An Experiential Learning Approach to Industrial IoT Implementation of Smart Manufacturing through Coursework and University-Industry Partnerships

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From the EDITOR

Dear Engineering Technology Colleagues:

With some delay, the Fall 2023 issue of the Journal of Engineering Technology® has finally arrived. We are posting this issue on the ASEE Engineering Technology Division (ETD) website, and will send the printed copies via post mail in late December. I hope you will find time to read the articles during the winter break.

Within the pages of this edition, we showcase three notable articles. The first, an invited paper titled “An Experiential Learning Approach to Industrial IoT Implementation of Smart Manufacturing through Coursework and University-Industry Partnerships,” describes the development of a course for training the next generation manufacturing professionals and supporting regional companies by implementing the needed IoT solutions. Notably, this paper received the 2023 ASEE Annual Conference Manufacturing Engineering Division Best Paper Award. The second paper, “Development of a Smart Fuzzy-PID Active Control System without the Need for Direct Muscle or Brain Command Signals,” presents an advanced smart control system for active prosthetic management. This applied research project, suitable for inclusion in a mechatronics curriculum, can provide students with a hands-on, integrated learning experience. Our third paper, “Holistic Review: Math Anxiety and the STEM Profession,” is a comprehensive review of research on the math anxiety issue among students. As a review paper, it identifies the research topic, summarizes previous findings, and discusses research opportunities that can be of significant interest to Engineering Technology researchers and educators.

With this Fall 2023 publication, we continue to share the noteworthy contributions to ET research and education made by our colleagues. I encourage you to consider the Journal of Engineering Technology as a prime venue for disseminating your work. For the forthcoming JET issues, I look forward to receiving your manuscript through the Scholastica website at https://jet.scholasticahq.com/for-authors.

Best wishes for a wonderful holiday season,

Best regards,

Jyhwen Wang
Editor-in-Chief
Journal of Engineering Technology®

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COVER: Figure from “Development of a Smart Fuzzy-PID Active Control System Without the Need for Direct Muscle or Brain Command Signals.”
INVITED PAPER FROM THE 2023 ASEE NATIONAL CONFERENCE

An Experiential Learning Approach to Industrial IoT Implementation of Smart Manufacturing through Coursework and University-Industry Partnerships

by Eunseob Kim, Lucas Wiese, Hector Will, Alejandra J. Magana, and Martin Jun

This study delves into the course's pioneering design, rooted in the experiential learning theory (ELT), highlighting the significant outcomes and showcasing the collaborative projects that seamlessly integrated classroom learning.

Holistic Review: Math Anxiety and the STEM Profession

by Elizabeth C. Wilkinson

Over the course of the author’s teaching and research experience, available research was gathered and organized to answer six questions that will be explored in this holistic review.

Development of a Smart Fuzzy-PID Active Control System Without the Need for Direct Muscle or Brain Command Signals

by Ammar Alzaydi

In an innovative approach to active prosthetic management, this paper introduces a method for intelligent control that circumvents the necessity of expensive sensory systems directly linked to user brain activity, such as muscle signals.
1. Introduction
As Internet of Things (IoT) and artificial intelligence (AI) continue to reshape industrial processes and product lifecycles, the need for retraining current workers and attracting future ones to the manufacturing industry has grown. Nationwide, the US manufacturing sector is expected to have 2.1M unfilled jobs by 2030, a shortage that will be led by gaps in filling and retaining skilled positions. The US Bureau of Labor Statistics shows that manufacturing jobs in Indiana grew back to pre-pandemic figures with a need for 526,000 workers in 2021, compared with 539,000 in 2019, resulting in the country’s highest concentration of manufacturing jobs (Regions 2022). The problem further intensifies because although the manufacturing workforce growth results in new jobs and higher wages, manufacturers face challenges in recruiting well-qualified workers (ReliablePlant n.d.).

While reskilling and upskilling efforts will be needed for the current workforce, particularly in the plant floor, new jobs and occupations will emerge. These new jobs will require professionals and future managerial employees to have strong data science skills to effectively design and oversee future AI-enabled manufacturing systems. However, a critical gap exists between traditional analytic/numeric engineering education and computer science/AI development that can provide skills to effectively enact and manage the full data science cycle.

Specifically in Indiana, findings from the 2019 Indiana Manufacturing Survey (IUPUI 2019) concluded that there is a serious shortage of skilled and unskilled laborers, with the expectation that the number of skilled jobs will increase; this skills gap impedes manufacturing growth. Furthermore, manufacturers, especially middle-size companies, have limited options for supporting their own workforce development and expect public secondary schools to help address this shortage (IUPUI 2019).

To take steps toward preparing engineering graduates to effectively work with data, starting from data collection through sensors to data analysis and insight enabled by dashboards, Purdue University designed and implemented a graduate course in partnership with local industries. This course has the dual purpose of training the next generation of manufacturing professionals and in the process supporting regional companies in addressing problems that could be solved with IoT or AI innovations. The goal of this study is to describe how the course was organized and delivered following design principles of Experiential Learning Approach to Industrial IoT Implementation of Smart Manufacturing through Coursework and University–Industry Partnerships
Learning Theory, and, as outcomes of the approach, we provide a description of the projects the students implemented within the regional manufacturing companies.

2. Pedagogical Framework

Kolb’s Experiential Learning Theory (ELT) (D. A. Kolb 1984; A. Y. Kolb and Kolb 2009) was used as an explanatory approach to describe the course design and implementation. ELT learning is “the process whereby knowledge is created through the transformation of experience. Knowledge results from the combination of grasping and transforming experience” (D. A. Kolb 1984). This form of learning is represented in a model (see Figure 1) that depicts two modes of grasping experience (i.e., concrete experience and abstract conceptualization) and two modes for transforming experience (i.e., reflective observation and active experimentation).

According to the cycle shown in Figure 1, learning occurs when learners construct knowledge by experiencing the tensions among the four learning modes, concrete experience, reflective observation, abstract conceptualization, and active experimentation, created by contextual demands. Thus, ELT’s implications for the course’s design consisted of guiding learners through recursive processes of experiencing, reflecting, thinking, and acting to respond to the learning situation. That is, “immediate or concrete experiences are the basis for observations and reflections. These reflections are assimilated and distilled into abstract concepts from which new implications for action can be drawn. These implications can be actively tested and serve as guides in creating new experiences” (A. Y. Kolb and Kolb 2009). Specifics of how ELT guided the course implementation are described below.

3. The Course

The course titled Industrial IoT Implementation for Smart Manufacturing provides an introduction to the industrial internet of things (IIoT) implementation on real production machines for smart manufacturing. It is a practical lab/project course that allows engineering students to implement IoT sensors and devices on real production machines at local manufacturing companies, collect data, perform data analytics for the company’s benefit, and demonstrate the visualization of the analyzed data. Students worked with local Indiana manufacturing companies and institutes to support the implementation of deployment of sensors and devices to a production machine, collection of data, analytics, and visualization. The partnering manufacturing companies are small and medium sized enterprises (SMEs). A significant number of SMEs may not be equipped to cope with the forthcoming alterations in Industry 4.0 due to a scarcity of qualified personnel or their reluctance or uncertainty towards technology strategies, which are still uncharted territory for them (Kim et al. 2019). The collaboration projects might be a favorable opportunity for local manufacturing companies to try IIoT on their shop floor. Students can gain valuable experiential learning opportunities by applying the theoretical and technological skills acquired in the course to real-world industrial settings.

