ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #47505

# Engaging End-Users, Reconceptualizing Research Plans: Graduate Research Training in Translational Engineering

**Milica Miladinovic, Worcester Polytechnic Institute**

Milica Miladinovic is a PhD candidate in Mechanical and Materials Engineering at Worcester Polytechnic Institute (WPI), currently working as a Research Assistant in Professor Pratap Rao's lab. She holds a BS and MS in Mechanical Engineering from the Faculty of Mechanical Engineering at the University of Belgrade (Serbia). Her research focuses on wearable, flexible, and stretchable printed electronics and sensors. She is particularly interested in convergence research and translational engineering, with an emphasis on creating real-world impact from academic work. The NSF-funded National Research Traineeship (NRT) "Future of Robots in the Workplace" (FORW-RD) Fellowship has provided her with the opportunity to explore these interests more deeply through hands-on experience in designing and leading convergence research projects.

**Ceren Yilmaz Akkaya, Worcester Polytechnic Institute**

Dr. Yilmaz Akkaya is a postdoctoral researcher in Nanoenergy Group under the Department of Mechanical and Materials Engineering at the Worcester Polytechnic Institute (WPI). She holds BS degrees in Chemistry and Molecular Biology and Genetics from Bogazici University. She completed her Master's and PhD Degrees in Materials Science and Engineering at Koc University. Her research focuses on improving people's lives by providing solutions to environmental and medical problems, and promoting diversity and equity in higher education.

**Dr. Yunus Doğan Telliel, Worcester Polytechnic Institute**

Yunus Doğan Telliel is an Assistant Professor of Anthropology at Worcester Polytechnic Institute. He is in the Humanities and Arts department and has collaborative faculty appointments in the Interactive Media and Game Development program and the Robotics Engineering department.

**Prof. Pratap Mahesh Rao, Worcester Polytechnic Institute**

Pratap Rao is an Associate Professor in the Department of Mechanical and Materials Engineering at the Worcester Polytechnic Institute (WPI). He received his BS in 2007 from WPI and his PhD in 2013 from Stanford University. He has co-authored over 50 peer-reviewed articles that have appeared in Advanced Energy Materials, Nano Letters, Flexible and Printed Electronics, and other journals, and have collectively been cited over 4,000 times. His work on printed flexible and stretchable electronics has been funded by the U.S. Department of Defense through the NextFlex Manufacturing USA Institute and the SEMI-FlexTech program; and by the Commonwealth of MA through the Massachusetts Manufacturing Innovation Initiative. His work on photo-catalytic materials for water treatment and clean hydrogen production has been funded by the U.S. National Science Foundation, the Massachusetts Clean Energy Center, and the U.S. Army DEVCOM Soldier Center. At WPI, he is a recipient of the Harold L. Jurist '61 and Heather E. Jurist Dean's Associate Professorship and the James Nichols Heald Research Award.

# Engaging End-Users, Reconceptualizing Research Plans: Graduate Research Training in Translational Engineering

Milica Miladinovic, Ceren Yilmaz Akkaya, Yunus Doğan Telliel, Pratap M. Rao

Worcester Polytechnic Institute

**Abstract**

Significant time, effort and resources are invested into graduate engineering education and research. However, despite existing programs that bridge university research and the real world, there is a lack of deep training of PhD students in the skill of creating value through their research. We propose a new scalable framework, Graduate Translational Engineering Research, that gives PhD students the opportunity to train deeply in the process of value creation by incorporating an interdisciplinary PhD thesis committee and qualitative end-user study methods in the formulation of their PhD research proposal. The proposed framework involves PhD students conducting end-user studies early in their program to gain insights into the needs and challenges associated with the knowledge or technology they are developing. The purpose of this study is to understand the effect of assessing real end-user needs on the development of the engineering PhD research proposal through a case study. The hypothesis is that an understanding of the end users' needs in the early stages of research formulation will enable PhD students to devise research proposals that are more focused on creating value by addressing the problems that are important and relevant to the end-users, and will improve the ability of the PhD students to communicate their plans and results to non-expert end-users. In this case study the PhD student prepared an initial research proposal before conducting any end-user studies, and then conducted an end-user study through face-to-face interviews, under the guidance of an interdisciplinary committee consisting of both engineering and social science faculty. The questions focused on the needs, features, performance metrics and barriers to adoption of the specific technology being developed by the student. The responses were thematically coded to identify the most important factors from the end-user perspective. Incorporating insights from this end-user study, the student reconceptualized their PhD research proposal in consultation with the faculty advisors. The reconceptualized proposal demonstrated a clear structure, actionable steps, and focus on user feedback, effectively addressing key challenges and practical applications, unlike the original, which lacked specificity and a clear plan. In addition, a workshop was conducted with a group of STEM graduate students to obtain additional student perspectives on this approach and gauge its wider applicability. This interdisciplinary Graduate Translational Engineering Research approach provides an example of using social science research methods in the early stages of graduate engineering research to enhance both graduate research and training in value creation through research.

*Keywords: Technology transition, translation engineering, value creation, adaptation of technology, lab to market transition, graduate engineering research, research proposal, user research, workshop*

## 1. Introduction

Today, embracing science, technology, engineering and innovation is considered an important strategy for socioeconomic growth and well-being around the world [1], [2], [3], [4]. In this context, STEM doctoral education plays a crucial role in sustainable socioeconomic growth as it prepares the next generation of technical knowledge creators who will create value through solving the most pressing problems of tomorrow as well as the next generation of educators who will train subsequent generations of researchers and technical leaders. However, enabling increasing innovation, job creation, societal impact, competitiveness, and economic prosperity requires the training of entrepreneurs that have the skills to transfer innovative technologies from labs to markets [5]. This translation of inventions and discoveries into innovations into the real world via commercialization is achieved through value creation strategies. However, one of the challenges in STEM graduate education and research is how to embed value creation into graduate research at a deep level.

Under the traditional paradigm of doctoral STEM education, doctoral students are mainly set up to be subject area experts with contributions to scientific literature through publications of their technical research in peer-reviewed journals and in their dissertations. Graduate training based on this desired outcome is adequate to prepare PhD holders to meet initial career expectations and for sustainable university research output. However, with the changing economic and academic landscape it has become harder for PhD holders to secure stable professional academic positions [6]. Hence, most of the recent transformation in doctoral STEM education, including the creation of professional, industry, and collaborative PhD programs, has been focused on preparing doctoral students for industrial positions post-graduation (both in research and non-research related fields) [7]. To enhance the employability of PhD holders outside of academia [7], many programs implemented seminars, courses, and training for developing 'soft skills' (e.g., communication, teamwork, problem solving, critical and innovative thinking, creativity, self-confidence, ethical understanding, capacity of lifelong learning, the ability to cope with uncertainty [8]). While these interventions provide graduates of such PhD programs with certain transferable skills, they fall short of deeply training the students in the skill of creating value through their research.

The current operational paradigm in graduate research, and particularly doctoral (PhD) research in engineering, is based on a structured training model that encompasses the following key milestones: i) course-based training on conceptual and methodological knowledge in specific fields, ii) comprehensive subject matter exams, (iii) identification of a dissertation advisor and appointment of a dissertation committee, (iv) formulation of a PhD research proposal, (v) defense and confirmation of this developed research proposal, (vi) supervised research culminating in the publication of peer reviewed journal papers and a dissertation, and (vii) defense of the dissertation [7], [9]. While this operational paradigm provides doctoral students with the technical knowledge and skills to create research output, there is no inherent pathway in this structure to provide students with skills to identify research topics that create additional socio-economic value. Some PhD students are supported as research assistants within an existing grant-funded project and mostly work on fulfilling the established objectives of that project. Other students, who are supported as fellows or teaching assistants, might be given more freedom to select their research topic. However, it is typically assumed that the research area of the PhD advisor is inherently valuable, and the PhD student operates as if the PhD advisor is the end user of the research. Students typically go through the exercise of reviewing existing literature, which serves to gauge the academic value of the proposed research. However, students are not always required to go through an independent activity on creating additional socio-economic value through their research or evaluating the broader impacts of their research. Therefore, the current STEM doctoral education model needs to be revised to deeply embed broader value creation into the formulation of the PhD students' research proposal.

Value creation is the process of identifying the stakeholder needs and then developing, implementing, and evolving solutions that meet an unmet societal or market need [10]. In this context, we are defining **creating value through research** to involve 1) identifying the users of the knowledge or technology to be created by that research, 2) using qualitative research methods to determine what is valuable for targeted end users, 3) communicating the technical scope of the research to the end users that are potentially outside of the field, 4) helping stakeholders and end users how the created knowledge and technology can be useful to meet their needs, and 5) understanding how to translate user needs into the specific objectives or questions that will be addressed through graduate research (Fig. 1).

