AC 2009-977: DEVELOPMENT OF AN INTERDISCIPLINARY GRADUATE PROGRAM FOR AUTOMATION IN NUCLEAR APPLICATIONS

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Abstract

This paper outlines the motivation for – and development of – an interdisciplinary graduate level curriculum for robotics and automation in the nuclear domain. For cost, safety, and security purposes, the Department of Energy and nuclear related industries hope to automate mission critical tasks for handling and manufacturing sensitive materials from nuclear waste to weapon components to spent fuel. Design in this challenging domain requires an interdisciplinary expertise in nuclear engineering and flexible automation (robotics). Our experiences have shown that there is a shortage of interdisciplinary trained engineers in this area which has led to either 1) an inherent lack of cutting edge automation technologies in the nuclear domain or 2) an inability to precisely define the operational and environmental requirements for proposed automation systems. This paper outlines the generalized material and course requirements for an interdisciplinary graduate program from domain relevant application requirements as well as interactions with the DOE complex and industry. A course structure and timeline is outlined and mapped to the proposed curricula and project development. Students in the program are additionally mentored by DOE personnel to complete interdisciplinary research projects relevant in nuclear application areas.

Background and Motivation

The idea of automating the multitude of hazardous tasks associated with all phases of the nuclear fuel cycle (whether it be weaponized or energy producing) is not a new one. The positive impact of successful automation for safety and security is clear, yet the few successes have been costly and time consuming. A review (as examples, Y-12[1], LANL[2], INL[3], ORNL[4], SNL[5, 6], and Academia[7]) of the multitude of projects teaches an important lesson. Automation in the nuclear domain requires expertise in two diverse engineering fields: robotics and nuclear engineering. Consider the following challenges that will be difficult to meet in extremely hot environments without cutting edge automation.

- **Target fabrication of minor actinides for transmutation in advanced recycling reactors**. Due to radiation fields and radiotoxcity, fabrication must take place inside shielded, fully automated cells. The complex fuel pellet machinery will require the ability to be remotely maintained.
- **Generalized Radiochemistry.** To date, it has been impossible to fully characterize actinide elements as thoroughly as, for example, concrete, steel, and other stable elements. Even the simplest experiments must be performed behind shielding and processes must be strictly adhered to with full consideration given to fault contingencies. These experimental processes are expensive and often take years to design, verify, certify, and execute. Open, flexible experimentation allows for real-time procedural flexibility given new data or insight (even idle curiosity) from the experimenter.
- **Decommissioning and Decontamination**. D&D tasks are time consuming, hazardous and difficult to automate since processes are difficult to quantify ahead of time.

Previously deployed automation has been extremely conservative in its objectives in order to avoid failures that exacerbate the D&D task.
- **Routine Radiation Contamination Testing.** RCT tasks (routine surface testing, positive radiation sensor signal response, etc.) are at best repetitive and at worst placing additional humans in harm's way. Yet RCT is difficult to automate due to the changing environment and variation in response needed.

These example application areas all demonstrate a need for sophisticated and flexible automation in hazardous or potentially hazardous environments. Yet, the development of flexible automation in the nuclear domain has been outpaced by similar efforts in the military[8], medical[9] and space[10] domains. We stipulate (based on the lessons learned in part from the projects referenced above) that the fundamental obstacle to flexible automation in the nuclear domain is a lack of engineers with a nuclear background capable of fully understanding the complex requirements of deploying virtual *any* technology in high radiation environments. Our interdisciplinary program is motivated by the need to bridge this gap.

Program Objective and Overview

Our program ***objective is to develop future engineers and researchers with the requisite background and experience to bring advanced, flexible automation to the national-industrial nuclear complex***. To meet this objective, the university has developed a program with three key elements: (1) complete a highly customized interdisciplinary curricula (described below) (2) science-based research projects supervised by faculty members from the Nuclear Engineering (NE) and Mechanical, Systems and Design (MSD) departmental programs that address fundamental academic and scientific issues related to automation in high radiation environments, and (3) continually collaborate with a mentor at a national lab and complete summer internships in a relevant application area.