Specifically, the course had five specific objectives, including (LO1) formulating a framework for managing collected sensor data from production machines; (LO2) describing communication protocols for implementing wired and wireless connections to machines; (LO3) identifying proper sensors for measurement of desired data; (LO4) implementing data analytics and machine learning tools for extraction of desired information; and (LO5) demonstrating
personal and professional development in communication and management in the context of smart manufacturing. The course was coupled with laboratory reports, written reports, and oral presentations to achieve these objectives and capture evidence of students’ learning and skills development.

Of particular relevance for this course was the integration of ELT principles to coordinate and orchestrate the laboratory assignments that built the necessary skills and practices so students would successfully complete their semester-long projects and, at the same time, address a company’s needs. Table 1 presents a description of how ELT principles guided the implementation of the course. Specifically, students acquired concrete experiences by working directly with IoT sensors in the process of installing them, implementing wired and wireless connections to machines, and acquiring the data. These experiences were then used as the basis for observations and reflections that further prompted the students to create frameworks for managing collected sensor data from production machines. These reflections were then further assimilated and distilled into abstract concepts in the form of visualizations or dashboards representing data. These dashboards were used to gather insight and interpret the data from which new implications for action and recommendations were drawn. These implications can be actively tested and serve as guides for improvements and recommendations.

The course implemented nine laboratories organized into four main topics to build a foundation of knowledge and skills. The first topic was around IoT and data collection, consisting of three labs. The second topic was related to connectivity and middleware, consisting of two labs. The third topic focused on data storage and visualization tools, also consisting of two labs, and the fourth and last topic focused on machine learning composed of two labs. Each lab assignment consisted of two parts: (1) a prelab assignment to introduce concepts and prepare for (2) the main lab assignment. Students completed the prelab assignment asynchronously before coming to the in-person lab meeting time to work on the main lab assignment.

### 3.1. Topic 1: IoT Sensor Communication and Data Collection

Table 2 describes the three laboratory assignments associated with the first topic of IoT sensors and data collection, along with the learning objectives for the prelab and lab assignments. Figure 2 illustrates the schematic of this topic. During the 10 lab assignments, students frequently interacted with a Raspberry Pi computing device (Raspberry Pi Foundation 2022), external hardware connections and sensors, and software configurations. As such, Section 1 of this course was focused on how IoT sensors can collect and communicate data.

To begin, Lab 2 briefs students on the Python programming used to interact with the temperature and humidity sensor, DHT11. Then, the students are asked to connect the DHT11 sensor to their Raspberry Pi which then interacts with Python programming code to collect data. Next, Lab 3 follows suit with a lesson on accelerometer and signal processing, and how frequency domain plots are useful for analyzing sensor data from machining equipment. For the completion of this lab, students need to wire an accelerometer to a fan and input the time/frequency-domain data into their Raspberry Pi environment,
IoT sensors and applies real-world sensors to real data analytics, resulting in a fundamental understanding about how manufacturing equipment can interact with computers and provide useful insight and input.

3.2. Topic 2: Connectivity and Middleware

Table 3 describes the two laboratory assignments associated with the second topic of connectivity and middleware, along with the learning objectives for the prelab and lab assignments. Figure 3 illustrates the schematic of this topic. A typical manufactur-
ing environment runs different types of equipment, sensors, and standards, a middleware is required to appropriately aggregate and handle data. The second topic of this course focuses on how to use the MTConnect standard.

Students will begin with Lab 5 introducing the concepts of middleware and how the MTConnect Agent is a critical part to bridge hardware sensors and adapters into an application-ready data stream (MTConnect 2022). In this lab, students are asked to run an MTConnect Agent on their Raspberry Pi and simulate the MTConnect data pipeline. Then in Lab 6, students are introduced to the MTConnect Adapter. There are hands-on activities to prepare students to work with multiple adapters, and multiple agents, and connect those to computing devices. During this lab, students become familiar with how to parse and interpret incoming data to then present in database management tools. As it is seen, this section prepares students to handle complex manufacturing environments by using middleware to interact with various types of manufacturing equipment.

### 3.3. Topic 3: Data Storage and Visualization Tools

Table 4 describes the two laboratory assignments associated with the third topic regarding data storage and visualization tools, along with the learning objectives for the prelab and lab assignments. Figure 4 illustrates the schematic of this topic. Once IoT sensors can interact with an edge computing device like the Raspberry Pi, and MTConnect can appropriately aggregate the multiple data streams, then database and visualization techniques are required to gain meaningful insight for manufacturing. As such, the third topic of this course covers how SQL and Grafana are utilized to interact with data in a database and visualize it for application-use (Grafana 2022; PyMySQL 2021).

To do this, Lab 7 covers introductions and basics to SQL programming. Students learn about basic SQL scripts to write functions to interact with data.
Then, Lab 8 showcases how the Grafana visualization tool creates dynamic and rich visualizations of input data. Students will learn how to integrate multiple technologies and concepts learned up to this point and build a monitoring system to simulate a manufacturing environment. Through completion of this lab assignment, students will understand how large amounts of raw data can aggregate into human-readable formats.

### 3.4. Topic 4: Machine Learning

Table 5 describes the two laboratory assignments associated with the fourth topic on machine learning, along with the learning objectives for the prelab and lab assignments. Figure 5 illustrates the schematic of this topic. Prior to topic 4, students have been able to interact with data and interpret data visualizations, but now machine learning techniques allow for more complex data analytics and deeper insights for manufacturing processes and efficiency. The fourth topic of this course introduces students to machine learning (ML) basics and how ML can be implemented in the manufacturing data pipeline. Throughout this section, students are introduced to basics of ML and neural networks, classification techniques, edge device TinyML computing using TensorFlow (TensorFlow 2022), and monitoring systems using TinyML.

To begin, Lab 9 briefs students on ML fundamentals, then scaffolds students through building a machine learning model to classify and analyze time- and frequency-domain data from Lab 3. Students experience extensive hands-on learning for utilizing ML in manufacturing equipment. Then, Lab 10 explains how technologies surrounding TinyML allow for machine learning models to be installed on small and low power devices in a manufacturing environment. To do this, students learn about and install TensorFlow on a Raspberry Pi to prepare for loading the ML model they developed in Lab 9 (TensorFlow 2022). Students complete Lab 10 by integrating the TinyML data streams into a monitoring system discussed in Section 3. This section of the course in-
Introduces students to practices and concepts encompassed by Industry 4.0 revolution which redefines the way organizations have utilized technology to optimize operations and production. In conclusion, it is essential for students to understand these Industry 4.0 technologies to help transform manufacturing practices and stay ahead of global competition.

4. Impact and Outcomes of the Course

A primary delivery of the course consisted of a team-based, semester-long project consisting of implementing an IoT solution for a local company. From the beginning of the semester, representatives from each company and institute delivered presentations during lectures as a form of a seminar. In the presentations, they had a speech about the importance of IoT technology and applications in the real field as well as they explained the scope and details of the collaboration project. If the project scope is undecided, the company and students came up with the project subject together based on course contents and company needs. Performing the projects was a team of 2 or 3 students. There were one research institute, one education institute, and six companies, participated in the collaboration projects. After the presentations from the companies and institutes, students put in for a project upon their interests.

