An REU Experience on the Industrial Applications of Sensing, Modeling, and Control

Mohamed Abdelrahman,[1] Sally Pardue[2]

Abstract – This paper describes a research experience for undergraduates (REU) program that focuses on multidisciplinary high-tech opportunities in the metalcasting industry, resulting in a set of multidisciplinary research projects. Undergraduate students and mentors from electrical, mechanical, and chemical engineering and industrial technology are involved. We discuss the lessons learned and the challenges that we have faced in the recruitment and operation of the program during the first two years. We also discuss in detail the benefits and drawbacks of the unique model, Student as the Principal Investigator (SPI), utilized in our program. In this model, undergraduate students define their own research question within a given framework instead of following a plan defined for him/her by the mentor. Mentors were involved to a limited extent in defining and updating the research question while the students maintained ownership of the research. Although the model is generally positive, some issues arise in the implementation. Future plans for the 3rd year are also presented.

Keywords: Research experience for undergraduates, REU, metalcasting, research training

INTRODUCTION

The current paper describes the details of a research experience for undergraduates (REU) program. It also focuses on a unique aspect in the implementation of this REU program. This aspect is mainly related to the roles of the students and mentors during the summer research. In this program, the students assume the role of the principal investigators and hence the model is termed 'Student as Principal Investigator (SPI) model'. A description of the general aspects of the REU program is given in the remainder of this section, followed by details of the implementation in the first two years of the program. Characteristics of the SPI model and how it compares to traditional models are then discussed along with the theoretical basis of the model. Observations of the principal investigators on the challenges and advantages of the SPI model are presented and the paper concludes with open questions regarding the SPI model.

The main aim of our REU program is to provide research experience to undergraduate students in the field of industrial application of sensing, modeling and control. Students' research focuses on the metalcasting industry, a multibillion dollar industry that has been struggling as a result of foreign competition and lack of research innovation. The program is complementary to two major research projects [1, 2] that are currently underway at Tennessee Tech University in association with a number of industrial partners which include General Motors, Foseco Morval, Inc, and Metal Casting Technology and in partnership with the Oak Ridge National Laboratory (ORNL). These projects present innovative approaches to introducing technologies for monitoring, modeling and control of traditional sand casting and evaporative (lost) foam (LF) casting. The proposed technologies enable better control

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[1] ECE Department, Tennessee Technological University, 115 W. 10th St., Cookeville, TN 38505, mabdelrahman@tntech.edu

[2]ME Department, Tennessee Technological University, 115 W. 10th St., Cookeville, TN 38505, spardue@tntech.edu

over the casting processes resulting in reduced scrap rate and variance in the casting quality as well as increase in the productivity of foundries. The program also aims at enhancing the image of the metalcasting industry where high technology opportunities exist. The latter is especially effective in encouraging highly qualified engineering and technology students to choose to do research in the metalcasting industry. A dissemination plan is designed to further increase visibility of high tech research opportunities in the metalcasting industry [3].

The program utilizes expertise from multiple disciplines as it addresses different sensing technologies, modeling of physical processes and automatic control of the casting process. It involves students and mentors from Electrical, Mechanical, and Chemical Engineering and Industrial technology. This multidisciplinary program is conducted at Tennessee Tech University and Oak Ridge National Laboratory where facilities for carrying out the proposed research including a foundry, laboratories and computing facilities are readily available. The number of students for each summer of the program is typically 10, with five students to be recruited from TTU and 5 students to be recruited through a nation wide search with particular focus on minority institutes and principally undergraduate institutions. These students participate in the research for 9 weeks during the summer.

This research is focused on increasing the competitiveness of the US metal casting industry, reducing energy consumption and environmental impact and changing the image of this Multi-billion dollar industry as a field fertile with research opportunities. It is focused on addressing the lack of highly educated workforce by fostering interest in multidisciplinary, high tech research in the important metalcasting industry. Moreover, many of the technologies under investigation are cross-cutting with opportunities to be utilized in other manufacturing industries. The site offer students from underrepresented groups and minorities and students from institutions that do not offer research opportunities a chance to participate in high quality applied research.