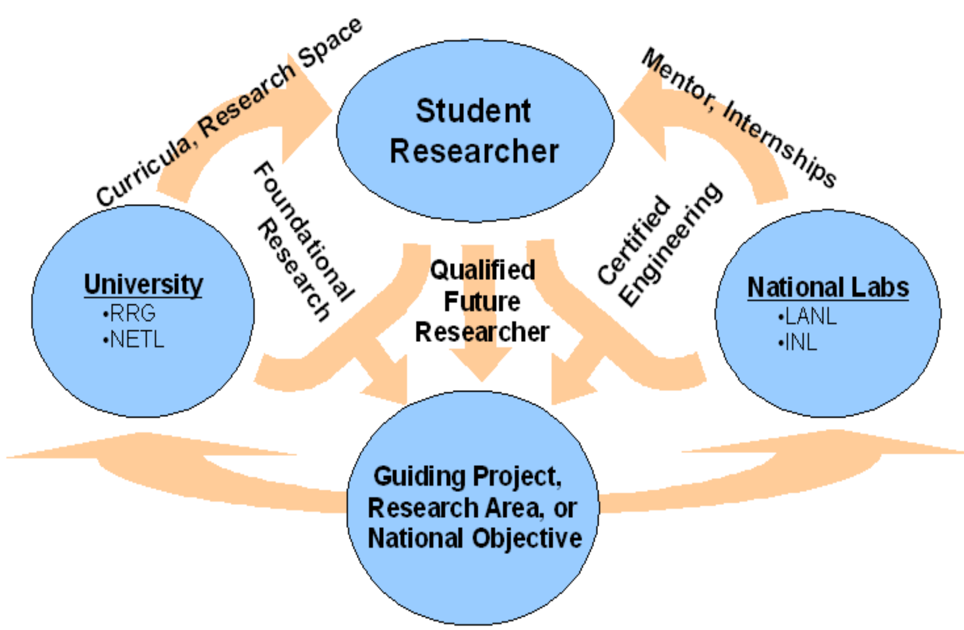

Figure 1: Program Overview and Member Contributions

These three elements are highly coupled as illustrated in Figure 1. The application area identified and agreed to by university faculty and researchers at the national labs will ideally motivate academic research beyond system design. Thus academic supervisors at the university must find the correct balance between relevance to a short term national lab need and its own high standards of research. Conversely, students and mentors must work together to successfully transfer promising research into the lab via detailed design, testing and certification during their collaborative periods.

Students (more importantly, future researchers) become the conduit of knowledge and experience between the two institutions. Potential antagonism between the objectives of the university and national lab are acknowledged and addressed when the application area is first identified. Critical to the success of the collaboration is domain specific knowledge imparted by the highly customized interdisciplinary course curricula discussed below. By developing a working knowledge in both automation and nuclear science, the student is in a better position to understand the complete spectrum of requirements associated with developing mechanical systems in high radiation environments.

The implementation of numerous interdisciplinary programs is documented in the literature. Several are of particular interest here as they also address issues that may arise when collaborative partners have slightly different expectations. Edwards and Lee[11] devised a similar program related to advanced control techniques for improved power distribution from U.S. power plants. They utilized previous funding and equipment grants to formalize a curricula around the captured knowledge. Akbar and Dutta[12] address the balance that must be found between research and education that is complicated by the inclusion of both government and industrial labs. They conclude there is a "synergistic benefit of such an approach and reinforce a prevalent belief that innovation in research can help enrich education." Finally Newberry[13] developed a missile system design graduate curriculum that strove to balance scientific development and robust design. He emphasized that "Design and judgment are the essence of engineering; they are the primary factors that differentiate engineering from science." This is a lesson that should not be forgotten even as we work hard to advance our scientific knowledge in radiochemistry and other high radiation research areas.

Curricula Development

Although this curricula is designed for students who have completed an undergraduate degree in Mechanical Engineering, only slight modification in the mandatory courses are necessary for students with nuclear engineering or other science-based degrees. For example, we are successfully progressing a student whose undergraduate degree is in physics through the program. The Masters Program is divided into three course areas: Prerequisite, Mandatory and Specialization Courses shown in Figure 2.