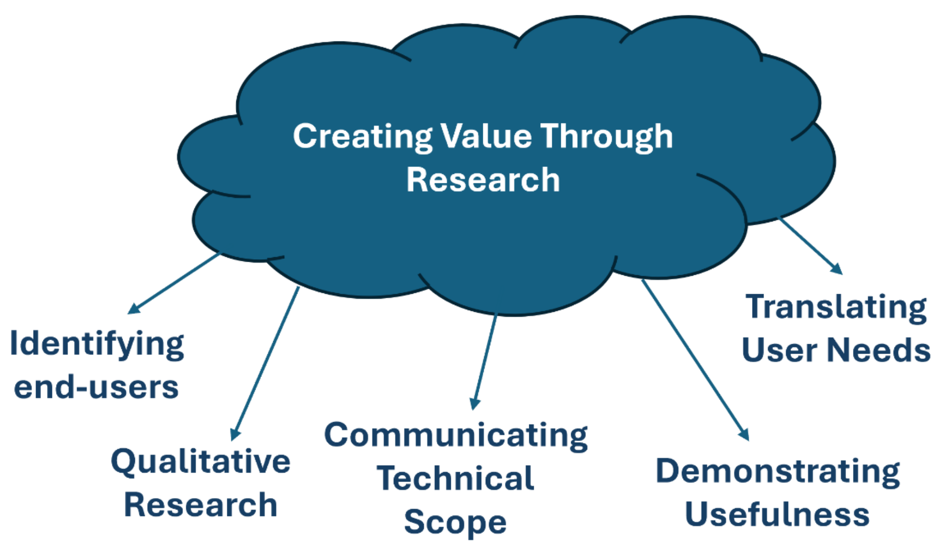


**Figure 1.** Value creation

Various programs have been developed and integrated in doctoral education to promote commercialization of academic research including entrepreneurship education courses/programs, incubator facilities, and projects that link the university with regional businesses [5], [9], [11]

[12], [13], [14], [15], [16], [17]. Although some of these programs have been widespread and very successful, there are financial and administrative challenges to create sustainable, accessible education opportunities, especially in the early stages of PhD research. Some of the programs require external funding based on eligible business ideas with a high technology readiness level, which makes them inaccessible to a large group of doctoral students at the early stages of their program. Programs with industry partners might not be sustainable as the current financial model of private corporations does not align with the long-term time commitments that doctoral research might take. Course-based implementations have more potential to become widely accessible with a lower investment requirement by academic institutions. However, impactful entrepreneurial education programs might require dedicated teaching teams since most of these courses are designed to include seminars and workshops taught by academic and industry experts from varying fields. Moreover, most of the course-based approaches, though effective in improving entrepreneurial mindset and readiness, are not sufficient to enhance commercialization of university research - that is, the transfer of knowledge and technology from lab to market. Even though there are some established positive outcomes (as described in Section 1.1.), they are discussed to be indirect impacts of those educational programs [18]. In addition, project work assignments in the courses are often not directly related to doctoral students' technical research. Hence, even though there are many programs for technology translation, creation of value for end users is not usually considered in the PhD research formulation stage.

In this paper, we propose an accessible and scalable 'Graduate Research Training in Translational Engineering' model in which socio-economic value creation is blended into STEM doctoral research. In this model, doctoral students conduct qualitative end-user studies in the specific area of their technical research with the support of an interdisciplinary dissertation committee. We discuss the effect of assessing real end-user needs on the development of the PhD research proposal in engineering within a case study. Our hypothesis is that a more thorough understanding of the end user's needs in the early stages of research formulation will enable academic engineering researchers (both PhD students and their faculty advisors) to devise research proposals that are more focused on solving the problems that are most important and relevant to the end-users, and will also help the researchers to communicate their plans and results to the end-users in a manner that would increase the likelihood of adoption. This interdisciplinary approach provides an accessible, scalable example of using qualitative research methods in the early stages of graduate engineering research to enhance both graduate research and training in value creation, as well as the translation of technology to real-world use.

### 1.1 Overview of Existing Programs

Developed programs to promote innovation and entrepreneurship at the doctoral level can be categorized into three domains:1) training and research proposal formulation within the PhD Program, 2) technology translation and commercialization programs, and 3) hybrid programs.

*Training and research proposal formulation within the PhD Program*

Although Entrepreneurship Education (EE) has been a part of undergraduate STEM education for some time, educational activities at the doctoral level are relatively recent. The most common activity is the introduction of an EE course [19], which includes workshops on various entrepreneurial topics and on new business development [4], [15], [18]. One iteration was the Entrepreneurship in Theory and Practice (ETP) course, providing practical training in developing and presenting venture ideas, collaborating across disciplines, and understanding the commercialization process. In ETP, students were then asked to develop their 'own ideas', which resulted in proposals for new spin-off firms, formulation of new research projects, or new methods for analyzing research data [14]. Learners then vote on the ideas they are most interested in and work on those in interdisciplinary groups. Since the ETP course was introduced in 2006, 20 new firms have been founded where a PhD student who has taken the course played a central role in establishing a company. More recently, a business management orientation was added to a STEM PhD program to equip doctoral students with transdisciplinary competencies in addition to their domain specific knowledge to assist with navigating the innovation management and commercialization processes [16]. This course aimed to create 'T-shape' professionals who have both deep expertise in their main discipline (vertical dimension; as represented with the vertical stroke of the T) and transdisciplinary knowledge and necessary skills for collaborating across disciplines and domains (horizontal dimension; as represented with the horizontal stroke of the T). Integrating business management orientation into a PhD program built on a T-shape approach was shown to improve PhD students' managerial skills, entrepreneurial readiness, and their self-awareness on entrepreneurial capabilities. Participants of the initial pilot were selected among third- and last-year PhD students that are 'business addicted with ongoing research activities on business venturing'. Although these course-based programs were practically oriented and successfully developed entrepreneurial skills, they were either based on case studies and independent reading or on teaching business management skills for later stage PhD students with already-established research plans. Hence, these programs do not provide for the students to practice value creation through their own PhD research.

*Technology translation and commercialization programs*

Some of the developed programs are dedicated to supporting incubators and development of new technology-based companies in the form of university spin-offs with varying degrees of mentorship and administrative support (such as protecting intellectual property, navigating licensing agreements, and connecting with potential licensees or investors) [20]. These programs provide structured training, facilities to reduce overhead costs, professional business coaching, and network building to guide PhD students to refine their existing business ideas and develop their ventures. Recognizing the importance of collaborations between PhD students and industry partners to facilitate translation of research from lab to market, programs that encourage an additional 'industry' supervisor or sponsor 'mobility placements' of doctoral students to do research in industry were developed [13]. In the US, a large-scale, nationwide entrepreneurship training program, the Innovation Corps (I-Corps), was introduced by the National Science Foundation (NSF) in 2011 (pilot) to advance commercialization of federally funded research outcomes and assist STEM graduate students to become next generation of innovators and entrepreneurs, such as [21]. Formally launched in 2012, the NSF I-Corps is a highly structured program with 6-8 weeks of immersive training after which researchers are required (and funded) to interview at least 100 potential customers to gather sufficient market data to validate assumptions about their potential business models [21], [22]. The program is built on an Innovation Network Model connecting multiple universities and industrial partners across regional hubs. The success of the program led to NSF partnerships with other US federal agencies to create specific adaptations of I-Corps, including the National Institutes of Health (NIH), Department of Energy, Department of Defense, and U.S. Department of Agriculture [2], [23]. Although this program has been successful with nearly half of the participant teams launching start-ups, it is more focused on faculty members as long-term change agents [2] and on transitioning existing technologies to the marketplace, rather than facilitating early consideration of value creation in the students' PhD research proposal itself. This means that it tends to cater to a fraction of PhD students who are working on research topics or technologies that are closer to maturity.

*Hybrid programs*

Recently, programs that transform the current doctoral education structure with integrated support in technology transfer have been introduced. One such initiative is the Pathways to Entrepreneurship (PAtENT) Program [24]. Based on a student-centered philosophical paradigm, the PAtENT Program provides an alternative PhD model where students may choose to develop patentable technology and submit a peer-reviewed patent application instead of a dissertation. Students in the PAtENT pathway are supported by management courses and training boot camps within their doctoral program requirements. The decision to enroll in the PAtENT pathway is made in consultation with students' dissertation committee, and students can pursue the entrepreneurial career track without additional academic load or time-to-degree. Another recently introduced innovative student-centric STEM doctoral education model is the Pasteur Partners PhD (P3) track, which is based on use inspired research [17]. The P3 program follows the current structured education model (Fig. 2) with the following additional features: i) an optional pre-program summer internship; ii) inclusion of industry researchers as co-advisors; iii) courses that teach professional skills; and iv) a residency at an industrial partner site to complete a significant part of the dissertation research. However, engagement of university administration, buy-in and large time investment from faculty, development of industrial connections, and continuous long-term financial dedication from industrial partners are needed for P3 program. Establishing the

PAtENT program might be more accessible, though it is assumed that students will be working on faculty members' research projects that show promise to be patentable or closer to commercialization. Therefore, these programs require a challenging re-design of PhD education and multiple stakeholders actively working to build the new structure, and/or a research topic that is close to commercialization, which might not be an option for all students and academic institutions.