Table 6 summarizes the participating company/institute and project goals. In Table 6, the first column, No., means the assigned team number. To make project progress, students had meetings in-person or virtually with the company once or twice a week for two months. They also had several visits to deploy sensors, edge devices, and/or other implementation procedures. Part of the students’ visits were also meant to determine implementation schedules with the company to ensure the company can minimize downtime and continue their production. As these were semester-long projects, students conducted project work alongside lab work. And, as such, students...
students had regular meetings with the instructor and lab TA to discuss approach, progress, feasibility, difficulty, and so on. If they were stuck on technical or practical issues, TA and instructor gave feedback and suggested solutions. The main focus of these projects was to take the IIoT and AI learning outcomes and apply what they learned to the real shop floor.

There were two presentation days: midterm presentation and final presentation. For each presentation, students submitted reports. In the midterm presentation, the instructor gave feedback and evaluated the progress. In the final presentation day (Figure 6), all teams presented their project. Representatives from the company/institute joined and discussed each project in Q&A session. The category of the project subject, outcome, and benefit of company are summarized in Table 7. Projects were categorized in “monitoring system deployment,” “AI application,” and “software development.” Throughout the project, not only do students learn how IoT techniques and knowledge are able to be applied to the real field but also the company benefits from the collaboration project.

### 5. Discussion and Conclusion

At the end of the semester, course evaluation was conducted anonymously by the students. Table 8 shows the evaluation items related to the project and lab activities and score. The score was calculated based on responses of each evaluation item. Response options (score) are Strongly Agree (5), Agree (4), Neither Agree nor Disagree (3), Disagree (2), and Strongly Disagree (1). Therefore, the maximum and minimum scores are 5 and 1, respectively. The enrollment of the course was 21, and the response rate for the course evaluation was 57.14%. Students mostly responded positively to the course, and specifically, the learning content included in the lab portion of this course. Moreover, students indicated that the
combination of the semester-long project work and lab work helped them achieve practical and applicable skills—even asking to expand the content within the lab.

On top of that, in the course evaluation, we also asked students to share comments about lab. The sentence to ask for comments was “We welcome your comments below. What is something/are some things that the instructor does well, e.g., something you hope that the instructor will continue to do in the class in the future?” All responses were as follows.

- The prelab and lab material were extremely helpful for learning. The assignments made me understand the tasks better. Everything was ready when we arrived to the lab, it was well-structured.
- Lab activities are very helpful for students to experience a broad range of course topics which include sensor implementation, data collection, data storage, data analysis with machine learning models, and visualization. I hope the lab activities will be continued in the class.
- The class instructor did an excellent job during the semester. I consider the class structure outstanding; all the assignments, the laboratories, and the presentations of the industry sponsors made the class develop in an excellent way and increased my interest.
- He does a good job relating the material to real-world use. Also, I would like to highlight TA (because I don’t see a specific spot for him) because he has been an incredibly valuable resource for the lab portion of this class. He has been the most

Table 7. Project category, outcome, and benefit.

<table>
<thead>
<tr>
<th>No.</th>
<th>Category</th>
<th>Outcome and Benefit</th>
</tr>
</thead>
</table>
| 1   | Monitoring system deployment    | • Real-time monitoring system for injection molding machine  
|     |                                 | • Empirical power consumption model based on constructed system |
| 2   | AI application                  | • An AI model to predict running state of machine tool based on sound and power consumption                                                 |
| 3   | Monitoring system deployment    | • Real-time monitoring system for welding lab equipment  
|     |                                 | • Ventilation motor running state and vibration monitoring |
| 4   | AI application                  | • Real-time monitoring system for gearbox condition                                                                                               |
| 5   | Monitoring system deployment    | • An AI model for spindle speed prediction of milling machine based on sound sensor                                                               |
| 6   | AI application                  | • AI models and comparison results for failure prediction of heating element of furnace                                                            |
| 7   | Software development            | • MTConnect adapter software                                                                                                                       |
| 8   | AI application                  | • An AI model to predict cutting state of machine tool based on sound                                                                          |
| 9   | Software development            | • MTConnect adapter software development for measuring workpiece in CNC machine using linear encoder                                                 |

Table 8. Course evaluation and score relevant to lab and project.

<table>
<thead>
<tr>
<th>Evaluation item</th>
<th>Score Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>The course is well organized.</td>
<td>4.58</td>
<td>0.67</td>
</tr>
<tr>
<td>The assignments aid me in achieving the class objectives.</td>
<td>4.83</td>
<td>0.39</td>
</tr>
<tr>
<td>The projects or laboratories aid me in achieving the class objectives.</td>
<td>4.83</td>
<td>0.39</td>
</tr>
<tr>
<td>Lab procedures are clearly explained to me.</td>
<td>4.67</td>
<td>0.89</td>
</tr>
<tr>
<td>Prelab lectures are helpful in my understanding of the lab experiments</td>
<td>4.67</td>
<td>0.89</td>
</tr>
<tr>
<td>The content of the lab is a worthwhile part of this course.</td>
<td>4.92</td>
<td>0.29</td>
</tr>
</tbody>
</table>
attentive and helpful TA I have ever had. He will always help you understand the material and has done a great job supporting the students.

In addition, students suggested to improve the course. The suggestion request sentence was “Make a suggestion(s) for improving the course.” All the responses were as follows.

- The lab sessions can be extended. I really liked the content and the material during lab sessions. The only improvement could be having more time to practice with more lab sessions.
- I would recommend the instructor to maintain the projects with the industry sponsors, as well as the laboratories. Personally, those were my favorite things about the class.
- Maybe doing less labs overall and making them bigger. Some of the steps were repeated between labs, but I think if there were less labs we didn’t repeat steps as much then the extra time could be used effectively for the project.

To summarize, students preferred to perform lab activities over other course materials even when the topics seemed broad and extensive. This may be a result of their motivation to complete the semester-long project, as they saw the connections between that and each lab. By doing industry-collaboration projects, students were able to apply IoT and AI technologies learned from the lab activities to the real field. While the learning outcomes for each lab (indicated in Tables 2-5) were not directly measured, the intentions were to prepare students for real-world work. And, as it is seen, the students perceived the lab/course material to help them complete the project. Vice versa, the skills and experience gained during the project helped them achieve the course and lab learning outcomes. As part of future work, we will explore the feasibility of adapting the course for undergraduate students and scaling it up to wider audiences. A potential strategy we will explore is to repurpose the final projects as case studies and laboratory assignments and provide students with the real data already collected in previous years. Ultimately, by taking an experiential learning approach, students effectively learned IIoT knowledge in smart manufacturing settings to apply their knowledge in real-world practice.

6. Acknowledgments

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References

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Lucas Wiese

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Alejandra J. Magana

Dr. Alejandra J. Magana is the W.C. Furnas Professor in Enterprise Excellence in the Department of Computer and Information Technology and Professor in the School of Engineering Education at Purdue University. Dr. Magana holds a B.E. in Information Systems and an M.S. in Technology, both from Tec de Monterrey, and an M.S. in Educational Technology and a Ph.D. in Engineering Education, both from Purdue University. Her research program investigates how model-based cognition in Science, Technology, Engineering, and Mathematics (STEM) can be better supported by means of expert tools and disciplinary practices such as data science computation, modeling, and simulation. In 2015, Dr. Magana received the National Science Foundation’s Faculty Early Career Development (CAREER) Award for investigating modeling and simulation practices in undergraduate engineering education. In 2016, she was conferred the status of Purdue Faculty Scholar for being on an accelerated path toward academic distinction. And in 2022, she was inducted into the Purdue University Teaching Academy, recognizing her excellence in teaching.