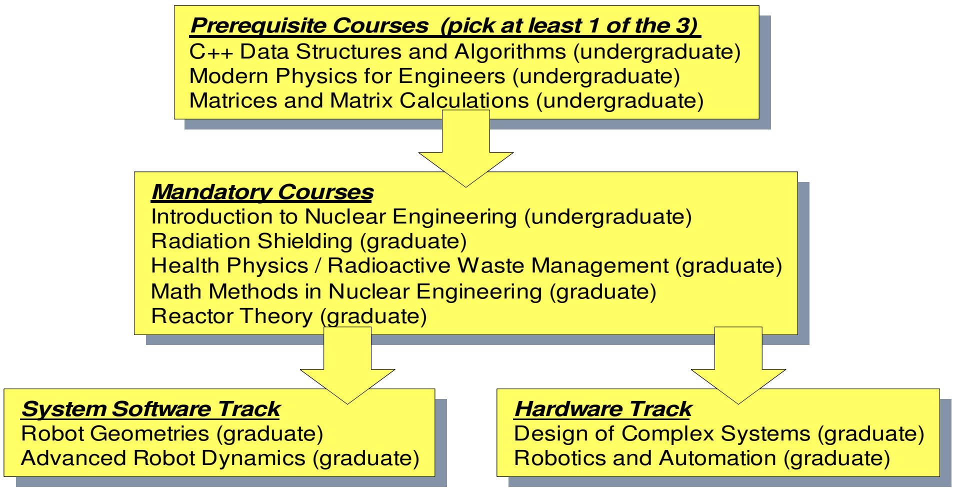

Figure 2: Masters Level Curricula (30 total hours including 6 hours for MS thesis.)

Most undergraduates complete their degree with some but not all of the prerequisite courses identified above. If necessary, more than one course may be taken or other courses may be identified depending on the student's background. All the mandatory courses are necessary to complete the degree. Fundamental to the success of these researchers will be the confidence their future employers or sponsors have in their ability to work in the nuclear domain. This full complement of challenging courses at the graduate level will fully prepare students for the challenges that lay ahead. Finally, the flexible automation component of the curricula is divided into two tracks. The system software track will focus on the flexible control and operation of the robotic systems. Emphasis is on learning the fundamentals of system design and operational algorithms that are generalized, flexible and fault-tolerant. The second specialized Hardware Track focuses on the design, testing and operation of the individual components (actuators, sensors, tooling, etc.) that are the fundamental building blocks of the robotic systems. Emphasis is on performance, survivability, maintainability, and domain-specific testing.

Note, that although the course areas are illustrated sequentially, they are in fact completed in parallel allowing students to integrate their interdisciplinary experience early in their graduate research. An estimated 6 additional course are needed at the PhD level with the emphasis trending towards automation.

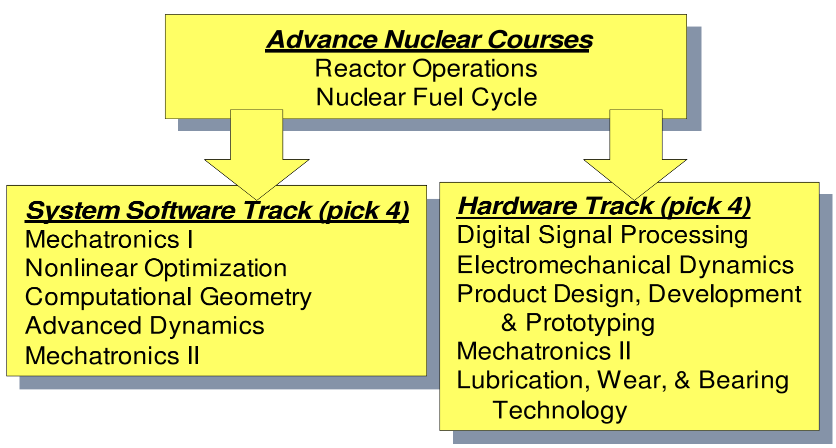

Figure 3: PhD Curricula (estimated 6 additional courses)

Coordinated Workforce Development Component

Critical to the success of the program is the continual feedback and confirmed relevance of efforts to meet the current and future needs of government and industrial nuclear partners. To ensure our success, university faculty recruit a mentor from the national lab for each student in the program. An *ideal* interaction timeline for a PhD student is shown in Figure 4.