### 2.1 Proposed Graduate Research Training in Translational Engineering Framework

The proposed Graduate Research Training in Translational Engineering program is envisioned to be a flexible, low-barrier educational model that simultaneously enhances the value creation skills of PhD students (or more broadly any graduate students performing thesis-based research) and commercialization of university research. The framework is based on a culture change in academia within the existing committee-level advising of engineering PhD students in their research rather than re-structuring the broader doctoral programs. Modifications to the current training structure at the appointment of a dissertation committee stage and the PhD research formulation stage are proposed, which do not compromise the technical rigor or the original intent of the doctoral STEM programs (Fig. 2).

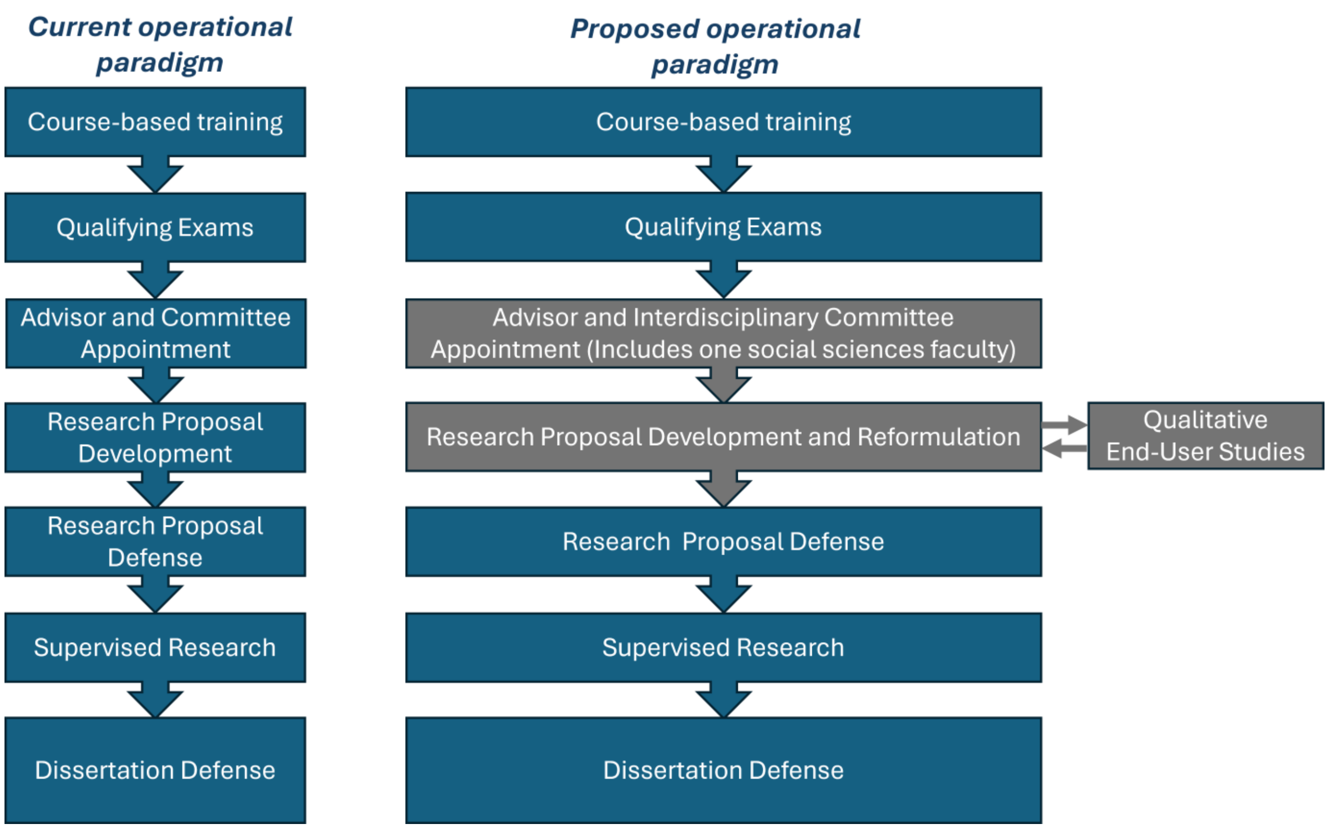


**Figure 2.** Current and proposed operational paradigm

Within this framework, doctoral students do not need to be enrolled in additional courses to fulfill their degree requirements, instead they perform an independent inquiry into value creation through their technical research itself. As doctoral students work on developing their PhD research proposals, they identify potential end users of the knowledge and/or technology that will be created by their research. Supported by an interdisciplinary PhD dissertation committee that includes at least one faculty advisor with background in social sciences, they then use qualitative research techniques (such as conducting interviews) to understand the current unmet needs of the selected end user group and communicate how their research would be beneficial to them. The analysis of the collected information regarding user needs will inform the formulation (and iterative re-formulation, if necessary) of their PhD research proposal.

The proposed framework is a scalable and widely accessible education model since it can be implemented at the individual committee level without other resources. However, this process is ideally embedded within a graduate program that provides 1) course-based training (as part of the usual course load of the PhD program) in user experience research and ethics, and 2) seminars and workshops on interdisciplinarity and convergence as well as professional development on soft skills, networking, and exposure to a range of career opportunities believe this 'end user-inspired PhD research' can act as a vehicle for intentional value co-creation and a potential catalyst for technology transfer.

### 2.2 Objectives of the Study

The objectives of the present study are:

I) to generate data to evaluate the proposed "Graduate Research Training in Translational Engineering" framework through a case study —the PhD research of a particular student who completed a qualitative user study and conducted interviews, and then reconceptualized their PhD research proposal.
II) to evaluate additional student perspectives on how the "Graduate Research Training in Translational Engineering" framework can apply to PhD research through a workshop involving additional graduate students.

### 2.3 Institutional Context

This study was conducted at Worcester Polytechnic Institute—a medium-size private US university that values applied and interdisciplinary education and research and has invested in value creation training and commercialization programs. Furthermore, the study was conducted within an NSF-funded National Research Traineeship (NRT) 'Future of Robots in the Workplace' (FORW-RD) program that combines research training in engineering sciences and social sciences towards a specific societal need. The NRT FORW-RD program includes coursework in applied ethics and end-user studies in addition to discipline-specific engineering courses, seminars on interdisciplinary and convergent research, and professional development workshops.

Two of the authors (Rao is an engineer, and Telliel is an anthropologist) are in the principal investigator team of the NRT program. Rao is the PhD student's primary dissertation advisor, while Telliel is a member of the PhD student's dissertation committee.

### 2.4 Study methodology

The PhD student prepared a comprehensive research proposal before conducting the end-user studies. In August 2024, the end users were identified by narrowing down the application for specific technology, as explained in Section 3.2. During September and October 2024, the student conducted user studies by gathering input from end users through face-to-face interviews. The interview questions focused on the needs, features, performance metrics, and barriers to adoption of a technology that the PhD student's research was contributing to. Interviews were conducted with five surgeons, who have expertise in laparoscopy, abdominal surgery, colorectal surgery, head and neck cancer surgery and robotic surgeries. A detailed methodology is provided in Appendix A. The interview responses were thematically coded to identify the most important factors from the end-users' perspectives. Incorporating insights from these studies, the student reconceptualized the PhD research plan in consultation with faculty advisors. Both the original and reconceptualized PhD proposals can be found in Appendix B. Additionally, in December 2024 a workshop was conducted with eight STEM graduate students to assess their needs, interests, and perceptions regarding the inclusion of user studies in their PhD research. Also, the PhD students were asked to evaluate whether the interview feedback was properly incorporated into the reconceptualized proposal. All participants were PhD students from the Robotics Engineering, Mechanical Engineering, and Computer Science programs at the same institution. A detailed methodology of the workshop is provided in Appendix A. The workshop aimed to explore how end-user studies could be generalized in STEM graduate education as a tool for translating lab-based research into real-world applications.

## 3. Reconceptualizing PhD Research Proposal - A Case Study

### 3.1 The student's PhD research field and topic

The student pursues their PhD in Mechanical Engineering within a Mechanical and Materials Engineering department. Their research is conducted in the lab led by a PI specializing in printed electronics and sensors. Specifically, the student's research focuses on the fabrication and performance of a specific type of stretchable sensor material. This material can be integrated into a motion capture glove technology that tracks the movements and positions of the user's arms, hands, and fingers. The tracking capability is used to control the movements of a surgical robot performing robotic surgery on a patient. Additionally, the glove provides force feedback from the robot to the user's finger knuckles using the pneumatic haptic muscles (Fig. 3-b). Compared to current methods, this device feels more intuitive. Unlike bulky wearable devices, it resembles wearing a thin glove, thanks to its integration of stretchable sensors and electronics that are printed. Figure 3 represents the first prototype of the motion capture glove (Fig. 3-a), and the overall motion capture glove system (Fig. 3-b). The overall idea is to enable a user to conduct a robotic procedure (either in the same room or remotely) through wearing a motion capture glove that controls a remote robot operating on a patient.