Hector Will

Hector Will is an Assistant Professor in Creative Technologies and Mathematics. His research interests are at the intersection of Science, Engineering, Technology, and Learning. He has experience developing learning materials for emerging topics such as Machine Learning and Quantum Computing using novel technologies.

Martin Jun

Dr. Martin Jun is a Professor of the School of Mechanical Engineering at Purdue University, West Lafayette, IN, USA. Prior to joining Purdue University, he was an Associate Professor at the University of Victoria, Canada. He received the BSc and MASc degrees in Mechanical Engineering from the University of British Columbia, Vancouver, Canada in 1998 and 2000, respectively. He then received his PhD degree in 2005 from the University of Illinois at Urbana-Champaign in the Department of Mechanical Science and Engineering. His main research focus is on advanced multi-scale and smart manufacturing processes and technologies for various applications. His sound-based smart machine monitoring technology led to a start-up company on smart sensing. He has authored over 150 peer-reviewed journal publications. He is an ASME fellow and Area Editor of Journal of Manufacturing Processes. He is also the recipient of the 2011 SME Outstanding Young Manufacturing Engineer Award, 2012 Canadian Society of Mechanical Engineers I.W. Smith Award for Outstanding Achievements, and 2015 Korean Society of Manufacturing Technology Engineers Damwoo Award.
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1. Introduction

Demand for STEM professionals in the US is growing. However, some students interested in becoming STEM professionals are finding math anxiety (MA) to be a barrier to their success. STEM professionals, such as mathematicians (M), engineers (E), and natural scientists (S-Nat), depend heavily on theoretical mathematics (math “knowing”), while social scientists (S-Soc) and technologists (T) depend on practical applications of mathematics (math “doing”). Furthermore, technologists need more mathematical literacy than non-STEM professionals. STEM professions that depend on “math knowing” and those that depend on “math doing” require different levels of mathematics, which may be a significant consideration when choosing a STEM major and deciding whether to remain in that major. Math anxiety (MA) appears to be a factor in both the selection of a STEM major and retention in that major. Much of the past research on MA has been dependent on convenience sampling, resulting in student populations from mostly social science (such as psychology) and mathematics or were not differentiated by major. There is a significant lack of data on MA in engineering and technology majors. There has also been limited exploration of the salient variables contributing to MA in these students. The appropriate method for measuring MA in this population is the AMAS test instrument (Hopko et al. 2003). There is a demonstrated connection between MA and math self-efficacy, perceived math value, and perceived control over the math assessment outcome. The author postulates a conceptual framework that uses Bandura’s Self-Efficacy Theory (SET) (1977) and Pekrun’s Control-Value Theory (CVT) (2006) as a canvas upon which to develop subsequent research.

While teaching math-rich courses to technology (T) and engineering (E) students, anecdotal observations suggested that mathematics anxiety (MA) was a potential problem, especially for the T students. Courses would need to be designed to accommodate this problem. The author discovered that the available research on MA was often not applicable to the kind of challenges observed in the students. Many T students assumed the courses were designed to make them engineers; therefore, they were not seeing the value in the subjects for their future as
2. Problem/Topic

Over the course of the author’s teaching and research experience, available research was gathered and organized to answer six questions that will be explored in this holistic review.

1. Why should there be a US national interest in MA? A healthy pipeline (Lord et al. 2019) of technology and engineering technology (T) graduates is important to the US economy. There is increasing demand for professionals with STEM skills, including technologists and engineering technologists, to work on the design and manufacture of products. In the following sections, the author explores the US national interest in MA as reflected by research spending and how it may relate to STEM retention rates and recruitment efforts that increase the number of future STEM professionals. A link is demonstrated between US national interests in STEM professionals and the role that MA plays in that effort. A persistent problem with MA is that it affects recruitment efforts and retention rates.

2. What are the differences between math anxiety and test anxiety? This holistic review defines MA and demonstrates that it differs from other forms of anxiety. It has often been assumed to be the same as test anxiety. There is a functional difference between these two types of anxiety triggers.

3. What are the differences in math knowledge application across STEM career paths? The systematic analysis of a large STEM university shows that the functional application of mathematics skills varies across each STEM profession subgroup. The analysis shows that each STEM subgroup uses math in functionally different ways. The analysis implies that MA may hold a greater importance to the recruitment and retention of technology (T) students.

4. What is the most appropriate method for measuring MA in postsecondary populations that has been validated for race, socioeconomic, and gender differences? A systematic deep dive into the existing MA research on various populations identifies which populations have been studied and what lessons have been learned from those past studies on MA within STEM. A careful review of the literature is required to recommend an MA test instrument for postsecondary STEM students. It requires knowing what methods have been validated for postsecondary populations while considering other variables such as socioeconomic status, gender differences, and racial distinctions.

5. What is not well understood in the characterization of MA in postsecondary STEM populations? The article describes the methods for analyzing the existing body of research and delineates the remaining gaps that should be explored while considering the previous revelations. The history of MA research shows a dangerous reliance on convenience sampling, revealing that T students are missing or were never differentiated in the body of MA research. There are gaps in methodology and weaknesses demonstrated by the available MA meta-analyses.

6. Finally, the author reveals important connections to existing theories with the question, “What connections are known to exist between MA and Bandura’s Self-Efficacy Theory (SET) (1977) and Pekrun’s Control Value Theory (CVT) (2006)?”. There are important connections between MA and other education research topics, such as self-efficacy, value, and control. This holistic review relates the connections that MA has with SET and CVT. The conclusion suggests a conceptual framework that uses SET and CVT as a canvas upon which to design future research and methodologies. This provides a framework for a purposeful and organized plan for exploring MA in T students.

3. Literature Review

3.1 US National Interest in Mathematics Anxiety

3.1.1 Research Dollars

An African American mathematician, Katherine Johnson once said, “We will always have STEM with us. … there will always be science, engineering, and technology. And there will always, always be mathematics (Wild 2015).” The US federal government maintains a database on grants.gov for research opportunities in all sectors of government-funded research related to federal, state, county, or local government goals. A brief search of that database shows that the term “STEM” AND “retention” has 47 posted grant research opportunities. If these are narrowed down to just those within the category called “Science and Technology and Other Research and Development”, it still nets 33 opportunities with funding sources through the Department of Commerce.
The NSF is the “only federal agency whose mission includes support for all fields of fundamental science and engineering. (“About NSF - What We Do | NSF - National Science Foundation” 2022).” Of the seven grant opportunities in the search, the NSF intends to fund $80.8 million to check retention in a minority population (funding opportunities 22-611, 22-602, 20-590, and 18-509); $187 million to provide easier financial access through scholarships (funding opportunities 21-578 and 22-527); and $75 million to two-year institutions that offer STEM degrees within the technology sector. The NSF is “tasked with keeping the United States at the leading edge of discovery in a wide range of scientific areas, from astronomy to geology to zoology (“About NSF - What We Do | NSF - National Science Foundation” 2022).” If the NSF is willing to dedicate $342.8 million of their $8.8 billion (3.9%) annual budget (“At a Glance | NSF - National Science Foundation” 2022) to study STEM retention, it is because STEM retention is one of the “high risk, high pay off (“About NSF - What We Do | NSF - National Science Foundation” 2022)” efforts that ensures that the US is at the leading edge of discovery and remains an influential global power. The NSF defines “high risk, high pay off” as transformative research that can change the understanding of important concepts or lead to the creation of a new paradigm (“Learn About Transformative Research” 2023).

