Chapter 6

Teleoperation from a Cave Automatic Virtual Environment: A Multidisciplinary, Multilevel Systems Engineering Project for Undergraduate Education

STEPHEN GLENN¹, MAGDALINI LAGOUDAS¹ and TAMÁS KALMÁR-NAGY²
¹Space Engineering Institute, Texas A&M University, College Station, TX, USA. ²Department of Aerospace Engineering, Texas A&M University, College Station, TX, USA. E-mail: icce2008@kalmarnagy.com

There is a constant need to promote retention and better prepare students for their engineering careers in educational programs. Nationally, about 50% of students entering engineering drop out by the junior year. In a typical curriculum, students are exposed to little or no systems engineering concepts until they become seniors. Soft skills and some problem solving skills cannot be effectively developed in a traditional lecture-style setting. Cooperation with a multidisciplinary team with varying levels of experience is also an important component of undergraduate education that receives little emphasis. The Space Engineering Institute (SEI) at Texas A&M University supports multidisciplinary and multilevel (freshman to senior) applied research projects for undergraduate engineering students. This paper describes one such project and evaluates its effect on undergraduate education.

INTRODUCTION

The need to raise achievement levels of U.S. students in science, technology, engineering and math (STEM) and to increase the number of graduates in these areas is a highly active area of research and discussion [1]. Minority students are especially prone to attrition and underachievement, particularly in introductory STEM courses at universities.
[2]. New methods for teaching undergraduates have shown promise in the literature, such as methods that emphasize discovery [3], inquiry [4, 5], projects and problem solving [6] and the scientific process [7], as well as workshops that promote group studying facilitated by a graduate student [2]. Other studies focus on preparing early childhood educators to use technology in science and math curricula [8]. Universities are also recognizing the need for more hands-on and interdisciplinary experience in undergraduate engineering education [9]. An emerging phenomenon in this area is the Conceiving-Designing-Implementing-Operating (CDIO) framework which provides a standard for project-based engineering curricula.

The Space Engineering Institute (SEI) was designed to attract underrepresented groups to address several educational/economical issues of the U.S. raised in the 2005 Rising Above the Gathering Storm report [10] and also to improve retention by engaging students early on in applied research projects. After five years, the first year retention is at 92% while the overall retention is at 76%. The key elements of our program are excitement and exposure: we aim to excite undergraduate students about the possibilities in engineering and we aim to expose undergraduate students to our testbed of robotic vehicles (in the spirit of NASA’s Robotics Education Project). This testbed currently consist of a heterogeneous team of interacting robots outfitted with actuators and sensors (reprogrammed Roombas, LEGO Mindstorm robots, RC choppers).

The SEI Teleoperation Team project involves the design of a prototype system that allows for the teleoperation of a robotic vehicle from a Cave Automatic Virtual Environment (CAVE), which is a virtual cockpit viewable with 3D glasses. The team is led by a graduate student mentor (Glenn) with guidance and support from a faculty member (Kalmár-Nagy), the SEI director (Lagoudas), and engineers at NASA.

The students participate in weekly team meetings to discuss the workings of the system and subsystems, coordinate activities, and troubleshoot technical problems. Technical communication skills are sharpened in the process of producing reports and presentations throughout the project. The engineering process, safety and ethics are emphasized.

This paper will describe the approach of the team to build the CAVE system, developing control code for teleoperating a vehicle, hazard analysis, and collecting test data. We will also discuss the types of technical skills acquired by the students and the value of the project to the students’ engineering careers. Finally, recommendations are provided for improving undergraduate education based on lessons learned from the project.

**PROJECT**

In the near future, teleoperable rovers will be exploring the moon and performing search & rescue work in hazardous environments. On the moon, rovers will spend only a small fraction of their time under direct control by astronauts. The majority of their time will be spent under the command of an Earth-based teleoperator. NASA has already performed extensive teleoperation exercises on the Science Crew Operations and Utility Testbed (SCOUT) rover which is a four-wheeled rover designed to carry two suited astronauts and equipment. It serves as a platform for testing new ideas on improving the effectiveness of rovers in their interaction with astronauts and teleoperators. To aid in the teleoperation of SCOUT, NASA has developed and tested a five-screen virtual cockpit using a combination of live video with a synthetic environment. The synthetic
environment, which is a 3D model created for the robotic vehicle’s operating environment, offers increased situational awareness over live video alone. Waypoints, markers, danger-zones, and objectives can all be displayed directly on the virtual terrain. Customizable head-up displays (HUD) can present relevant information in a way best suited for different teleoperators and different situations. An additional advantage is the savings on data transmission—situational awareness can be increased without having to transmit large amounts of video. Complex lunar missions involving robotic interactions with structures and payloads will require a high-level of situational awareness for teleoperators. Search & rescue teams will also need a data-rich, immersive environment to properly teleoperate their robotic vehicles in dangerous situations. The Teleoperation Team at SEI is developing a prototype teleoperation system to test a Cave Automatic Virtual Environment (CAVE) with stereoscopic (3D) capability. The CAVE functions as a remote cockpit for the vehicle, providing 3D viewing of a geo-referenced model of the operating environment.