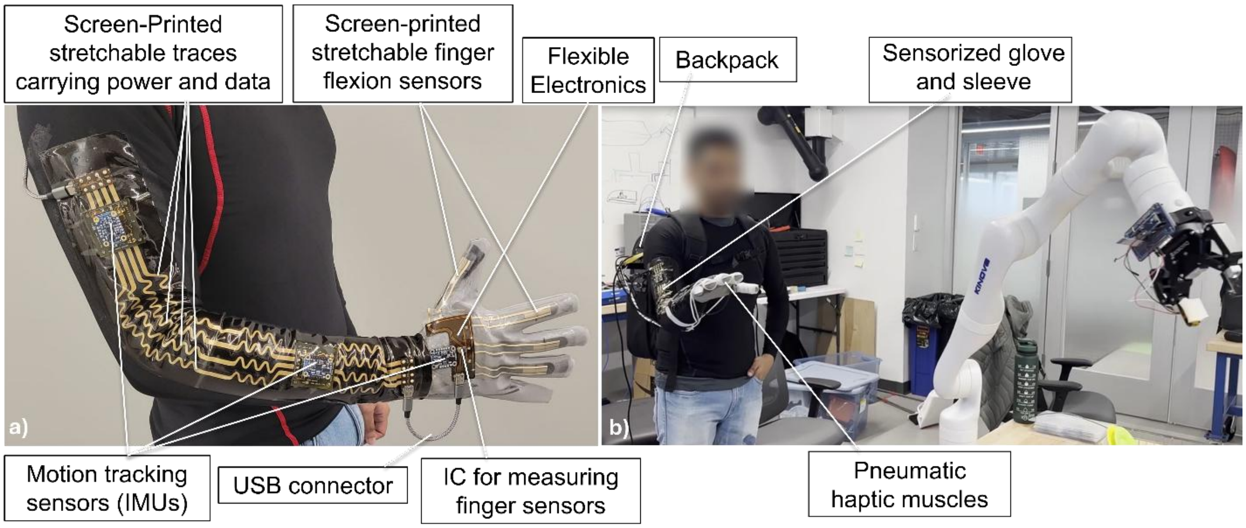


**Figure 3**. Soft Robotic Glove and Sleeve Human Machine Interface (HMI).

### 3.2. The identification of the end users

The original research proposal did not focus on the motion capture glove technology. Instead, it was centered on integrating the specific type of stretchable sensor material into a broad set of application areas such as biomechanics, prosthetics, and sports. While these applications demonstrated the technology's versatility, they were speculative and lacked clear direction. To create value, the specific application focus of the research was narrowed down through discussions with fellow researchers who have expertise in robotic-assisted surgery research. These researchers collaborate with a nearby large medical teaching hospital, as well as the university's testing facility that provides research and development resources for accelerating the release of new healthcare technologies. The combination of interest in robotic-assisted surgery research, access to key collaborators, and advanced testing resources led to the primary application for the specific sensor: its use in remotely controlled motion capture glove technology for telesurgeries, operated by surgeons. All these individual factors led to the primary application for the specific sensor: its use in remotely controlled motion capture glove technology for telesurgeries, operated by surgeons. This laid the groundwork for a smoother translation of the technology from lab to market in the future.

### 3.3. The interview data

Originally, the motion capture glove technology was conceived as a tool to enable surgeons to perform telesurgery by controlling a remote robot operating on a patient. However, based on their vast experience, interviewees expressed general concerns about this technology such as:

- Safety concerns
- No real economic model or major market
- Medical-legal issues

Because of these concerns interviewees proposed more specific applications, including robotic surgery in the same room (by integrating the glove system into the existing Da Vinci operating system), disaster response, and more (Table I). These applications demonstrate how the sensor's high stretchability and sensitivity can meet critical societal needs.

**Table I:** User study insights

| ***Applications*** | ***Current System Challenges*** | ***Possible Benefits of Proposed Technology*** |
|---|---|---|
| *Glove system implementation into the current existing systems (Da Vinci)* | • Lack of comfort<br>• No haptic feedback | • Better personal fit/ergonomics<br>• Freedom from the console<br>• Comfort throughout the process<br>• Intuitive Use<br>• Haptic feedback |
| *Telemonitoring For Da Vinci system* | • Steeper learning curve<br>• Complex interface | • Remote student training<br>• Faster resident education<br>• Increase confidence |
| *Telehealth* | • High transportation costs<br>• Resource-Intensive | • Support for distance health programs<br>• Remote specialist assistance |
| *Other* | • Security concerns | • Disaster response<br>• Military medicine |

Following the end-user study, the PhD research proposal was updated to incorporate findings from it, such as the need for improved safety, reliability, and sensitivity. The key change was demonstrated in the shift from theoretical possibilities to a more practical, user-centered approach, informed by real-world challenges.

### 3.4. The PhD student's research proposal before and after user studies

Following the revision of the proposal, the changes made were evaluated to assess whether they appropriately incorporated the feedback received from end-users. The evaluation was conducted by eight PhD students who were part of the workshop. The workshop consisted of a presentation on an introduction to end-user studies, its potential benefits for engineering research, a specific student case study as an example, and a survey. The survey included questions regarding students' perspectives about the incorporation of user studies into their research (discussed in Section 4) as well as questions regarding evaluation on the specific case study. The latter set of questions aimed at obtaining students' opinions on the extent to which the end-user feedback was successfully incorporated into the revised proposal. In particular, the eight PhD students were provided with the originally written proposal, the summarized interview feedback, as well as the revised proposal. Next, they were asked to evaluate whether the revised proposal properly incorporated the interview feedback.

The participants compared the initial research proposal with the revised version that incorporated user study feedback. The revised proposal stood out for its clear structure, actionable steps, and a strong focus on feedback from surgeons. It addressed critical issues such as safety, cost-effectiveness, and legal challenges, while also including real-world applications. By contrast, the original proposal lacked specificity and a clear plan. On average, participants perceived the revisions made as impactful, rating them at 4.5 out of 5, with many highlighting the improvements regarding the proposal's clarity and focus.

### 3.5 PhD student experience in conducting the end-user study

The case study student was responsible for writing the original proposal, conducting interviews and reformulating the PhD research proposal. The PhD student was interested in conducting the end-user study because they wanted to showcase the prototype to potential users in order to gain insights into how interested end-users were in the technology, whether they would be willing to use it, and what the most important aspects and needs of the end-users were.

The PhD student performed the end-user study to ensure that the development of the technology aligned with the real challenges of the end users' everyday tasks. Through this experience, the student found the user study of high interest because it revealed ranging users' opinions about the technology and its potential applications. Also, the interviews provided an environment that facilitated interaction with individuals with very different backgrounds, which resulted in new ideas and ways of thinking. The student found them very educational and beneficial for the development of the technology.

Due to the lack of previous interviewing experience, the student gained valuable personal experience of discussing complex concepts with individuals who are not familiar with the given technology. That presented the hardest challenge, as the imperative of the interviews was to keep

the technical discussion general enough such that the interviewees who are not familiar with the technology felt comfortable to engage in discussion and brainstorm ideas. Keeping the discussion general was achieved by going back to the first principles when thinking about the development of technology, which provided a fresh perspective that was more conducive to generating original ideas.  Additionally, another part of the user study process that was challenging was scheduling interviews with the surgeons. Surgery is a very busy profession, which leaves very little time for surgeons to communicate with outside researchers to schedule interviews, let alone participate in them.
This kind of study equipped the student with communication skills, that could be utilized in job interviews, which require discussions of complex systems with very experienced professionals, who may not be familiar with such systems.

Overall, by conducting this kind of study, the student improved their understanding and gained ability to better explain research overall, in addition to gaining confidence. During the process, the student had increased motivation to enhance the technology to meet real-world needs, as determined in the interviews, which significantly benefited the technical aspect of the research. In addition, the student gained new perspectives on specific technology through communication with interviewees who are experts in other fields, which provided a diverse set of perspectives.

## 4. Evaluation of Student Perspectives and General Applicability of the Approach

A workshop was carried out on integrating end-user studies into STEM graduate education. The goal of the workshop was to evaluate other PhD students' perspectives on adopting user-centered design into their PhD research. The survey assessed participants' interest in the study approach, its potential usefulness for their research, and possible challenges to implementation. It also explored the ideal timing for conducting such a study and gathered initial ideas for study design.