IMPLEMENTATION

In 2006 and 2007, this program has offered 21 undergraduate students opportunities to participate in cutting edge research focusing on the improvement of the casting industry. Students from electrical and computer engineering, computer science, mechanical engineering, chemical engineering and industrial technology have participated in the multidisciplinary program. The theme has remained focused on injecting high-tech sensing, modeling, and control into the expendable (lost) foam casting process.

The student-designed research questions have focused on many aspects of the lost foam process including:

- Monitoring of the profile of metal fill during a casting process through the utilization of capacitive sensing. offered opportunities for research in electronic sensor design, signal analysis and wireless sensor networks research. It also offered opportunities for utilizing finite element analysis and capacitive tomography for inferring the fill profile from sensors' measurements.
- Automatic control of the casting process with feedback from the new fill monitoring techniques utilized a counter-gravity casting system in which the pressure, under which the metal is introduced to the casting, can be varied. Dynamic modeling and simulation of the counter gravity machine and the design and implementation of different closed loop control algorithms for improving the machine's performance.
- Non-destructive evaluation of foam patterns used in lost foam casting focused on vibrations, ultrasonic, and infrared imaging of the foam patterns to evaluate fusion level and density profiles of the foam.
- The chemical decomposition of the foam during metal pour and the diffusion of the gases through the foam were investigated with numerical simulation and lab scale measurements. The gas behavior through the metal and the pre-melt foam influences the final casting by introducing potential porosity and changing the foam characteristics affecting metal fill rate.

A key feature of the instructional design is the intensive Week One training in the overall research program, research methods, and project management. The PI and coPI use active learning techniques [4, 5] to introduce the multidisciplinary research areas of casting and to generate group discussion of the primary steps to conducting engineering research. The REU participants formulate their own research question, develop hypotheses and plan the required steps to achieve the data needed answer their question. The students take a public path of question development through the use of posters in the meeting space. Peers as well as the technical mentors review the posters throughout the week and make suggestions that refine the students' research question. At the end of the first week, the students have become the PI of their own research. The TTU faculty mentors, graduate students, and R&D engineers, as well as the program PI and coPI, then become facilitators to the student PIs. Rigorous weekly reporting requirements keep the projects on task and help the program mentors to coach necessary changes in the research approach. The REU participants formally close their research at the end of the nine weeks with a written report, a verbal presentation, and a poster session. The comprehensive training approach ensures students are exposed to not only how to conduct research specific skills but also how to design their own research program.

STUDENT AS THE PRINCIPAL INVESTIGATOR (SPI) MODEL

The Student as the Principal Investigator (SPI) model for training a student to research is presented next and contrasted with traditional models for training undergraduate researchers. We need to define what we mean by the traditional models of training students to conduct research, whether working with undergraduates in a compressed time frame of one summer, or working with graduate students over a period of years. We can base such a broad definition on our own past experiences and on observations of how we and our colleagues currently carry out research training of students. We can also ask the students what their experiences have been. We can search the literature and extend into educational theories and models for student learning.

Contrast to traditional models

In formulating our training approach, we find ourselves asking: How did we learn to "research?" Given that a natural tendency is to teach as you were taught, it is important to identify the expectations and understandings that many of us bring to the research environment in light of trying to communicate this process to new researchers. Perhaps most of us in engineering would find our training in research was an implicit process where we learned to emulate good practice by observing our major professor in action over a period of years. If so, then how do we systematically transfer this process to the next generation? And if all we have to model is a process that took years to produce results, what can we hope to accomplish in a few short weeks? Addressing some of these concerns, we seek to make our research training model an explicit one, with clear steps to engage the student in an authentic experience and to facilitate its implementation in the nine-weeks of the REU.