In addition to the stated goals, the project is designed to improve retention, communication skills, and teamwork. Hands-on exposure to engineering problems will increase excitement and reduce the likelihood of students becoming disenchanted with engineering and dropping out. With help from other engineering students, individuals on the team can improve their skills and gain confidence in their abilities. The multidisciplinary nature of the project and the multilevel composition of the team require the students to communicate clearly with each other and with the team advisors. The students also quickly learn to depend on each other since individually they have neither the experience nor the time to have a working knowledge of all aspects of the project.

The team consists of 6-12 undergraduates from aerospace, electrical, and mechanical engineering, as well as computer science. The students are paid hourly for up to 10 hours per week. Deliverables include weekly individual reports on progress and problems, end-of-semester reports and presentations, and attendance of the weekly team meeting. A graduate mentor provides technical and project management assistance, provides feedback on the team’s reports and presentations, and maintains communication with the SEI director, faculty advisor, and NASA mentor through weekly reports and meeting minutes. The graduate mentor also monitors the performance and progress of each team member and provides them with constructive criticism and support. The SEI director oversees funding for the project as well as overall progress. Further technical assistance is provided by the faculty advisor and NASA mentor. Feedback on the direction of the project as well as on reports and presentations is provided by all.

The weekly team meeting, facilitated by the graduate mentor, provides updates on progress, brings problems to the attention of the team, and reminds everyone about upcoming deadlines and additional meetings. In this way, each team member develops a reasonable understanding of how all the parts of the teleoperation system work and stays on top of the project schedule. This pays off in anticipating and solving problems and enriches their engineering education. Through the meetings, the students learn about each others’ expertise and know whom they should ask for help on certain problems.

Overview of Teleoperation System Design

In this Section we present some system diagrams designed by the students. Teleoperation systems are composed of a vehicle and base station connected through a network as shown in Figure 1. The teleoperator sends commands to the vehicle using a control
device. Actuators react to these commands and change the state of the vehicle. Sensors collect data on the state of the vehicle and send the information back to the base station. This feedback is interpreted and displayed for the teleoperator.

During the first year of the project an iRobot Create served as a preliminary test vehicle. The implementation of the above general teleoperation system structure for the Truck (a vehicle which will be used for a future project) is presented in Figure 2 below. A computer on the truck will run MATLAB and C code to communicate with the sensors and actuators. The installed sensors are a GPS unit, an Inertial Measurement Unit (IMU), and a video camera. These allow the location, orientation, velocity and other details of the state of the vehicle to be recorded.

The Base Station uses three computers. The Control PC runs Simulink code to handle the joystick input, allowing the teleoperator to control the vehicle. The other two computers provide feedback to the teleoperator as part of the CAVE system, used to immerse the teleoperator in a virtual environment. The CAVE PC’s are running a software package called LandForm that displays the vehicle’s state within a three-dimensional environment based on the sensor data received from the vehicle. This environment is displayed using two stereoscopic projectors, offering a wide, 3D field of view. An emitter sends a signal to a special pair of glasses that creates a sense of depth to the projected display. This is intended to improve the teleoperator’s situational awareness while controlling the vehicle.
CAVE

In the Base Station, a Cave Automatic Virtual Environment (CAVE) system is utilized to provide data-rich, immersive feedback for the teleoperator. A diagram of the Base Station, including the screens and stereoscopic equipment that comprise the CAVE, is presented in Figure 3. The CAVE system is located indoors, and in the case of the Truck will not have direct line of sight. High-powered wireless routers are used to enable communication with the Truck outside the building. The CAVE is comprised of two projectors that display a continuous image across two screens. The screens are mounted at a 90-degree angle to each other to allow for a wider simulated field of view.