Firstly, participants highlighted several challenges for conducting end-user studies, such as translating user needs across disciplines, lack of established connections limiting access to professionals, and constraints like time, resources, and recruitment. Emerging fields face additional hurdles, including low public awareness and limited participant pools. Other concerns included ensuring the quality and usability of prototypes, effective marketing, and managing qualitative data collection and analysis. Secondly, most participants agreed that user studies should be conducted multiple times throughout a graduate program, particularly in the second year or during the early-to-mid stages, such as proposal development, prototyping, and testing. Application-driven research benefits from early feedback, while theoretical work often requires input later, when potential applications are clearer. Finally, participants shared ways they would incorporate end-user studies into their research, such as reaching out to therapists, neuroscientists, industry professionals, and others in relevant fields. They suggested leveraging advisors, personal networks, and platforms such as LinkedIn to establish connections. They would place the focus on practical questions, such as addressing gaps in current technologies, understanding sector-specific needs, and refining the research based on feedback.

Half of the participants found end-user studies highly relevant to their research and believed their advisors and committees would support such efforts. While some raised concerns about how these methods apply to fundamental research areas, many saw value in integrating social science approaches into graduate education.

**5. Committee feedback on the proposed framework**

The proposed Graduate Research Training in Translational Engineering program was presented in an oral presentation and a written document to the student's dissertation committee members. Upon analyzing the written document and listening to the student's oral presentation, the committee expressed strong support for the proposed framework, recognizing its potential to significantly enhance student preparation for careers in industry.

In their feedback, the committee members agreed that there is value in connecting students to end users early in their research, expecting this will lead to increased motivation, engagement, and reduced burnout. They stated that understanding the broader impact of the work can help students remain focused on their research goals and better tailor their research to real-world needs. One committee member also pointed out the benefit of involving end users as early as the research formation and recruitment stage – prior to the proposal development – which can help students clarify and concretize their interests early on.

Other committee comments were directed at extending and scaling the model. In addition to involving end users, some committee members suggested engaging stakeholders throughout the entire research lifecycle and even including them in dissertation defenses. Other suggestions included broadening the scope to include interdisciplinary teams, which intensify collaboration across different fields, such as Mechanical Engineering and Robotics. The committee members discussed the potential value the model outside of the medical devices field, suggesting that future studies be done on implementing this approach in other fields. Additionally, in order to facilitate meaningful and sustained engagement. The idea of building an ecosystem of researchers and end users was proposed by the committee members.

After the meeting, one of the committee members sent comments comparing the initial research proposal with the revised version:

> *In terms of the comparison of the two versions of your proposal, I can see the following:*
> - *much more clearly identified application of the proposed research*

- *more concrete examples with figures showing the applications and significance of the research*
- *the education benefit for STEM is a nice addition to the main research as a broader impact.*

Additionally, one of the committee members emailed a note that captured the committee's discussion as a whole:

> *This is a great development that will better prepare students for careers in industry. I also foresee positive changes in student motivation, engagement, and reduction of burnout as students connect to potential end users and visualize potential impact of their work. My suggestions would be to think of integrating End User and other stakeholder engagement at different states of the program, not only at the Research Proposal Development stage. At an earlier stage, research advisors could work with end users to formulate possible design challenges and problems that need to be addressed, and this information could be beneficial as early as at student recruitment stage, attracting students based on specific applications and interests, and possibly impacting the choices of courses. As later stages, students and advisors should be encouraged to seed feedback from end user at Supervised Research stage, and, where appropriate, engage them as committee members at Dissertation Defense stage.*
>
> *If the future, this model can be extended to interdisciplinary team projects, where not one graduate student is involved, but several (e.g., from ME and Robotics, etc), and possibly teams can involve MQP students, providing an experience in collaboration.*

## 6. Concluding Discussions and Implications

A Graduate Translational Engineering Research model that integrates socio-economic elements into STEM doctoral research through early end-user studies was introduced. The model emphasizes deep immersion in value creation through PhD research itself, equipping students with skills to design solutions that are both relevant and impactful. A key point of the model is the involvement of PhD students in qualitative end-user studies, supported by an interdisciplinary dissertation committee. This preliminary case study shows that by blending interdisciplinary collaboration with qualitative research methods, this approach has the potential to enhance graduate education and value creation training, accelerate technology translation, and improve the likelihood of adoption by end users. The proposed model is designed to be flexible, scalable, and low-cost, addressing the need for transformative changes in graduate education to prepare future researchers to solve complex real-world challenges.

Feedback from students and faculty suggests that further study analyzing scalability of this transformation is warranted. Future work requires a longer duration to better assess the framework, and evaluation of the proposed model across a larger number of PhD students in different disciplines. We also suggest future work may focus on investigating the following factors:

1) Culture of research: What are some approaches to create opportunities in engineering research environments for student-centered/-led exploration of translational research?
2) Applicability to applied vs basic research: How can consideration/definition of end-users be extended/modified for this framework to be beneficial to students doing fundamental research?
3) Timing: How does the timing of the implementation of this model within the PhD timeline impact the usefulness of the gathered data in driving the students' research and formation of their professional networks?

**Acknowledgments**

This material is based upon work partially supported by the National Science Foundation (NSF) under Grant No DGE-1922761. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

We are grateful to Professor Loris Fichera for connecting us with the end users. We sincerely thank the study participants, as well as the PhD committee members—Professor Lyubov Titova, Professor Aswin Gnanaskandan, and Professor Yihao Zheng—for their valuable contributions.

## References

[1] M. Roach, “Encouraging entrepreneurship in university labs: Research activities, research outputs, and early doctorate careers,” *PLoS ONE*, vol. 12, no. 2, p. e0170444, Feb. 2017, doi: 10.1371/journal.pone.0170444.

[2] C. C. Nnakwe, N. Cooch, and A. Huang-Saad, “Investing in Academic Technology Innovation and Entrepreneurship: Moving Beyond Research Funding through the NSF I-CORPS$^{TM}$ Program,” *technol innov*, vol. 19, no. 4, pp. 773–786, Jun. 2018, doi: 10.21300/19.4.2018.773.

[3] S. Al Haddad, T. O’Neal, I. Batarseh, and A. Martoncik, “Enabling academic entrepreneurship: the I-Corps experience,” *ET*, vol. 63, no. 7/8, pp. 1027–1042, Nov. 2021, doi: 10.1108/ET-03-2019-0045.

[4] P. Rippa, G. Landi, S. Cosimato, L. Turriziani, and M. Gheith, “Embedding entrepreneurship in doctoral students: the impact of a *T* -shaped educational approach,” *EJIM*, vol. 25, no. 1, pp. 249–270, Jan. 2022, doi: 10.1108/EJIM-07-2020-0289.

[5] A. Marin, A. Parvatiyar, R. K. Mitchell, and D. Villegas, “From Lab to Market: Learning Entrepreneurial Marketing Through Multi-Semester, Stage-Gate, Capstone Project in STEM MBA,” *Journal of Marketing Education*, vol. 45, no. 3, pp. 226–246, Dec. 2023, doi: 10.1177/02734753231185415.

[6] L. McAlpine and E. Emmioğlu, “Navigating careers: perceptions of sciences doctoral students, post-PhD researchers and pre-tenure academics,” *Studies in Higher Education*, vol. 40, no. 10, pp. 1770–1785, Nov. 2015, doi: 10.1080/03075079.2014.914908.

[7] H. Horta, “PhD students’ self-perception of skills and career plans while in doctoral programs: are they associated?,” *Asia Pacific Educ. Rev.*, vol. 19, no. 2, pp. 211–228, Jun. 2018, doi: 10.1007/s12564-018-9532-y.

[8] C. Succi and M. Canovi, “Soft skills to enhance graduate employability: comparing students and employers’ perceptions,” *Studies in Higher Education*, vol. 45, no. 9, pp. 1834–1847, Sep. 2020, doi: 10.1080/03075079.2019.1585420.

[9] A. Rorrer *et al.*, “Pathways to Entrepreneurship (PAtENT) Program: Reimagining STEM Doctoral Programs,” in *2021 ASEE Virtual Annual Conference Content Access Proceedings*, Virtual Conference: ASEE Conferences, Jul. 2021, p. 37568. doi: 10.18260/1-2--37568.

[10] “Heinricher, Art, Carlson, Curtis, Robbins, Emily, Gaudette, Glenn, Zafiris, Janet, Polizzotto, Len, and Sarah Wodin-Schwartz. 2020. ‘Worcester Polytechnic Institute - The Value Creation Initiative at WPI’. Engineering Unleashed. Thursday, January 23, 2020. https://engineeringunleashed.com/card/1891”.

[11] A. Marin, A. Parvatiyar, R. K. Mitchell, and D. Villegas, "From Lab to Market: Learning Entrepreneurial Marketing Through Multi-Semester, Stage-Gate, Capstone Project in STEM MBA," *Journal of Marketing Education*, vol. 45, no. 3, pp. 226–246, Dec. 2023, doi: 10.1177/02734753231185415.

[12] S. P. Hernando, "Transferring knowledge: PhD holders employed in Spanish technology centres," *IJTM*, vol. 68, no. 3/4, p. 228, 2015, doi: 10.1504/IJTM.2015.069665.