What do students say about their prior research experiences? A comprehensive set of surveys, querying over 4000 students, have been conducted for NSF by SRI International [6]. These surveys focused on Undergraduate Research Opportunities (UROs). The surveys were conducted in 2002 to 2005 with final summary reports in 2003 and 2006. The 2006 summary of the follow up survey [7] includes a finding that only 1/3 had primary responsibility for designing the project they worked on. This demonstrates a lack of independence allotted to 2/3 of the students who responded.

Our current definition of a traditional model is: The ultimate goal is to instruct the student in specific research skills that support the exercise of creating new work. This work may be part of a larger body of research being conducted by the faculty mentor; wherein, clearly defined subtasks have been broken down for completion by graduate students, and these may be further digested for the use of undergraduate researchers. Characteristics of this traditional model are:

- the research goals are fixed and set by the mentor
- the mentor dictates the work to be done and sets the expected timeline
- the mentor has anticipated the outcomes drawing on past experience in shaping hypotheses
- the mentor will lead the student around obstacles, having already seen them well in advance

In contrast, the Student as the Principal Investigator (SPI) model is defined by: The ultimate goal to have the student experience an authentic independent engineering research process. The characteristics of this model are:

- the research goals are flexible and set by the student
- the student plans the research steps, setting and continually adjusting the timeline

- the outcomes are not predetermined
- roadblocks must be planned for and navigated, but may inevitably stop work

Dealing with the "then what?" of the last bullet point of the SPI model is what provides the authenticity of the full engineering research process. The tension that stopped work and tight timelines forms in the students and in their mentors can invite resolution via vital opportunities for critical thinking, creative solutions, and personal growth.

Theoretical basis for the SPI model

Learning theories that support the implementation of this model are found in cognitive theory, social learning theory, and constructivist theory [8]. We, as PIs, are somewhat new to the field of engineering education research, and thus new at forming connections to the wide body of literature that informs education specialists. We recognize the value in forming these connections and have started by mapping how the SPI model relates to learning theories. In future work, we intend to examine the student motivation theories and also models for student development to enrich our development of the SPI model.

Our design of the week one of research training and introduction to the lost foam casting process embraces aspects of instructional interventions based on cognitive theory. Six key aspects are pointed out by Svinicki [8] are: 1) attention, 2) working memory, 3) encoding, 4) long term memory storage, 5) retrieval and active processing, and 6) metacognition. The structure of week one requires the students to pay careful attention to all the information being shared, since they will be selecting pieces to use in formulating a working research question throughout the week. The peer learning that occurs during discussions ensures that students are actively working with the new material, encoding it into their prior knowledge base and constantly accessing it during formal and informal meeting times. Engaging the students in not only producing their research question, but helping them see there is a process to follow to take a general interest into a formalized question truly addresses the sixth aspect of metacognition.

Social learning theory, or social cognitive theory, provides the grounding for the cognitive apprenticeship model for student learning. Instruction based on this theory involves the use of 1) models, 2) consequences, 3) observation, and 4) student development[8]. The models are used by the student to learn behavior – in this case, how to research. For example, when the students are introduced to the library resources on campus, the reference librarian has them actively search the literature databases using key words from their research questions. The consequences influence the learner's behavior – in this case, successful completion of week one means recognition by your peers and faculty mentor that you are mastering a new skill of forming a research question. Further consequences are stipend continuing to be delivered and the growing sense of competency and ultimately the celebrated completion of the summer work. The observations the student makes of how to conduct research is really the heart of the SPI model, and one that is common to the traditional model that we outlined previously. In seeking to ensure that all elements of the research process are explicitly observable, we are strengthening the training and perhaps shortening the time it takes to comprehend the nuances of research process.