The illusion of depth is achieved by creating two versions of the display—one for the left eye and the other for the right eye. The distance between common points in each version is the separation distance. Larger separation distance results in a point appearing closer to the viewer, while smaller separation distance makes a point appear farther away. As the two versions are alternately displayed, LCD shutter glasses prevent each eye from seeing the display version intended for the other eye. The rapid alternation of slightly different left-eye and right-eye versions of the display is interpreted by the brain as a single 3D image.

LandForm

The 3D virtual environment displayed by the CAVE is first modeled using LandForm Gold by Rapid Imaging Software, Inc. LandForm allows the user to place flags and 3D objects at specific GPS coordinates as well as model the terrain elevations and overlay satellite imagery. LandForm can then render the environment in 3D from a viewpoint of the user’s preference, and modify the view accordingly as the coordinates and heading change in real-time. This is referred to as synthetic vision. Transferring these parameters requires little memory and bandwidth compared to transferring video, yet provides a high level of situational awareness. Synthetic vision is more helpful than video in situations where visibility is obscured by environmental factors such as fog or darkness. LandForm can also improve navigation by placing waypoints directly on the environment and by showing speed and heading in a custom HUD. A major limitation is that LandForm models will not include obstacles the modeler was unaware of or that appeared after the model’s creation. For this reason, the teleoperation system includes live video and the vehicles are restricted to the boundaries of the modeled terrain.
Vehicle Controls

To successfully teleoperate any vehicle from a remote location, a control system capable of reading the teleoperator commands and sending these commands to the vehicle must be properly designed, tested, and implemented. The type of command signals sent to a teleoperated vehicle depends upon the type of vehicle being used and its function. For this application, a simple Simulink control system was designed to send the Truck commands regarding its speed, direction, and acceleration. The system incorporates velocity and GPS position feedback from the Truck.

Wireless Communication

In order to teleoperate the vehicle there needs to be communication between the Truck and the Base Station. A wireless network is used to enable a large range of movement for the vehicle. The network utilizes two TROPOS 5110 MetroMesh outdoor wireless routers, which are high performance, high-powered routers that follow the 802.11b/g wireless networking standard. These routers are expected to have a range of about a mile with direct line of sight. TROPOS routers are also 10 times more sensitive to receiving incoming signals than standard routers, which allows for safe teleoperation of the Truck with negligible loss of wireless signal.

PROJECT RESULTS

Teleoperation System

The Team demonstrated the successful, independent operation of all the major functional components of the system: control device, feedback, communication, sensors, and actuators. A Simulink program reads, formats, and transmits joystick input. Using LandForm, the Team created a geo-referenced model of the test site and set up a two-screen CAVE that displays two independent stereoscopic images that synchronize with the CrystalEYES glasses for 3D viewing. A wireless network using the high-powered TROPOS routers successfully communicates between the Base Station and the outdoor Truck test area. The Team created MATLAB code that logs and transmits both GPS and IMU data in real time. Another MATLAB program, in combination with a program written in C, commands the DAQ to output the appropriate analog voltages on the correct channels for operating the actuators.

The Team also integrated the major functional components into two meaningful pieces of the overall teleoperation system. The first piece integrates sensors, communication, and feedback. Live GPS and IMU data successfully transmit wirelessly to LandForm via SIL and update the view in the CAVE. The second piece integrates the control device, communication, and actuator functions. The joystick input data successfully transmit wirelessly to the Truck PC where MATLAB and C code receive and format the input and then command the DAQ to produce voltage for controlling the actuators. The output voltage was verified by comparing multimeter measurements for different joystick inputs with the expected output voltage based on specifications in Massey [11].

Finally, the Team integrated the Truck simulator with the two pieces of the teleoperation system mentioned above. The Truck PC wirelessly receives commands from the joystick and sends them in the form of DAQ commands to the simulator, which outputs GPS coordinates. These coordinates are sent wirelessly back to the Base Station.
where SIL receives them and properly updates LandForm and the view in the CAVE. The yaw data in this configuration is sent from the real IMU, not the simulator. The importance of safety is emphasized throughout the project, and a small programmable robot called iRobot Create was used as a safer alternative to the Truck for testing the control software. As with the Truck, the joystick commands are sent through the gateway-configured TROPOS wireless router to the mobile-node configured TROPOS router which is connected to a PC. This PC receives the commands, formats them, and sends them using serial communication to the iRobot. The iRobot’s built-in software then reads the serial commands and acts accordingly.