[13] D. Bienkowska and M. Klofsten, "Creating entrepreneurial networks: academic entrepreneurship, mobility and collaboration during PhD education," *High Educ*, vol. 64, no. 2, pp. 207–222, Aug. 2012, doi: 10.1007/s10734-011-9488-x.

[14] M. Klofsten, D. Jones-Evans, and L. Pereira, "Teaching science and technology PhD students in entrepreneurship-potential learning opportunities and outcomes," *J Technol Transf*, vol. 46, no. 2, pp. 319–334, Apr. 2021, doi: 10.1007/s10961-020-09784-8.

[15] G. Pisoni, F. Renouard, J. Segovia, A. Rossi, B. Molnar, and O. Mutanen, "Design of small private online courses (SPOCs) for Innovation and entrepreneurship (I&E) Doctoral-level education," in *2020 IEEE Global Engineering Education Conference (EDUCON)*, Porto, Portugal: IEEE, Apr. 2020, pp. 1662–1668. doi: 10.1109/EDUCON45650.2020.9125153.

[16] P. Rippa, G. Landi, S. Cosimato, L. Turriziani, and M. Gheith, "Embedding entrepreneurship in doctoral students: the impact of a *T* -shaped educational approach," *EJIM*, vol. 25, no. 1, pp. 249–270, Jan. 2022, doi: 10.1108/EJIM-07-2020-0289.

[17] M. Roach, "Encouraging entrepreneurship in university labs: Research activities, research outputs, and early doctorate careers," *PLoS ONE*, vol. 12, no. 2, p. e0170444, Feb. 2017, doi: 10.1371/journal.pone.0170444.

[18] M. Klofsten, D. Jones-Evans, and L. Pereira, "Teaching science and technology PhD students in entrepreneurship-potential learning opportunities and outcomes," *J Technol Transf*, vol. 46, no. 2, pp. 319–334, Apr. 2021, doi: 10.1007/s10961-020-09784-8.

[19] G. Hägg, "Experiential entrepreneurship education: Reflective thinking as a counterbalance to action for developing entrepreneurial knowledge," Doctoral Dissertation, University of Turku, Lund, 2017.

[20] A. Bergek and C. Norrman, "Incubator best practice: A framework," *Technovation*, vol. 28, no. 1–2, pp. 20–28, Jan. 2008, doi: 10.1016/j.technovation.2007.07.008.

[21] "NSF I-Corps." [Online]. Available: https://new.nsf.gov/funding/initiatives/i-corps/about-i-corps

[22] N. Duval-Couetil, A. Epstein, and A. Huang-Saad, "Catalyzing U.S. Innovation and Entrepreneurship: Approaching the Evaluation of the National Science Foundation's I-Corps

Program," in *2022 ASEE Annual Conference & Exposition Proceedings*, Minneapolis, MN: ASEE Conferences, Aug. 2022, p. 40727. doi: 10.18260/1-2--40727.

[23] "NIH I-Corps." [Online]. Available: https://sbir.cancer.gov/commercialization/business/icorps

[24] A. Rorrer *et al.*, "Pathways to Entrepreneurship (PAtENT) Program: Reimagining STEM Doctoral Programs," in *2021 ASEE Virtual Annual Conference Content Access Proceedings*, Virtual Conference: ASEE Conferences, Jul. 2021, p. 37568. doi: 10.18260/1-2--37568.

**Appendix A - Detailed methodology for online interviews and workshop**

**Methodology – Interviews**

This research study involved online interviews with five surgeons, recruited through professional and personal networks. The interviews were guided by prewritten questions, with an emphasis on engaging in discussions to better understand the surgeons' perspectives on the technology in question. Each interview included a concise explanation of the motion capture glove technology and lasted approximately 30 minutes. The questions covered the following five categories:

1. Potential benefits and applications of the motion capture glove technology in telesurgery
2. Essential features of the motion capture glove
3. Potential cost savings
4. Safety and expectation
5. Future applications of the motion capture glove technology

**Online interviews – Questions**

**Concise explanation of the motion capture glove technology**

The overall idea is to enable a surgeon to conduct a telesurgery through wearing a motion capture glove that controls a remote robot operating on a patient. The motion capture glove tracks the movements and positions of a surgeon's hands and fingers, and it sends it to the robot performing the surgery. Compared to current methods, this device feels more intuitive. Unlike bulky wearable devices, it resembles wearing a thin glove, thanks to its integration of stretchable sensors and electronics that are printed.

*Questions*

1. Potential benefits and applications of the motion capture glove technology in telesurgery
   i. What kind of surgeries do you perform, and could you see yourself ever conducting telesurgeries in the future?
   ii. What part of your job could benefit from the motion capture glove technology?
   iii. What surgeries or procedures do you think would benefit the most from the motion capture glove technology?
2. Essential features of the motion capture glove
   i. What specific challenges do you expect from using the motion capture glove for telesurgeries?
   ii. Please rank the following features starting with the most important and elaborate what is the importance of each one.

a. Sensitivity in detecting delicate human motion
b. Feedback from the robot to surgeon
c. Comfort
d. Durability/Longevity
e. Maintenance/Cleaning
f. Safety/Reliability

iii. Would you be interested in trying the motion capture glove in order to provide essential feedback that will be used in further glove development?
iv. What systems and technologies should the glove be compatible with in order to optimize its performance?

3. Potential cost savings
    i. Can you see any cost being eliminated from your usual practice due to the usage of this device?
4. Safety
    i. What level of regulatory standard testing does it need to pass in order to persuade you to use this device?
5. Training and preparation
    i. What level of preparation or training on this device would be sufficient to convince you to use it?
6. General concerns
    i. What concerns do you have, if any, regarding telesurgeries?
7. Future applications of the motion capture glove technology
    i. Do you see any other future potential for technologies similar to this one besides telesurgeries?

**Methodology and Questions – Workshop**

This research study will be conducted during a workshop with STEM graduate students from the ME, CHE, Chemistry, Robotics, and Physics departments. The workshop will include: 1) a brief introduction to user study experiences and their potential benefits for engineering research, and 2) a presentation of our as an example, highlighting how one graduate student's proposal was influenced by this approach. After the workshop, we will collect anonymous feedback from attendees on whether they find this type of study useful for their research, their interest in conducting a similar study, and their initial ideas for applying this approach to their work.

***<u>Survey questions</u>***

- Department/program
- Which of the following best describes your status?
    - Master's
    - PhD
    - Post-Doc
- How many years have you been enrolled as a graduate student/postdoc in your program?
    - Less than 1 year
    - Less than 2 years
    - Less than 3 years
    - 3 years or more
- What is your goal in participating in this workshop?
- How interested are you in this kind of study? (Likert scale)
- How impactful/useful do you think this kind of approach would be for your own research? (Likert scale)
- How interested do you think your PI would be in implementing this kind of study? (Likert Scale)
- How supportive do you think your thesis committee would be if you decided to implement this kind of study? (Likert Scale)
- What are some barriers/challenges you anticipate if you would like to implement this kind of study in your research? (Open-ended)
- At what stage of your program do you think this kind of study should be conducted? Why? (When would it be most helpful/impactful?) (Open-ended)
- If you were to conduct a similar study, what would your initial study design include? (For example: Who would you talk to? How would you connect with them? What would you ask? How do you think this information would influence your research?)

*Evaluating before/after of an example thesis proposal:*

- Please list some differences you observed between the first proposal and the revised proposal.
- How impactful do you think the changes in the proposal will be? (Likert scale) Why? (open ended)
- Based on the user study evaluations, what changes would you suggest the PhD candidate implement? (Open-ended)

**Appendix B – Pre-study and post study proposals**

**Original proposal - Thrust 3: Applications & broader impact**

**Gaps**:

1) The lack of scalable production of strain sensors with high stretchability and gauge factor, limits expanded utilization for human applications.
2) Gaining a deeper insight into the aspects of strain sensors that users prioritize for improvement and exploring additional applications for these sensors.

**Objectives**:

1) Identify potential human applications for $SnS_2$ strain sensor with high stretchability and high gauge factor, which will result in widespread adoption and overall positive effect on society.
2) Conduct online interviews to gather insights on areas for improvement in strain sensor and explore potential alternative applications.

One of the potential applications for the Tin Disulfide ($SnS_2$) strain sensor with high stretchability and gauge factor can be found in the field of biomechanics, particularly in gait analysis. Gait analysis refers to the study of the way a person walks or moves. This is crucial for assessing and diagnosing various musculoskeletal and neurological conditions, as well as tracking recovery and preventing further injury. $SnS_2$ strain sensors can be integrated into wearable devices that can be placed on skin or incorporated into clothing, to monitor and analyze the strains experienced by different parts of the body during walking or running.

