sensing problems. Most are direct offshoots of on-going research projects, or inspired by more advanced technology used in the Center. CenSSIS researchers serve as the teams’ “customers”, and provide the problem descriptions and consulting as the students develop their projects. These projects included:

- Electronics for electrical impedance tomography
- Propulsion, GPS navigation and control systems for an autonomous vehicle to support sonar sounding equipment
- LabVIEW controls for a wavelength controlled laser for biomedical imaging of cancer cells
- Motion detection systems using DSP platforms for image processing
- Control systems for acoustic scanning imagers
- Control systems for testing novel acoustic transmitters and receivers
- Electronics for ultrasonic, phased array therapy of kidney stones
- MATLAB image processing systems for ground penetrating radar for land mine detection

Student capstone teams are encouraged to visit related CenSSIS labs (e.g. the EIT group at RPI and the autonomous underwater vehicle group at Woods Hole Oceanographic

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Institute). This allows the students to see advanced technology and gather ideas about their design problems (which are deliberately scaled to be feasible for a student team of novice engineers).

Most senior capstone design teams working on CenSSIS projects have included one or more students who had prior undergraduate research experience in CenSSIS.

**STUDENT PROGRAM EXAMPLES**

Here we present a few students’ history of involvement in our vertically integrated research experiences program. Most undergraduate research students merely sample research by entering one or more of the above activities and then continue in a conventional way in their studies. Only a few start early enough, and are committed enough to research, to use the full vertical range of opportunities. These cases are presented to show how the coordinated offerings can make a substantial impact on the interested student, and how varied research experiences can be.

**K. Lopez**, a computer engineering student, worked as a freshman in a CenSSIS-funded hourly research assistant position, creating a printed circuit board for an acoustic sensor array. He also tested and improved MATLAB processing code initially created by a senior design team sponsored by Mathworks, a CenSSIS industrial sponsor. During his spring semester of sophomore year he took an Industrial-Undergrad Research Opportunity Program position at Mathworks, learning to use their new GUI toolbox. On returning to campus, he worked as a research assistant in an acoustics lab, developing MATLAB GUI tools for their instrumentation. As a senior, his capstone project developed MATLAB image processing tools for a system that used wireless web cameras to monitor a campus parking garage, to identify vacant spaces.

**J. Blake**, a biomedical engineering student, took the HTTTL class, and immediate continued as a CenSSIS-funded hourly research assistant. She initially worked on an image guided control system in LabVIEW that allowed the computer to control a slot car racer, based on imaging of the track. This became a popular station in HTTTL, with students competing against the PID controlled racer. This work became the basis for a UROP summer grant, to apply a similar PID controller in LabVIEW to a fluid control system that maintains a ball at a fixed height in a column of air. Her UROP symposium poster was also presented at our annual CenSSIS industry conference. As a junior she “graduated” to a research position outside CenSSIS in her major of biomedical engineering.

**E. Vidolova**, a electrical engineering CenSSIS Scholar, also came through the HTTTL class, and worked in the second semester of her freshman year as a undergrad lab assistant on a HTTTL station. She developed an integrated MATLAB package to control an Olympus digital microscope, and provide immediate image filtering tools to the user. In her sophomore summer, she became a CenSSIS REU student, working on MATLAB imaging tools with a CenSSIS mechanical engineering group studying acoustic imaging of coral growth patterns. In her junior summer she again won an REU award, this time with an electrical engineering group looking at motion detection in images. Her capstone project dealt with control of an imaging MEMS mirror array. She will attend graduate school in CenSSIS in the fall.

**L.F. Hui**, an electrical engineering student, took the HTTTL freshman module, but did not feel she had time for research until her junior year. She returned to the HTTTL, and wrote a successful UROP proposal to do multispectral thermal imaging to quantify the energy efficiency improvements in a dormitory renovation project. Using an IR thermal imager loaned by Raytheon, a CenSSIS industrial partner, she collected data from two dormitories and prepared a report to the campus construction group. Her senior project was not related to CenSSIS.

**H. Simpson**, a biomedical engineering CenSSIS Scholar, joined the HTTTL one semester after the freshman module. His task was to develop electronics and a PCB for an acoustic scanning imager system as an undergraduate lab assistant. After a semester of study abroad, he returned and continued working on his scanning station. In summer 2006, on the strength of his previous experience in CenSSIS, he won a CenSSIS REU position, working with a CenSSIS faculty member at Northeastern University. He plans to do his biomedical senior project in imaging.

**K. Matarrese**, an electrical engineering ENG Scholar (similar to a CenSSIS scholar, having an undergraduate research stipend), came to the HTTTL to use his research stipend. He worked several semesters and one summer on the electronics and LabVIEW software for an 8-element phased array acoustic source. He has just joined a space physics group and will do summer research on stepper motor controls for a satellite imaging device, using both his electronics and software skills.

**GENERAL IMPACTS**

Clearly, one kind of research opportunity does not fit all! Generally, students must be encouraged to participate, through advising, financial aid, fellowships, or the lure of publications, networking and professional experience. They must be supported in their efforts, with lab access, mentors, clear problems, adequate equipment and budget, and the encouragement of a larger research community. Finally, they must be able to grow in their experience, whether they enter their first research experience as freshmen or as a senior.

Table I shows statistics of student involvement in the CenSSIS undergraduate research programs. Overall, CenSSIS has been responsible for about 10-15% of the College’s undergraduate research experiences in this period.

**TABLE I**

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<th>Place of Text</th>
<th>CenSSIS</th>
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<td>CenSSIS (ENG) Scholars</td>
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<td>HTTTL module enrollment total (6 semesters)</td>
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<td>Undergrad research labs- hourly lab assistants</td>
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<td>UROP-supported students</td>
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<td>Capstone design students-CenSSIS projects</td>
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<td>CenSSIS technical electives</td>
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SUSTAINABILITY

Our goal is to maintain or expand the model of vertically integrated undergraduate research experiences, through continuing funding, and good advising and mentoring. CenSSIS funding will gradually need to be replaced with other sources. The HTTTL teaching modules are considered already to be part of the department’s teaching commitment. CenSSIS Scholars will need continued support ($1000/student) and may become part of the wider ENG Scholar program already supported by the College. The UROP program is already university funded, but student proposals are more competitive when faculty can provide matching funds ($2000/student/summer). These will need to come from external grants, grant supplements, or discretionary departmental funds. REU support must come from proposals, and our recent new site award in photonics will support some CenSSIS-related projects. The CenSSIS advanced technical electives are established courses. Capstone projects will continue to arise from CenSSIS faculty and industrial partners and affiliates.

Overall, it appears that most parts of the current undergraduate research structure in CenSSIS can be sustained with existing College and grant resources. Most importantly, faculty must provide good research advising and mentoring to create strong continuity in student research experiences and opportunities.

CONCLUSIONS

Undergraduate research experiences can be encouraged by marshalling existing resources in a vertical program of entry points and pathways. At Boston University, the CenSSIS program introduces freshmen to research through a special CenSSIS Scholars program and through an introductory freshman module in the High Tech Tools and Toys Lab. The HTTTL also serves as an initial incubator for interested students who advance to both internally (UROP) and externally (REU) funded programs for supporting more mature undergraduate research. A senior-level elective course and focused capstone design courses allow students to pursue advanced work that can inform their research and prepare them for employment or graduate study. This overall program has increased the visibility of undergraduate research and led to about a 10% increase in research participation in the last four years.

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REFERENCES