Constructivist theory, specifically social constructivism, emphasizes the importance of dialogue and interaction with peer learners to help develop understanding. The multidisciplinary nature of the casting research meant we as PIs knew all along that we would need to keep the students in close contact with one another just as their faculty mentors tend to work in teams. However, the SPI model as it has developed also meets this aspect of social constructivism. For example, our REU program requires weekly meetings of the students to discuss a text, *The Craft of Research* [9], and the students have noted that while they did not particularly enjoy reading the text itself, they found a great deal of value in the student led discussions. Instruction grounded in constructivist theory has four defining aspects: 1) student constructor, 2) problem based learning, 3) authentic testing, 4) role reversal. Examining each of these in greater detail reveals that the SPI could have initially been designed based on these principles, even though it truth the PIs were merely seeking to make the "how-to" of research more apparent to students. The first aspect of the student as an active constructor of their own knowledge means the instructor must step out of the center of the arena and let the student directly experience the environment. What better way than to carry this out than to say to the students "You will be deciding what to research this summer." As to the second requirement of problem based learning and the need to have students experience an authentic environment with authentic questions, we find that the SPI model (and traditional models for research training) includes this by definition of the act of engaging in research. The third feature of authentic testing is met through the student managing their own timelines and producing results based on those timelines with the final goal of producing a research report. The fourth feature is that the roles of the teacher and the student change. This means the student takes the lead role and strives to become their own authority, not relying on the teacher to be the one with the answers. This complete reversal of roles is a key aspect of the SPI model and is why we believe it offers a unique research training experience for undergraduates.

PRINCIPAL INVESTIGATORS' OBSERVATIONS OF SPI MODEL IN ACTION

Over the previous two years of implementation of the SPI model, the principal investigators had a chance to observe the SPI model in action. The nature of the research program being multidisciplinary allowed the PIs to observe the model at work across several disciplines of engineering and engineering technology. The number of student participants was 21 students. The number of mentors was 12. The following is an attempt to capture the qualitative observations of the principal investigators of the challenges, advantages and open questions that stemmed from the implementation of SPI.

Challenges

Challenges usually arise in the implementation of any program whether traditional or nontraditional. The REU program at TTU saw its share of traditional challenges that will arise in any program in different stages. The focus here is on the challenges that arose from what the PIs perceive as a result of the unique nature of the program itself.

Challenges for the Principal Investigators

As we will illustrate in the sections below, the PIs have to walk a thin line balancing many conflicting objectives for the success of the SPI model.

Guaranteeing the Mentors' Buy-in - Unlike more traditional REU experiences, SPI model requires the students to carry an independent investigation. It is important however for the mentors to have a vested interest in the students' research projects. Moreover, mentors usually have their doubts regarding students' ability to identify a research question and come up with a research plan during the first week of the summer. This anxiety is usually relieved during the first week as the students are guided to identify a problem that falls within the scope of research interest of the mentor and with agreement on a time schedule and milestones. The PIs' challenge is how to balance independence of the students' research and the vested interest of the mentors.

Continuous Involvement - In a traditional model where students are plugged into research teams, continuous facilitation by the PIs may not be required. The SPI model, however, requires continuous involvement and support for the student in his/her new role as the director of a research project. The PIs provide advice to the student on managing and updating research plans, accessing resources on campus and off-campus, documenting and presenting results and interacting with staff and personnel on campus. A balance between directing the project and facilitating students' learning needs to be struck by the PIs.

Conflict Resolution - With SPI model, students are empowered to take decisions regarding their research direction, which sometime conflicts with what the facilitators or mentors have envisioned for the project. This creates situations where informal mediation is needed by the PIs. In carrying out the mediation, it is always useful to remember that we need to balance the need for mentor's buy in with students' ownership and ability to grow as researchers.

Challenges for the Mentors

The mentors are an essential part of any REU program and although their role takes the shape of facilitators in the SPI model, they remain essential to the success of the program. Our model for a perfect mentor is one who facilitates the students' decision making process regarding the direction of their research such that the student still feels ownership of the project at all times.

This style can be challenging with mentors following styles that deviate from the perfect model. Some mentors revert to the assistant model giving detailed instructions to the students and asking the student to follow these instructions contradicting the SPI model. Other mentors take an approach where too many options are presented to the students. This can overwhelm the students given the limited amount of time available in the summer to investigate all the options. Other mentors take complete hands off approach where the students do not have a facilitator to help guide them as they make decisions regarding changes in the research plan. This can give the students the feel that their research is not important to the mentor.