$SnS_2$ strain sensors can also improve prosthetic limbs and orthotic devices, which are designed to assist individuals with limb loss or musculoskeletal impairments. $SnS_2$ strain sensors could provide valuable feedback on how the artificial limb interacts with the user's body during movement. This information can be valuable for prosthetists and healthcare professionals in optimizing the design and fit of prosthetics, ensuring that the artificial limb responds appropriately to the user's movements and minimizes the risk of discomfort or injury. Over time, this feedback can also be utilized to develop more adaptive and responsive prosthetic technologies.

Another potential application of $SnS_2$ strain sensors can be found in sports. Athletes undergo intense physical exertion, and monitoring biomechanical stresses on different parts of their bodies can provide valuable feedback for preventing injuries. Strain sensors with high sensitivity, such as $SnS_2$, could serve this purpose well by capturing subtle changes in athletes' muscles and joints. The obtained data could be used to prevent injury, improve movement patterns, and even identify specific deficiencies in athletes that can be addressed through specialized training programs.

The aim of Thrust 3 is to conduct the end-user studies. This research involves investigation into users' interactions, perceptions and general feeling when using a product (strain sensor). The goal of the research is to understand and try to improve the overall user experience, by gathering important insights through interviews. This feedback will be utilized to enhance the design and development process of the $SnS_2$ strain sensor. In addition to the end-user study, an objective is to also conduct interviews with individuals who do not already own a strain sensor gadget but can be viewed as potential future users of strain sensors. They will be inquired about new potential applications of the $SnS_2$ strain sensors, which could result in developing new wearable devices that incorporate $SnS_2$ strain sensors.

The potential development of scalable production of $SnS_2$ strain sensors with high stretchability and high gauge factor could lead to numerous new applications. Such applications can have a deep positive impact on society. For example, an expanded utilization of strain sensors could lead to injury prevention, improved injury recovery, better athletic performance, and improved mobility and well-being of individuals with limb loss. This positive effect could take place on both an individual and societal level, potentially reducing medical expenses and increasing the workforce participation among individuals with physical disabilities.

**Reconceptualized PhD proposal - Thrust 3: Applications & broader impact**

**Gaps**:

1) Prioritizing user needs for sensor improvements and exploring additional applications.
2) More research is needed to understand the role of end-user studies in bridging lab research and real-world applications.

**Objectives**:

3) Identify potential human applications for $SnS_2$ strain sensor with high stretchability and high gauge factor.
4) Conduct online interviews to gather insights on areas for improvement in strain sensor and explore potential alternative applications.
5) Conduct workshop with STEM students to explore and evaluate how end-user studies methodologies can be applied across STEM disciplines to enhance the practical impact of graduate research.

## 3.1 Translating research into the real world

The main application of the $SnS_2$ strain sensor is the use in the remotely controlled motion capture glove technology. A research group working on the motion capture glove technology has expressed its interest in integrating the $SnS_2$ strain sensor into its glove technology. The collaboration came to fruition because of the $SnS_2$ sensor's high stretchability and high gauge factor, making it optimal for sensing and tracking finger movements. The gauge factor (GF), a key parameter for strain sensing, indicates the sensitivity of the sensor by describing how much electrical resistance changes in response to an applied strain. The motion capture glove (Fig. 1) serves to collect input information from users, as well as to provide haptic feedback to users. Haptic feedback consists of both the kinesthetic (a sense of movement and position) and tactile (touch and texture) feedback.

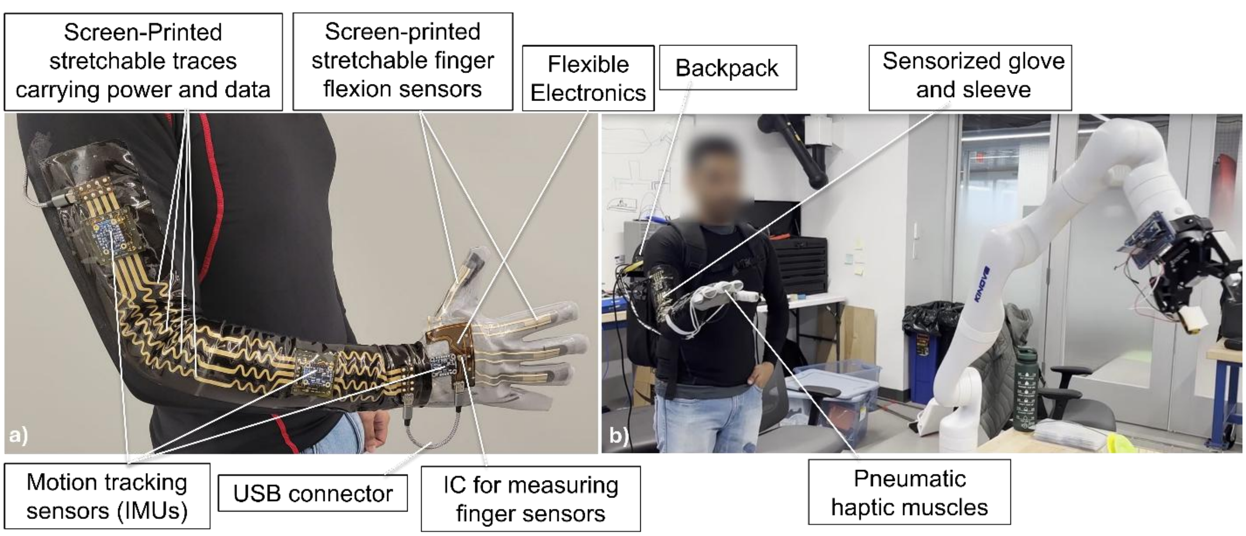


**Figure 1.** Soft Robotic Glove and Sleeve Human Machine Interface (HMI)

#### 3.1.1. User study insights

The initial idea for the application of the motion capture glove technology was to enable a surgeon to conduct telesurgery through wearing the glove that will be controlling a remote robot, which will be operating on a patient. To test this idea, as well as to gain surgeons' insights and their suggestions for other potential uses of the glove technology, the end-user study plan was outlined. The end-user studies included interviews with surgeons to investigate their interactions, perceptions, and overall opinions regarding the glove technology. The goal of the research is to understand and try to improve the overall user experience, by gathering important feedback. This feedback will be utilized to enhance the design of the glove technology, as well as to uncover other potential applications for it.

The first step of the end-user study, interviewing surgeons, has been completed. Efforts to connect to surgeons were made through both professional and personal networks. In total, 5 individuals were interviewed (4 surgeons and 1 emergency care doctor), with each interview lasting approximately 30 minutes. The interview process covered the topics related to the motion capture glove technology:

- Potential benefits and applications of the motion capture glove technology in telesurgery;
- Essential features of the motion capture glove;
- Potential cost savings;
- Safety and expectation; and
- Future applications of the motion capture glove technology.

Following the interviews, the transcripts of the conversations were generated, and the obtained feedback was analyzed with the coding and theming technique. Coding and theming technique is a qualitative research method used to analyze data by identifying, organizing, and interpreting patterns or themes. This process involves labeling segments of data (coding) and grouping these codes into broader, meaningful categories (themes) to facilitate analysis and draw insights [1]. The summarized insights and proposed applications were studied and incorporated in this chapter of the Thesis.

The interviewees ranked the most important features of the glove technology in the following order: 1) safety and reliability, 2) sensitivity in detecting delicate human motion, and 3) force feedback from the robot to the surgeon. Feedback from the interviews about the proposed idea of utilizing remotely controlled motion-capture glove technology for teleoperated surgeries, where the surgeon is not in the same room, highlighted numerous challenges that may not be resolved in the near future. The primary concern was the safety of such a system, particularly in emergency situations where the presence of an experienced surgeon is still essential. Additional concerns included medical-legal issues, the perception that this technology would offer only marginal improvements that may not justify its cost, and the lack of a viable economic model or significant market demand for this kind of system.

The interviewees proposed the use of the glove technology for providing medical help in disaster response scenarios.  These applications would entail providing medical assistance, such as performing surgeries, stitching wounds, or stabilizing injuries, in natural disasters such as earthquakes, as well as during crisis times like war zones and major industrial accidents. Also, another suggested application for the glove technology in times of crisis is bomb defusal, which would enable eliminating the threat, without risking human lives.

One of the first associations surgeons made when considering potential applications of the glove technology was its integration into the existing Da Vinci operating system (Fig. 2). The Da Vinci system robotic system is designed to assist surgeons in performing minimally invasive surgeries by allowing surgeons to conduct extremely precise incisions by eliminating hand tremors and providing high flexibility and control [2]. The system consists of robotic arms that are connected to surgical tools and a camera, a console through which the surgeon observes the operation, and hand controllers and foot pedals that the surgeon uses to control the robotic arms [2]. Some of the major criticisms that surgeons expressed relating to the Da Vinci system are the unintuitive nature of it and the lack of comfort, including poor ergonomics and the necessity to be placed right at the console. They suggested that such downsides of the Da Vinci system could be overcome by the integration of the glove technology which is more intuitive and provides haptic feedback.