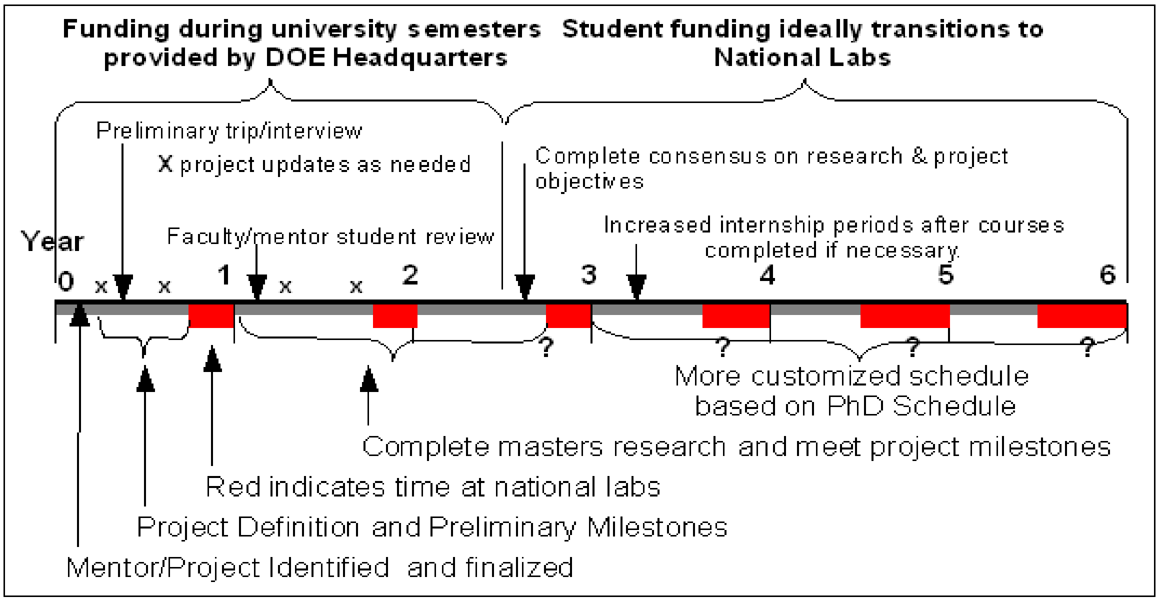

Figure 4: Possible student program progression. (assumes September start date)

Of course this interaction is ideal and is subject to a number of intangibles including available funding, workforce needs, project success, and obviously a positive outlook on the job and employee prospects from both the student and national lab respectively. Any successful program must be flexible to changing conditions even as we make efforts to successfully adhere to the ideal timeline. The key benefits for the proposed timeline are:

- **Early coordination between university and lab** leading to more relevant research topics and understanding student expectations.
- **Students hit the ground running** when they arrive at the lab since preliminary milestones negotiated with the mentor have already been completed.
- **Detailed engineering is done at the labs and not the university** where certifications for use in critical processes cannot be fully addressed.
- **University research is embedded in solutions** and is not itself the sole deliverable. Researchers at national labs often acknowledge the value of the university research, but do not have the short-term resources to implement it.
- **Early opportunities to recruit and perform security checks on potential employers.** Student-workers provide the labs with the opportunity to began the tedious process of performing a background check on potential employers prior to investing in a full-time position.

- **Labs provided with more information regarding the project and researcher when considering long term funding options**. In the scenario described in Figure 5, the ideal student/project may be funded by the National Lab at a level analogous to a full-time employee as they finish their degree and background checks are performed, allowing more flexibility in terms of scheduling and direction of research.

Ideally, the mentor (assuming he is qualified in terms of university policy) may participate more directly in the student's research as a member of their dissertation committee, which helps alleviate any potential antagonism that may exist between university standards and the national lab's needs.

Case Study: Chamber Decontamination Automation with Advanced Safety Features.

To exemplify the complementary nature of the research done at the University and project work completed at LANL, this section quickly discusses the accomplishments of the first student to enter the program. Note, the curricula component of the program was not in place during his first year at the university so here we focus on the workforce development aspect of the program.