One final piece of evidence of the importance of research in STEM recruitment and retention is an economic one. The pipeline for STEM graduates shows that only 6.9% of 9th graders chose STEM and only 4.2% graduated with a bachelor’s degree in STEM by 2008 (Miller 2015). That is, a retention loss of 39.1%. This ultimately costs the US money because $2.3 trillion in federal taxes are tied to 2 out of 3 workers whose jobs are supported by a STEM industry (IEEE-USA 2020).

US national interests are reflected in how the federal government spends the tax dollars entrusted to them. Just an exploration of the NSF budget revealed a strong national interest in STEM retention. STEM-driven industry is the economic “engine” that runs the US economy, but it is fueled by STEM graduates. One key to a healthy national economy lies in the recruitment and retention of STEM students. The reasons postsecondary students have given for leaving STEM or switching degrees within STEM are as varied as the MA solutions that have been studied.

3.1.2 Recruitment Efforts and Retention Rates

Attracting and retaining students within STEM has been an ongoing subject of research with a wide variety of causal links. Higher levels of MA are associated with lower rates of STEM career choice and reduced retention rates (Paschal 2017; Perez, Cromley, and Kaplan 2014), especially among females (Wierzchowska 2019; Levy, Fares, and Rubinsten 2021; Lin and Deemer 2021; Shapiro and Williams 2012) and minorities (McGee 2018; Meador 2018). Moakler and Kim found that “students were more likely to choose STEM majors if they had strong confidence in mathematics and academic areas and had parents with STEM occupations (Moakler Jr and Kim 2014).” Filer noted that despite females experiencing higher levels of social support and math course taking, they experienced lower mathematics self-efficacy and higher mathematics anxiety and as a result were less likely to enter a STEM field of study than their male counterparts (Filer 2009). Ramirez (N. Ramirez 2017) found that STEM degree retention rates are negatively impacted by MA. College students cited MA as one reason they changed from an engineering major, clearly denying themselves the opportunity to pursue a STEM career with significant economic value personally, locally, statewide, and nationally. The Ramirez dissertation (N. Ramirez 2017) found that engineering students switched disproportionately to technology degrees (41% who switched) and a disproportionate representation of females and underrepresented minorities (URM) switched their major out of engineering. URMs were also more likely not to graduate with any STEM bachelor’s degree. Females and URMs also showed a longer time to graduation, increasing the expense of their bachelor’s degree. The continuum of this negative effect of MA suggests that students starting out in technology degrees may also matriculate out of STEM altogether if MA proves to have a similarly daunting effect. It also suggests that there may be a negative impact of MA on females and URMs in technology or engineering technology degrees. These hypotheses remain to be demonstrated and are recommended future research topics.

Recruitment could also be dampened by MA. Bhowmick and colleagues found that marketing majors often choose their major to avoid the mathematics required of other fields (Bhowmick et al. 2017). Recruitment into STEM may be suffering a dampening effect because of MA. Qualitative research that definitively demonstrates the effect of acute MA on STEM degree choice is lacking.
3.2 Mathematics Anxiety Differs from Other Forms of Anxiety

It is instrumental to define what it means to have MA. The first modern research paper on the topic was by Dreger and Aiken (1957). Its authors “tentatively advanced the term ‘number anxiety’ as a label for the negative emotional reaction to numbers and mathematics (Mammarella, Caviola, and Dowker 2019).” The first mentions of the phrase “mathematics anxiety” occurred between 1960 when it was still called “mathemaphobia” by Aiken, L. R., Jr. (Ma 1999) and 1972 when the first quantitative measurement instrument was created and tested called the Mathematics Anxiety Rating Scale (MARS) (Richardson and Suinn 1972). It was Ashcraft that defined MA most succinctly. “Math anxiety is commonly defined as a feeling of tension, apprehension, or fear that interferes with math performance.” (Ashcraft 2002).

MA is distinctively different from test anxiety, which has a much older research history. Research has found that MA and test anxiety “are related but not equivalent concepts” and that MA “can be viewed as a form of test anxiety” (Kazelskis et al. 2000).” The difference is that test anxiety is related to any type of test-taking nervousness that interferes with performance prior to and during a test, regardless of the test subject.

MA can be experienced during a math test but also outside of a testing scenario. Construction managers, for example, are the engineering technology analog to construction engineers who would design entire temporary support systems such as for temporary earth retention. However, construction managers might have to determine how much force must be distributed with an appropriately sized mudsill underneath a crane outrigger foot to prevent the crane from sinking into soil, causing a loss of support. If construction managers are to choose a safe mudsill size, they must be confident in their grasp of the related stress calculation, for example. Construction managers who experience MA will lack that necessary confidence.

Through correlation analyses, Schillinger showed that MA is inversely related to numerical intelligence but has no correlation to verbal intelligence (Schillinger et al. 2018), directly confirming the predictions made by Dreger & Aiken (1957). Degree of intelligence is not a predictor of MA. Students can be highly verbally intelligent and still experience MA, and students with low verbal intelligence will not necessarily suffer from MA (Schillinger et al. 2018).

A STEM student’s confidence in mathematics may come from how they apply the knowledge they expect to learn when taking a math-rich course. For students pursuing a degree in mathematics, engineering, or the natural sciences, motivation may be more related to what they can know using math. On the other hand, social scientists, technologists, and engineering technologists are more likely to find themselves using math to do tasks. Technologists and engineering technologists use math to create objects through the tangible use of materials. There is therefore a spectrum for the purpose of mathematics in a STEM professional’s education and career. That spectrum will be explored in the next section.

3.3 Differences in Math Application Within STEM

The differences between math knowing and math doing can be represented as a continuum of theoretical to applied mathematics. As a practical way of illustrating this spectrum, the author examined the degree requirements of a large, public, mid-western, R1 research university with many nationally ranked STEM degree programs. The data generated was taken from the university website for each bachelor’s degree program. The 179 BS degree options were listed first by college, then degree (“Majors at Purdue - Undergraduate Admissions - Purdue University” 2022). Then, the highest required math course number was recorded for each bachelor’s degree.

At this university, the courses are given a 5-digit number with that number roughly correlating to the difficulty of the course. A 10000-level course is easier than a 40000-level course, for example. Anything 50000 and above would be considered a graduate-level course. Anything lower than 13800 is below the minimum required mathematics that satisfies the “Quantitative Literacy” foundational requirement all graduates are expected to meet. The highest required math courses were therefore used as an indexing factor for each bachelor’s degree. The theoretical application of math is taught in upper-level courses, while the practical application of math is taught in lower-level courses.

The course number that represents the highest required math was divided by 10,000 to generate indexing numbers ranging from 5.17 to 1.13. The degrees were then separated into which category they fit best within (science (S), technology (T), engineering (E), mathematics (M), and non-STEM). The results are shown in Figure 1 with a range for each category summarized in Table 1.