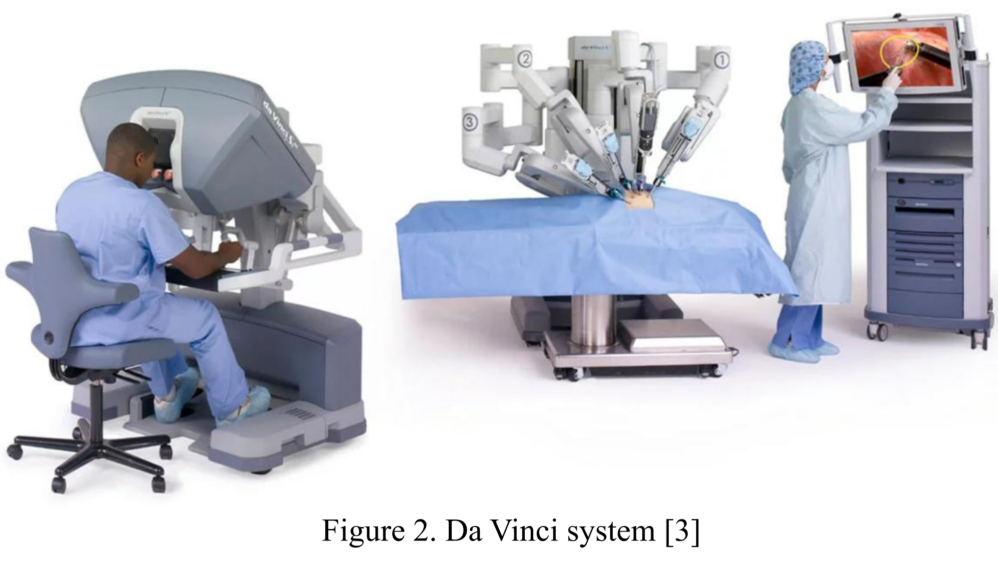

Figure 2. Da Vinci system [3]

The interview process also yielded an application of the glove technology in tele-training. Currently, teaching surgeons need to be physically present when training residents on various surgical topics, including the use of Da Vinci. This requirement for the teachers to be physically present puts more strain on scheduling training sessions, resulting in a slower training process. The use of the glove technology would greatly improve training efficiency, as teachers would not have to travel to provide their training sessions, which would provide more time for the training itself. In addition, the quality of the training could significantly improve as leaders in their fields of study would be able to hold training sessions internationally.

Another application proposed in the interview conversations was the use of the glove technology in telehealth. Such an application could help in various distance health settings and programs, including paramedics in the field conducting home visits and patient care. Also, this technology could be used in setups where an appointed individual who manages health equipment and monitors a patient could serve as a point of contact, enabling others to use the technology remotely to assist or work on the patient. The key advantage of this specific application of the glove technology would be the ability to provide help more promptly, while eliminating the substantial expenses associated with transporting remote patients to healthcare facilities.

### 3.1.2. Technical objectives gained from the user study research

As mentioned above, two of the key features required for this type of technology are reliability and sensitivity in detecting delicate human motion. The reliability of the $SnS_2$ sensor is measured by its drift, defined as the percentage change in resistance per cycle. The goal is to achieve a drift of less than 1% over 1,000 cycles, meaning the sensor would only require recalibration after 1,000 cycles. Therefore, per cycle drift change should be less than 1/1000 of a percent.

Sensitivity in detecting delicate human motion can be addressed by creating a strain sensor with appropriate properties, such as high stretchability and a high gauge factor. For example, finger movements, which are subtle, require strain sensors that can detect low strains (around 0.1% to 1%) [4], sufficient for capturing small deformations. Additionally, tracking the complete movement of a finger requires high stretchability of a sensor (typically around 20% [5]). The gauge factor amplifies these subtle strain changes, typically in the range of 10 to 40 [6], enabling precise tracking of small movements. In the case of $SnS_2$ strain sensors, their high sensitivity allows them to detect fine angular increments (typically between 5° to 90°) during finger flexion, making them ideal for applications that require detailed motion analysis [7]. Based on this information, the conclusion is that the change in resistance should reach 100% to reliably register the smallest finger movements. Thus, having a typical finger movement requiring strain around 20%, the minimum requirement for the gauge factor is 5 (100%/20%).

The most common suggestion from the interview for the application of motion capture glove technology was its integration into the existing Da Vinci operating system. The Da Vinci system consists of two major components:

1) the surgeon console where the surgeon controls the robotic arms and views the 3D image, and
2) the patient cart which holds the camera and surgical instruments positioned near the patient during surgery [8].

The proposed idea is to implement motion capture glove technology as an enhancement to the surgeon console system (Fig. 3).

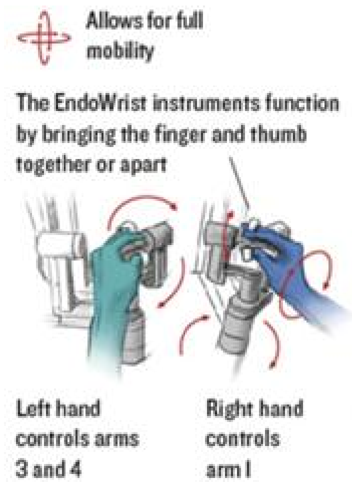

Figure 3. Master controllers

This integration would allow surgeons to use more natural hand motions, which would be mapped directly to the robotic end effector. $SnS_2$ strain sensors would be placed on the fingers, back of the hand, and wrist to capture all necessary movements currently detected by the master controllers. Additionally, the minimum response time for the $SnS_2$ sensor must meet or exceed 200 milliseconds, aligning with the current response time of the Da Vinci system. With respect to this, the interview feedback highlighting the importance of reliability, sensitivity and response time validates the initial research focus on developing a highly sensitive and reliable strain sensor.

### 3.2 Education benefits for STEM students

A significant amount of time, effort, and resources is invested in graduate engineering research, yet only a small fraction of the developed technologies is ultimately adopted in the "real world." User studies can bridge this gap by enabling graduate student researchers to effectively communicate their plans and results to end-users, thereby increasing the likelihood of adoption. Furthermore, user studies can help students, and their advisors identify practical, real-world problems that their research can address.

However, these studies require time and are most effective when conducted early in the PhD timeline, as they can shape the thinking and research directions of both advisors and students. Despite their potential, various barriers exist, and conducting such studies is not yet a common practice in academia.

To address this gap, a workshop will be conducted with graduate STEM students to assess their needs, interests, and perceptions regarding user studies. The goal is to analyze how end-user studies can be integrated into STEM graduate education as a tool to translate lab-based research into real-world applications.

This study seeks to provide insights into implementing such approaches, supporting the transition of lab-based graduate engineering research into practical applications, and offering a framework for potentially transforming graduate education. By examining the impact of this interdisciplinary approach on graduate research planning, the study aims to propose recommendations for integrating social science research methods early in graduate engineering research to enhance the translational potential of technology development.

## References


[1] J. Saldana, *Fundamentals of Qualitative Research*. in Understanding Qualitative Research. Oxford, New York: Oxford University Press, 2011.

[2] C. Freschi, V. Ferrari, F. Melfi, M. Ferrari, F. Mosca, and A. Cuschieri, "Technical review of the da Vinci surgical telemanipulator," *Int. J. Med. Robot.*, vol. 9, no. 4, pp. 396–406, 2013, doi: 10.1002/rcs.1468.

[3] "Da Vinci Systems," ELvation Medical. Accessed: Dec. 04, 2024. [Online]. Available: https://www.elvation.de/en/da-vinci-systems/

[4] Y. Si, S. Chen, M. Li, S. Li, Y. Pei, and X. Guo, "Flexible Strain Sensors for Wearable Hand Gesture Recognition: From Devices to Systems," *Adv. Intell. Syst.*, vol. 4, no. 2, p. 2100046, 2022, doi: 10.1002/aisy.202100046.

[5] Y. Du, L. Sun, L. Yang, C. Jiang, and W. Xu, "Flexible Piezoresistive Sensor With High Strain Sensitivity and Pressure Insensitivity for Motion Monitoring," *IEEE J. Flex. Electron.*, vol. 3, no. 1, pp. 4–9, Jan. 2024, doi: 10.1109/JFLEX.2023.3332567.

[6] S. S. Mechael, Y. Wu, Y. Chen, and T. B. Carmichael, "Ready-to-wear strain sensing gloves for human motion sensing," *iScience*, vol. 24, no. 6, p. 102525, May 2021, doi: 10.1016/j.isci.2021.102525.

[7] L. Wang, T. Meydan, and P. Williams, "A Two-Axis Goniometric Sensor for Tracking Finger Motion," *Sensors*, vol. 17, no. 4, p. 770, Apr. 2017, doi: 10.3390/s17040770.

[8] "Da Vinci Surgery | Da Vinci Surgical System | Robotic Technology." Accessed: Dec. 04, 2024. [Online]. Available: https://www.intuitive.com/en-us/patients/da-vinci-robotic-surgery/about-the-systems