Figure 5: Spherical Decontamination Vessel, Robotic Hardware and Simulation[2]

The research component of this effort focused on using a 7DOF (redundant) robotic arm to clean legacy spherical containment vessels quickly and efficiently while exposing operators to lower dose. Since it is not known what is in each sphere, the decommissioning process must be flexible. Research already completed at the sponsoring university is capable of controlling the redundant system and ensuring the arm does not collide with the inside of the cylinder. Certification of both the commercially procured hardware and university developed software is essential and the performance benefits over existing control methods is expected to be substantial but needs to be internally documented. Also note in Figure 5 there is the potential for an operator to interact with the robot inside the sphere to either change tools or provide support with a hand-held tool. From a university perspective, this project provides an excellent opportunity to deploy mature technologies developed at the university that need additional testing from a national lab perspective.

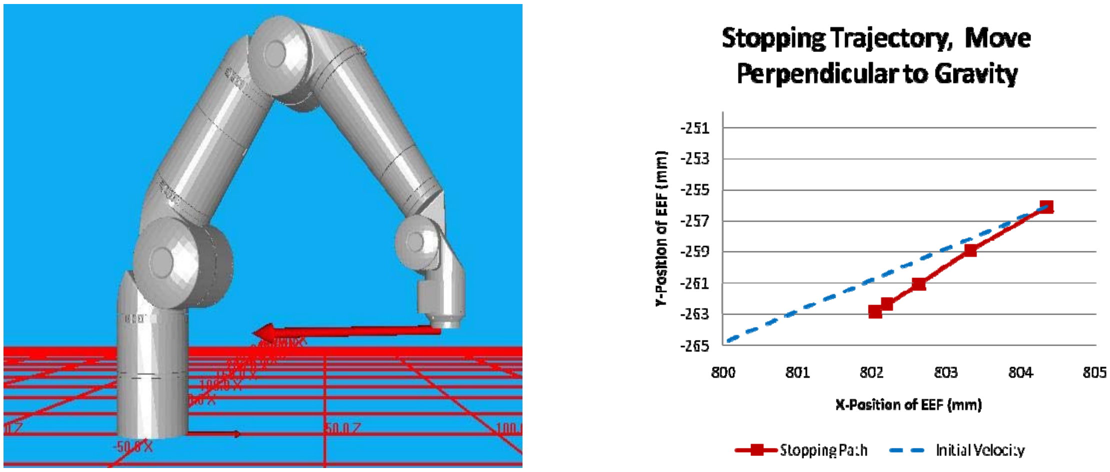

Figure 6: Stopping Dynamic of Robotic Manipulators

Looking ahead from a research perspective, we see this task as further evidence of the growing collaboration between robotic and human devices and move the research in that direction while complementing the existing project. Robotic devices can be quickly stopped using a few different strategies: without tool trajectory deviation, full deceleration on all joints, immediate power down with joint brakes applied, or some inferred retraction from the offending move. In each case the robot's joints and tool will come to stop in a different configuration and elapsed time.

If compliant robot devices are to be used in tight spaces, understanding these differences may help prevent damage or injury and further illustrate the relevance of integrating university research into engineering solutions.

Conclusions

This paper reviews interdisciplinary nuclear and automation program implemented as shown in Figure 1. One pilot student has completed the workforce development program as a Masters student with two working semesters at LANL. Three PhD students are currently completing their second semester of course work. Both lab and research projects have been organized for each student and the feedback from the National Labs is preliminary but very positive, including demand for additional students.

Most importantly, this program fulfills the higher level objectives of each participant.

- **Student Researcher –** It provides year-round funding to perform relevant research while exploring the opportunities in both academia and the research laboratories.
- **National Laboratories** – Summer student workers arrive prepared to contribute since project work begins in the university and is guided by laboratory engineers. They additionally gain exposure to cutting edge research at the university while directly supervising its transition into the labs. Detailed engineering work is completed under their control.

- **DOE** – As the primary funding source for student salaries during school semesters, they have a documented return on their investment in terms of providing both the workforce of the future and deployed technology.

As stated earlier a number of intangibles including funding, workforce needs, project success, and obviously a positive outlook on the job and employee prospects from both the student and national lab are relatively unknown and often uncontrollable variables impacting the long-term success of the program. To address these issues, communications lines must remain open and new relationships in the DOE complex must continually be fostered. Early setbacks must translate into adjustments and not cancellations if our overall mission is to modernize, not only our nuclear weapons, waste, and fuel complex, but our workforce to maintain it as well.

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