Thus, although mentors have to accept students' independence, they still need to show students that they are interested in what they are doing. They also still need to keep an eye on the progress of students and how they are adapting to the SPI model. Some students require more facilitation than others. So mentors have to dynamically adjust their level of intervention based on students' progress and adaptation.

Challenges for the Students

Fear Factor - Students participating for the first time in an REU program are usually anxious about the experience that awaits them over the summer and how will they will be able to meet expectations of the mentors and the program directors. The SPI model can amplify these fears, if the student anxiety is not handled properly. This is due to the fact that they are in charge of the design and direction of their summer research. Proper design of the first week's activities in which they see their peers going through the same experience have usually resulted in reduction in the anxiety. Most students over the past two summers have been able to come up with a satisfactory research plan that is acceptable to their mentors and PIs. The changes in the plan come in a more natural way as a result of consultation with the mentors.

Lack of Technical Preparation - Another challenge to the student is to find himself/herself unprepared to take charge of her research question due to being technically unprepared. However, identifying this problem early on can improve the outcome. Some of this can be done during the recruitment phase and while matching students with mentors. Students in previous sessions have shown that a combination of the right attitude and hard work can overcome that hurdle. An illustrative example is that of one of our students worked on a system identification problem of a dynamical system even though he had not had any formal courses in control systems. The student started by focusing on learning the relevant aspects of modeling of linear systems and the MATLAB Identification Toolbox over the first few weeks. His learning curve was impressive, with data collection and analysis of a real problem aiding that learning.

Peer Interactions - For many of the students another challenge arises through the SPI model in which they are possibly for the first time responsible for running a research project that may be interdependent on that of one or more of the other students. This interdependence raises sometimes interesting situations where students learn that their success is not only reliant on their own work, but on others' work as well. Another interesting situation could arise from competition for the attention and praise of a common mentor. This could be also one of the challenges for the mentors in balancing their attention to each of the new researchers looking for a proof of their success. This is similar to siblings' rivalry.

Advantages

This section summarizes what the PIs perceive as advantages of the SPI model for the REU. It does not delve into advantages of traditional REU programs which are discussed elsewhere.

Advantages for the Principal Investigators

Growth in Management Skills - The principal investigators are not only responsible for placement of the students within functional teams, but rather the creation of new functional teams that involves the student PI. This creates a real opportunity for the PIs to learn how to manage multiple independent teams, addressing all the challenges that arise and learning to create a positive technical and social environment in which these teams can function.

Opportunity to Test a Model of Research Training - The SPI model is to our knowledge not widely used and thus the PIs get the academic opportunity to test and compare the effectiveness of this nontraditional model to that of traditional REU models. A more quantitative approach to the measurement of the SPI model effectiveness is currently in progress.

Advantages for the Mentors

Time Saving - The mentors are consultants to the students who are acting as the PIs for their research questions. Thus, a partnership is created in which there is the potential for requiring less faculty time due to the student taking of the leadership role.

New Collaborators - There is also the potential for gaining technically from allowing the students to freely explore their ideas. Although the period of the summer is not enough to put together a complete solution to a problem, it is enough for proof of concepts that may lead to more advanced exploration by the mentors' teams.

Exploring Mentoring Strategies - The program also offers the mentors the chance of exploring SPI as a new mentoring strategy or style. If the style is successful it can be generalized to a form of active learning.

Advantages to the Students

The SPI model focuses its attention on providing students with growth opportunities at different fronts including both personal and technical.

Personal Growth

- Team skills: Students have to work in a team where their teachers are now consultants and graduate students and other REU participants are peers. This allows them to develop a sense of worth and learn not to just accept orders, but evaluate what the effect of these will be in their own research project.
- Time management: This is an essential skill needed under any of the models whether traditional or SPI. In the SPI model students learn to manage their own time and that available for them for consultation with their mentors.
- Project planning: As the project manager students have to learn to schedule lab and foundry time, order supplies, reschedule and change milestones dynamically as the project progresses throughout the semester. No longer would it be someone else's responsibility to get things ready, it is the student responsibility to make sure it happens using the proper channels and resources.