The iRobot testing will also involve the use of LandForm. The iRobot’s location will be tracked using odometry techniques and will be displayed within LandForm after undergoing a transformation to convert the coordinates of the iRobot to GPS coordinates. Both the LandForm model and the coordinate transformation have been developed. The model consists of a tiled carpet and traffic cones, which corresponds to a real-life carpet and traffic cones, and includes a model of the iRobot for chase-plane viewing. By navigating the iRobot within this test environment using the control system and LandForm, the team will have a functioning alternative teleoperation test bed that operates on a smaller scale and entails less risk.

Space Engineering Institute (SEI)

The SEI program has four goals: increase the participation of underutilized groups pursuing careers in space engineering, improve the retention of these students in engineering, enhance their engineering education of undergraduates, and produce high quality technical output for the sponsor. The program targets underutilized groups but it is open to all students. The backbone of the SEI activities is team projects and problem-based learning. Each team is formed at the beginning of each academic year when freshman are invited to join existing teams. Each project runs on a semester basis with all SEI team presenting their work at the end of the semester. Most team projects run for multiple academic years. Freshman students are placed in interdisciplinary teams with majors supporting the technical needs of each project. An ideal team will include a group of about eight students with two freshman, two sophomores, two juniors and two seniors. Such a structure allows students to learn outside their major and be mentored from upper level students. Each team is assigned a graduate student mentor who acts as the project manager and team leader. In addition, each project has a faculty and an industry mentor that provide technical guidance. Outside the team projects, the program offers a seminar series for both technical and professional development.

Educational Results

The students exhibited significant progress in communication skills and teamwork, and no students have dropped out of the program or engineering. As the students became more familiar with the project and their areas of responsibility, they became better able to prioritize information and communicate complex details and relationships. Through feedback on their reports and presentations and through their discussions with other team members, they improved their ability to clearly present ideas to those unfamiliar with the material. Throughout the two semesters, the students continued to develop as a team, with each student learning how their responsibilities and expertise overlapped and interacted with others’.
The systems engineering aspects of the project taught the students the importance of having documentation for specifications, hardware set up, operational procedures, software functionality, and interfaces. The students developed an appreciation for the fact that integrating components can be difficult even if the components work well individually. They also learned that the integrated system had properties such as response time and stability that the components do not necessarily determine on their own.

Additionally, the students developed technical skills such as programming, networking, modeling and hazard analysis. Those with previous experience in these areas shared their knowledge with the others and the whole group benefited. The technical and overall experience has helped them with attaining scholarships, internships, co-ops, and jobs.

<table>
<thead>
<tr>
<th>Number of Surveys Sent</th>
<th>Current Students (Freshmen)</th>
<th>Current Students (Non-Freshmen)</th>
<th>Program Graduates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Survey Participants</td>
<td>15</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>% Participation</td>
<td>100.0 %</td>
<td>90.6 %</td>
<td>25.0%</td>
</tr>
</tbody>
</table>

**TABLE 1**
**SURVEY PARTICIPATION**

In addition, during fall 2008, all SEI students (the students working on the teleoperation team and six other teams) participated in a survey to assess SEI impacts on retention in engineering majors, enhancement of the engineering education, and career plans. Surveys were sent to three groups of SEI participants: 1) current freshmen SEI students that have participated in the program for one semester, 2) current non-freshmen SEI students, and 3) program graduates that have either graduated or have left the program and have not yet completed their undergraduate degree. Survey participation is shown in Table 1. Figures 4 and 5 show some of the student survey results.
FIGURE 5
SKILLS THAT SEI PARTICIPANTS VALUE FOR THEIR POST-GRADUATE CAREER

FIGURE 6
SEI STATISTICS AND STUDENT RETENTION IN ENGINEERING
The program outreach efforts have resulted in attracting students from ethnic minorities and female students, as shown in Figure 6 over a period of six years.

In the U.S., the national average for student retention in engineering is about 50% [13] with much lower retention rates for students from underrepresented groups. In May 2008 we conducted a study of all students who joined the SEI program as freshman over the period of six years (2002-2008). The goal of that study was to find out how many of these students had either graduated with a degree in engineering or were still in school pursuing a degree in engineering. The results of that study are shown in Figure 7 with a minimum retention rate of about 70% compared to the national average of 56% (red line).