The non-STEM degrees were still listed below the quantitative literacy requirements because those degrees did not specifically require the higher math that meets the university’s quantitative literacy foundational requirement. The average indexing number for each category shows that, as expected, mathematics (M) degrees require the theoretical application of mathematics much more than those of the other...
er categories. Engineering (E) is also higher on the spectrum. Science (S) balances the spectrum, but if natural sciences such as Physics (S-Nat) are separated from social science degrees such as Anthropology (S-Soc), the spectrum of science degrees bifurcates into two distinct groupings. Technology and engineering technology (T) degrees lagged the other STEM degrees, which is lower than the social science degrees, but well above the non-STEM index.

The conclusion from this exploration of degree requirements is clear: mathematicians (M), engineers (E), and natural scientists (S-Nat) depend more heavily on the theoretical application of the math. However, social scientists (S-Soc), technologists, and engineering technologists (T) depend on practical applications. Clearly, technologists need more mathematical literacy than non-STEM professionals. While a more exhaustive refinement of the theoretical-applied spectrum should be performed using more than just one university, the distinctions suggest that the required level of mathematics may be a significant deciding factor for choosing a STEM degree and for retention rates within each degree. Students’ mathematics self-efficacy and experiences with MA within math-rich subjects can lead to a shift in matriculation within STEM (N. Ramirez 2017) and an as yet definitively researched loss of STEM students who experience MA.

4. Methods and Analysis

The historical context of MA measurement must include some of the earliest work on secondary populations, as these have been used as a springboard for validating the same on postsecondary populations. However, the landscape of research on MA is broad and must be narrowed to a scope relevant to this research.

4.1 Past Research Inclusion/Exclusion Criteria

The most productive databases to search were found by using the search term “mathematics anxiety.” Education Source (ES), Professional Development Collection (PDC), Technology Research Database (TRD), and Scopus were found to return a high percentage of peer-reviewed sources on the subject. It was important to include dissertations and theses because there are relevant dissertations with connections to “mathematics anxiety” in postsecondary populations. Since MA is a relatively young

Table 1. Tabulated theoretical-applied spectrum.

<table>
<thead>
<tr>
<th>Degree Path</th>
<th>No. of Programs</th>
<th>High</th>
<th>Average</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathematics (M) Degrees</td>
<td>13</td>
<td>5.17</td>
<td>4.378</td>
<td>3.01</td>
</tr>
<tr>
<td>Science (S) Degrees</td>
<td>59</td>
<td>5.03</td>
<td>3.111</td>
<td>1.38</td>
</tr>
<tr>
<td>Natural Science (S-Nat)</td>
<td>14</td>
<td>5.03</td>
<td>3.918</td>
<td>3.01</td>
</tr>
<tr>
<td>Social Science (S-Soc)</td>
<td>45</td>
<td>3.01</td>
<td>2.859</td>
<td>1.38</td>
</tr>
<tr>
<td>Engineering (E) Degrees</td>
<td>15</td>
<td>5.11</td>
<td>3.712</td>
<td>2.61</td>
</tr>
<tr>
<td>Technology (T) Degrees</td>
<td>40</td>
<td>3.50</td>
<td>2.498</td>
<td>1.38</td>
</tr>
<tr>
<td>Non-STEM Degrees</td>
<td>52</td>
<td>3.01</td>
<td>1.502</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Figure 1. Mathematics degree requirements on a theoretical-applied spectrum.
research topic, dissertations on that topic could be interesting to a Ph.D. candidate.

By refining the search terms to include “student” but excluding “child”, “adolescent”, and “elementary”, the list of peer-reviewed articles could be narrowed to just those most relevant to postsecondary populations. This initially resulted in too many peer-reviewed articles (ES (67), PDC (60), TRD (81), and Scopus (131)). An additional refining term was added, “self-efficacy”, effectively narrowing the scope (ES (13), PDC (6), TRD (0), and Scopus (77)). Self-efficacy theory (SET) suggests that “a person’s self-confidence about their ability to accomplish a task (Liu and Koirala 2009)” is related to the outcome of that task. As a result, the author dropped the TRD database. By linking to research that includes connections to SET, appropriate potentially testable interventions would also be included.

The next step was to organize the research, which would offer an understanding of where the knowledge gaps are. The list of MA research articles was first ordered by publication date and then by three broad categories: population education level (K-8, secondary, postsecondary, graduate), population subject type (undefined or general, science, technology, engineering, and mathematics), and measurement instrument (quantitative, qualitative, mixed-methods, not applicable). A not-applicable category was included to capture literature reviews, meta-analyses, and commentaries on methods. This effort is a little like mapping the “genealogical lineage” of MA research.

The author mined the bibliographies of some initial sentinel research papers chosen by the frequency of their citations by others (Cho 2022; Hembree 1990; Hopko et al. 2003; G. Ramirez, Shaw, and Maloney 2018; Schillinger et al. 2018) and an oft-referenced book, Mathematics anxiety: What is known and what is still to be understood (Mamarella, Caviola, and Dowker 2019). The author skimmed the articles for population characteristics, methods, MA measurement instruments, and results. This process was repeated for the initial articles’ cited works, then repeated until the origins of MA research and testing were revealed. This process helped confirm the initial sentinel research papers and the historical progression and evolution of the MA test instruments.

The author found a significant secondary observation. During the process of organizing the body of research as described above, the author found that the populations being sampled were frequently convenience samples that were predominantly derived from broad math courses or educational psychology courses.

### 4.2 Historical Context

The history of MA research is relatively short, with the earliest focus on math beginning with Dreger & Aiken (1957). Early test instruments were measures of test anxiety, so they were not ideal for MA. The first dedicated MA test instrument, the Math Anxiety Rating Scale (MARS), was developed and validated by Richardson & Suinn (1972). It quickly became the gold standard for MA quantitative measurement, but it is an onerous test instrument to administer because it is a 98-item, 5-point Likert scale self-report questionnaire. Other shorter tests were developed to address this issue.

A test instrument called the Mathematics Anxiety Scale (MAS) (Fennema and Sherman 1976) (10 questions, 5-point Likert scale) was initially developed for primary and secondary school populations. It was later validated for use on postsecondary populations (Betz 1978). However, the MAS was validated for postsecondary populations based on a small sample size and lacked test-retest data (Hopko et al. 2003). In fact, Bai also noted the relatively small postsecondary student sample and asserted that it weakened the generalizability of that study to other populations (Bai 2011).

Another shorter test instrument is the MARS-Revised (MARS-R) (Plake and Parker 1982) (24 questions, 5-point Likert scale). It was developed for postgraduate student populations and therefore may be less applicable to postsecondary students. One researcher noted that “significant methodological limitations are evident, including small sample sizes and lack of test-retest data” (Hopko 2003).

The Short Math Anxiety Rating Scale (sMARS) developed by Alexander and Matrassy (1989) (25 questions, 5-point Likert scale) is yet another derivative of the original MARS test. The sMARS was developed to test preservice teachers’ MA and later also tested on psychology students. These two populations are very different from the engineering and technology students for reasons previously illustrated by the theoretical-applied spectrum of mathematical application (Figure 1).