Technical Growth - In addition to the personal growth opportunity, the SPI model can be thought of as an active learning environment in which the student is motivated to prove his/her worth. Thus, they are more motivated to learn. Students are motivated to learn several new technical skills including:

- New analysis tools such as ANSYS for finite element analysis, PSPICE for electronic simulation packages, MATLAB toolboxes for dynamic system identification and simulation.
- Software Development: Students are often required by their research problem to learn new tools for software development such as NesC, C#, etc.
- Hardware Development: Hands on experience requires students to build and modify existing systems to address their research questions. These range from prototyping hardware circuits to modifying existing machinery adding sensors and actuators to get the job done.
- Multidisciplinary research: This is an aspect that may not be unique to SPI, but has always been part of the SPI model was created based on a Manufacturing theme. Students observe and sometimes interact with other students from different fields working on a complimentary problem. This multi-perspective view of the problem is beneficial to the students' understanding of research and real world problems.

Creativity - The students' creativity in an SPI model is usually more challenged than in a traditional framework due to the following:

- Open ended expectations: Students are not given a definite task. They define their task and often are motivated to go beyond that
- Troubleshooting problems: Problems occur and resources are available to help them overcome these problems, but they have to tap into these resources technical or personal to get these problems resolved.

- Finding alternative solutions due to short time frame: As the reality of the short time frame and the problems that arise along the way to challenge the original plans, students learn to find alternative solutions to cope with the challenges.

OPEN QUESTIONS

The authors have utilized the SPI model as an integral part of the REU program for 2 years. The model offers advantages to traditional approaches. However, many challenges also arise as the model is implemented. The following remain as questions that the PIs are striving to answer. These constitute the focus of our future work. We will be delving into motivation theory and student development models to help shape our exploration.

- What do you do when the SPI model doesn't work?
- What is the proper balance between mentors' or PIs' interest in the student's work and hands-off management approach of the SPI model?
- What is the minimum level of student development required to be successful in this model?
- When is it necessary to step in as a mentor monitoring student's progress or as a PI overseeing the mentors-students interaction?
- How to measure this model's effectiveness compared to traditional model?
- How to measure student progress from this model relative to traditional model?

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Mohamed Abdelrahman

Dr. Abdelrahman has a wide educational and research background. He obtained a Ph.D. in Nuclear Science and Engineering with focus on Reactors' control and an MS in Measurements and Controls Engineering from Idaho State University in 1994 and 1996, respectively. He obtained an MS degree in Engineering Physics and a BS degree in Electrical Engineering from Cairo University in 1988 and 1992, respectively. Dr. Abdelrahman has been the principal investigator on several major research projects involving intelligent sensing and control in industrial applications with over $4.0 millions in research budgets with funding from US DOE, NSF, ORNL, and the State of Tennessee. He has been a Fulbright scholar in 2007. Dr. Abdelrahman has co-authored with his students over 50 papers in refereed journals and conferences. As the principal investigator on an NSF funded REU program, Dr. Abdelrahman coordinated the research project and supervised mentor contacts with REU students. The program included 10 faculty mentors and 21 students.

Sally Pardue

Dr. Sally Pardue is dedicated to strengthening the educational process for engineering in equal measure to pursuing excellence in research. Her research in the use of vibration as a diagnostic and predictive tool for materials and structures has led her to serve as PI, co-PI and investigator on 10 projects regarding vibrations as an NDE tool. She has published 27 journal and conference papers. As co-PI on an active REU project for the past 2 years, she has coordinated the training of 21 undergraduate students through the program. Dr. Pardue is a member of the TTU STEM Center Executive Committee. Dr. Pardue has graduated 13 MS students, and 1 PhD student, is currently supervising 2 PhD students, and 1 MS student. She is a founder of the annual Engineering a Future (EaF) Event at TTU, a one day hands-on introduction for young women to explore careers and concepts in engineering. In the five years it has been offered, the program has been attended by over 740 young women in 5^{th} – 8^{th} grades.