![SEI Student Retention in Engineering](image)

**FIGURE 7**  
SEI STUDENT RETENTION IN ENGINEERING

**CONCLUSIONS**

The growing need to improve the number of STEM graduates produced in the U.S., especially in regards to minority students, has prompted widespread investigations into methods for improving undergraduate education. Incorporating a multilevel aspect into undergraduate education encourages older students to help younger ones develop skills more quickly, tackle classwork more effectively, and to aid them in identifying interest areas. Retention, exposure, excitement, and motivation are likely to improve as well with the increase in the number of people in a students’ support network. Exposing students to multilevel experiences early on would maximize the benefit they would receive. This approach is not yet widely adopted, at any stage, in undergraduate curricula.

Multidisciplinary learning is widely touted and within SEI the authors have observed its value in developing teamwork and communication skills while providing excitement and motivation. The students are also forced to learn about topics outside their area and to communicate with and depend on people from other majors. While multidisciplinary learning has been incorporated into undergraduate curricula, additional benefits could be garnered by applying them to every stage of the undergraduate curricula instead of as an optional course, as is currently the case.

The authors provide a close look at a particular project at SEI involving a multilevel,
multidisciplinary team. Students have documented and tested most of the components of
the teleoperation system and have successfully integrated essential subsystems. The
project targets typically underdeveloped skills such as teamwork and communication and
introduces systems engineering and project management much earlier in the students’
undergraduate careers.

Introducing the students to systems engineering earlier could provide additional
benefits as well. Students learn how to approach complex problems with interrelated
components and become familiarized with important tools and methods such as diagrams,
specifications, interface control documents, and system decomposition. They also come
to appreciate the difficulty of integrating components, designing robust systems, and
maintaining group knowledge in the form of documentation. In addition, the students
improve their communication and teamwork skills while gaining technical experience
and exposure in an exciting hands-on environment. Most undergraduate programs place
systems engineering in the last year of study, but an earlier introduction could increase
the benefits to students.

Project management is part of most real-world projects. In an undergraduate setting,
students would learn about milestones, Gantt charts, work breakdown structures, and
participate in periodic meetings, reports, and presentations. Introducing project
management before the senior design course could provide a boost to these often
underdeveloped yet vital skills.

Many of the benefits from the program are not provided to undergraduates for a
majority of their school careers and it is therefore recommended that institutions increase
their students’ exposure to multilevel and multidisciplinary projects involving systems
engineering and project management.

ACKNOWLEDGEMENTS

The authors would like to thank the following students for their efforts on this project:
Agustin Maqui, Amanda Collins, Angelo Bianchini, Caleb Wells, Christie Tipton, David
Roden, David Taylor, Ernie Everett, Jason York, J.C. Reeves, John Cassidy, John
Quinones, and Michael Yager. Special thanks to Frank Delgado at NASA-JSC for
providing the CAVE equipment and to Dr. Fred Fisher and Texas Engineering
Experiment Station (TEES) for the use of the Truck.

REFERENCES

1. D. D. Kumar, K. J. Crippen, “Science Education in Review: Response to the Secretary’s
pp. 143-145.

Program: Enhancing Student Performance and Retention in the Sciences Through Peer-
Facilitated Discussion,” Journal of Science Education and Technology, Vol. 14, No. 3,

3. D. Wolaver, “Can Discovery and Intuition Be Taught?” 35th ASEE/IEEE Frontiers in
Education Conference, Indianapolis, IN, 2005.


**Stephen Glenn** received the B.S. degree in Mechanical Engineering from Texas A&M University in 2006. He worked as a Graduate Mentor at the Space Engineering Institute from 2006-2008 while pursuing the M.S. degree in Mechanical Engineering at Texas A&M University.

**Magdalini Lagoudas** received a Diploma in Mechanical Engineering from Aristotle University, Thessaloniki, Greece and an M.S. in Mechanical Engineering from Lehigh University, Bethlehem, PA in 1986. She is currently the Director for the Space Engineering Institute at Texas A&M and is also the associate director for the Spacecraft Technology Center.

**Tamás Kalmár-Nagy** received the MSc in Mechanical Engineering from the Technical University of Budapest in 1995 and the PhD degree in Theoretical and Applied Mechanics from Cornell University in 2002. He is currently an Assistant Professor at Texas A&M University in the Department of Aerospace Engineering.