The Abbreviated Math Anxiety Scale (AMAS) (9 questions, 5-point Likert scale) developed by Hopko and colleagues (2003) solved some of the issues found in the earlier test instruments. It was developed and validated specifically for postsecondary students, and it investigated demographic characteristics using a statistically meaningful population size. Hopko and colleagues chose to test a large sample (N = 1239) and differentiate it by gender and race. The data gathered using the AMAS were validated against known test instruments. Hopko and colleagues included several additional test inventories. The study used
the MARS-R (Plake and Parker 1982), the State-Trait Anxiety Inventory (STAI, a 40-item scale used to measure state and trait anxiety) (Spielberger et al. 1983), the Test Anxiety Inventory (TAI) (measures anxiety in test-taking situations) (Spielberger 1977), the Beck Anxiety Inventory (BAI) (21-item measure of cognitive and somatic symptoms of anxiety) (Beck et al. 1988), the Fear of Negative Evaluation Scale (FNE) (Watson and Friend 1969) (assesses expectations of negative evaluation), and the 20-item Computer Anxiety Rating Scale (CARS) (Heinssen, Glass, and Knight 1987) which measures anxiety associated with a test-retest reliability interval of 2 weeks. Modifications should be made based on updated classroom language. The updated language should consider how semantics have changed regarding the classroom, using terms such as “screen” instead of “blackboard”, for example. There are two subscales to the AMAS, Learning Math Anxiety (LMA, items 1, 3, 6, 7, and 9 relate to “thinking” about math) and Math Evaluation Anxiety (MEA, items 2, 4, 5, and 8 relate to “doing” math). A high score indicates high math anxiety. The AMAS was also tested with a second independent sample and was found to be consistent with the previous results and reliable. Figure 6 reflects where math anxiety will fit within the conceptual framework that is structured around self-efficacy theory (SET) and control-value theory (CVT). Both theories are discussed in detail below.

The AMAS was later validated by others using English-speaking populations (Jameson and Fusco 2014; Lanius et al. 2022; Westfall, McAuley, and Millar 2021) and adapted to several foreign populations, such as German (Schillinger et al. 2018), Iranian (Vahedi and Farrokhi 2011), Polish (Cipora et al. 2018), Dutch (Schmitz et al. 2022), Spanish (Martin-Puga et al. 2022), and Italian (Primi et al. 2014) populations, making it an international standard. The Programme for International Student Assessment (PISA) study by the Organisation for Economic Co-operation and Development (OECD 2013) has suggested a shorter standard of just five (4-point Likert) statements but the AMAS is more detailed with its two subscales, LMA and MEA that relate well to math thinking vs math doing. This additional detail is important to the conceptual framework presented later. Therefore, the AMAS test instrument is more appropriate for the initial characterization of MA in an under-researched population subgroup, such as engineering, engineering technology, and technology students.

One notable limitation of the AMAS research was that it was not originally validated well for minority populations. Barroso and colleagues (2021) combined data from 104 studies, but only two were based on predominantly Black or Latinx (> 75%) populations. “In the development and validation of the AMAS, “only 84 out of the 1239 (7%) of Hopko et al.’s participants were Black or Hispanic (pg. 4). … Despite the ubiquity of this measure, there is a lack of studies assessing its validity [in underrepresented racial minority (URM) populations]. Moreover, almost all studies have administered the AMAS to a predominantly White (>75%) sample (Cho 2022).”

Cho used a direct measure of MA in URM populations, validating the AMAS as invariant across racial groups (Cho 2022). This is a meaningful trait for the population of engineering technology and technology (T) students. Within STEM, URMs are more represented in T degrees than in the other areas of STEM (N. Ramirez 2017). Community college populations (2-year colleges) have been studied and have been shown to have higher rates of MA (Cho 2022). These 2-year institutions are also frequently in Black or Latinx (> 75%) populations (Cho 2022), the two largest subgroups of URM populations. Two-year institutions are also higher in first-generation college students and students who have lower socioeconomic status (Pascarella et al. 2004; Schwartz et al. 2018; Wildhagen 2015).

It would be appropriate to acknowledge the deep impact that COVID-19 has had on learning any subject in recent years. The AMAS has also been used to study the effects of MA on emergency transitions to remote learning (Lanius et al. 2022). As COVID becomes endemic but managed, it is even more important that MA survey instruments be validated with online students in mind. This mode of learning is an increasingly popular way to earn a degree.

In conclusion, Hopko’s AMAS test instrument (2003) is the appropriate method for measuring MA in this population.

### 4.3 Gaps in the Research

Several gaps in the research were found. The first and most notable is a gap in of MA measurement in engineering, engineering technology and technology students. There is also an abundance of quantitative studies of MA but very few qualitative and mixed-methods studies. Additionally noteworthy, the meta-analyses are older (Hembree 1990; Ma 1999), potentially out of step with today’s generation of students (Ma 1999), or too generalized to a broad age range (OECD 2013; Barroso et al. 2021). New MA research should address each of these gaps.

#### 4.3.1 Population Gaps

There is a significant amount of quantitative research on populations of general postsecondary science (S) (often a social science such as psychology),
and mathematics (M) students. However, there is distinctly limited data on MA measurement and correlations performed on engineering students (E, (Leppävirta 2011)), and lack of data on technology, and engineering technology students (T, no studies were identified). The focus of most of the available research on MA within these STEM fields has been on students within engineering (Alves et al. 2016; Lippert 2020; Nordin et al. 2015), science (Grothérus, Jeppsson, and Samuelsson 2019; Hoffman 2010; Perker 2016), and mathematics (Jia Wang et al. 2017; Liu and Koirala 2009; Raufelder and Ringeisen 2016) or an undifferentiated population (Akin and Kurbanoglu 2011; Erzen and Odaci 2016; Hopko et al. 2013; Kalaycoglu 2015; Ozgen 2013; Primi et al. 2014; Tariq et al. 2013).

No studies of MA were identified on a T student population. A notable gap in T student populations is shown by Hembree’s meta-analysis (1990), discussed in detail below in the section called “Outdated or Broadly Focused Meta-analyses.” One notable study by Lucietto and colleagues (Lucietto et al. 2020) uses a test called the Cognitive-Experiential Self Theory (CEST) (Epstein et al. 1996) to evaluate problem-solving coping skills associated with MA, but it did not measure MA in the relatively small T student population (N = 88, 27 female, 60 male, 1 other). Building coping skills in problem solving is one method used to control the outcome of a math assessment. The “CEST evaluation of thinking styles [are] … two different modes that an individual will use to process information. These two modes are intuitive-experiential [“doing”] and analytical-rational [“thinking”] (pg. 5)”.

4.3.2 Gaps in Methodology

There are limited mixed-methods studies on MA. The ones found include dissertations by Ramirez (N. Ramirez 2017) and Lippert (Lippert 2020) and a study by Jameson (2020). It is incomplete to just measure MA. MA research must correlate it to other previously researched dimensions but also explore the causal links through interviews that clarify how MA is situated in the antecedent experiences of a population. It will be important to hear from the students through qualitative research using semi-structured open-ended interviews (SSOEI). This essential context matters. These studies help correlate the reasons behind mental roadblocks and will aid in identifying viable interventions.

4.3.3 Outdated or Broadly Focused Meta-analyses

Hembree wrote a thorough and frequently cited meta-analysis of the existing studies that quantitatively measured MA (Hembree 1990). The meta-analysis is over three decades old, so it does not include research in the last 32 years or use more refined methods of measuring MA. Additionally, it does not address well challenges faced by females or URMs, a later focus of research. There is a later meta-analysis by Ma (1999), but it focused on secondary and younger populations.

An updated meta-analysis by Barroso and colleagues (2021) noted much more research has been produced over the prior decades. In the meta-analysis by Barroso and colleagues, the population subgroups included were predominantly in subjects characterized as “statistics” and “math”. The math content topics included “approximate number system”, “basic number knowledge”, “whole number calculation”, “word problem solving”, “fractions, decimals, & percentages”, “geometry”, “algebra”, and “statistics”, yet this metaanalysis stretched across age groups spanning from kindergarten to postsecondary school. Here, again, an observed lack of technology-focused subjects and differentiation of postsecondary majors.

The PISA study by the OECD (OECD 2013) has suggested a shorter standard of just five (4-point Likert) statements. The PISA also included an age range of research spanning from kindergarten to postsecondary school, too generalized to a broad age range. The AMAS is more detailed and has two relevant subscales, LMA and MEA. These subscales are important when evaluating the effect that math self-efficacy and math control have on MA.

Nevertheless, there are lessons to be derived from these meta-analyses. Hembree’s goal (Hembree 1990) was “[to integrate the findings of the research on mathematics anxiety, regarding its nature, effects, and relief (pg. 35)]. One of Hembree’s screening criteria for their meta-analysis was that the study must use a validating test instrument called the MARS (Richardson and Suinn 1972). This test was the gold standard for MA quantitative measurement when Hembree’s study was completed in 1990, but, as referenced earlier, the MARS is an onerous test to administer.

Hembree screened 151 studies taken from 49 journal articles, 23 Educational Resources Information Center (ERIC) documents, 75 doctoral dissertations, and 4 reports in other sources. The studies were tabulated by education levels studied. This was important because it shows a skew towards postsecondary research populations (122 out of 151 of the studies included postsecondary populations).

Hembree also delineated the studies by course and major in their Table 7. Hembree found that courses with titles such as “Math for Elementary Teachers”, “Developmental Math”, “Remedial Algebra”, and “College Algebra” had high MA levels (all MARS >
200 indicating higher MA, listed highest first), but course titles such as “Precalculus”, “Elementary Accounting”, “Elementary Statistics”, and “Calculus/Analytical Geometry” (all MARS < 180, indicating lower MA, listed lowest first) were decided lower in MA. Algebra and trigonometry are often a minimum math requirement of technology degrees. Sometimes precalculus or even calculus is needed, especially for engineering technology majors, but it is infrequent for technology degrees to require higher than a precalculus course. Notably, Hembree concludes that “Higher achievement consistently accompanies reduction in mathematics anxiety (Hembree 1990).”

The same Hembree Table 7 shows that math anxiety scores are higher within “Elementary Education”, “Humanities”, “Social Sciences”, “Health Science”, and “Business” (all MARS > 187, listed highest first), but scores are lower for “Math/Science” and “Physical Sciences” (all MARS < 167, listed lowest first). The studies included in Hembree’s metadata either did not delineate students by major, or when they did, the data did not disaggregate engineering (E), engineering technology, or technology (T) students.

Although it still needs to be corroborated with data, Hembree’s meta-analysis implies that higher incidents of MA are expected for careers that fall more on the applied side of the theoretical-applied mathematical continuum illustrated by Figure 1. Those with lower math requirements appear to be at higher risk for math anxiety. Future studies should be developed to verify this implication with scientific reasoning.

These gaps in research represent an opportunity to reveal the nature and extent of MA within post-secondary technology student populations. There are studies that suggest that self-efficacy plays a role in a student’s experience with MA (Dmitri et al. 2020; Starr 2022). Other research posits that experience with MA is correlated with students’ perception of their control over the learning process or perceived future utility (intrinsic and extrinsic value) for mathematical concepts (Bieg, Goetz, and Hubbard 2013; Frenzel, Pekrun, and Goetz 2007).

The proposed conceptual framework posits that the present emotive response to math (such as experiencing MA) will be determined by how they have performed in the past and perceived future for the math skills. Figure 2 is the conceptual framework that proposes to relate MA to the three constructs: self-efficacy, expected value, and perceived control. The three constructs together make up the expected future relationship with math, defining their math self-concept. MA will see increases when one or more of the three constructs are low. Students are at higher risk for MA when they perceive that a math concept holds low future value, for example. A negative outcome produces a feedback loop that reinforces their perceptions, unless effective interventions to MA are deployed. The scholarly justification of these relationships is explored in more detail in the next few sections along with some proposed methods for measuring their influence on MA.

![Figure 2. Relationship of MA to self-efficacy, value, and perceived control.](image-url)
5. Connection Between Math Anxiety and Self-Efficacy Theory (SET)

Bandura was the researcher who defined and developed self-efficacy theory (SET) (Bandura 1977). Bandura defined self-efficacy as “people's judgments of their capabilities to organize and execute courses of action required to attain designated types of performances (pg. 295)” (Gallagher and Kaufman 2004). Math self-efficacy is the concept of confidence in mathematical ability. Interventions designed to increase self-efficacy in a subject are being applied to MA research and measurement because there is a positive correlation between high MA and lower scores on math tests and grades (Barroso et al. 2021; Randhawa, Beamer, and Lundberg 1993).

Proven SET interventions on a general population of postsecondary students can lead to the development of appropriate test-retest solutions on the subpopulation of students who experience MA. To find and understand the link between MA and SET, it should be noted that, self-confidence in one's ability to perform a task (Liu and Koirala 2009) is an affective judgement about oneself. Achievement is damped by negative emotions leading to lower perceived control (Ruthig et al. 2008) and self-efficacy (Villavicencio and Bernardo 2016). Students’ mathematics self-efficacy and experiences with MA can lead to a shift in matriculation or loss of STEM students who experience MA (N. Ramirez 2017). This matters because the spectrum of students’ math foci in STEM can be mapped along a continuum (Figure 1).

Research that has been done on SET has most often been paired with other subjects. Examples relating to mathematics include mathematics achievement (Randhawa, Beamer, and Lundberg 1993; Barroso et al. 2021), mathematical problem-solving (Pajares and Miller 1997), math beliefs (Verdín et al. 2018; Verdín, Smith, and Lucena 2021), math value (Pajares and Miller 1994), and work-related math performance (Stajkovic and Luthans 1998). This evaluation of methods and methodology will focus on the evaluation of mathematics self-efficacy in relation to a mathematics task. Math Confidence Scale (MCS) contains test statements by Hendy and colleagues (Hendy, Schorschinsky, and Wade 2014). The test was internally validated and subsequently revalidated in independent studies by others (Holm-Smith and Lee 2018; Moore 2018; Schuh et al. 2023) seeking similar confirmative answers related to math self-efficacy. The MCS should be used to assess math self-efficacy, but reverse scored. This reverse scoring will allow for consistency with the implied directionality of confidence, low score equals low confidence.

Math self-efficacy, referring to an individual’s judgments of their own mathematical abilities, should not be confused with math self-concept. Math self-efficacy forms part of a person’s math self-concept. Math self-concept, a more complex construct, relates to the belief in one’s ability to control learning and improve one’s math abilities, while math self-efficacy relates to one’s belief regarding their current math performance (Mammarella, Caviola, and Dowker 2019). Bong and Clark (1999) offered an explanation of the difference between self-efficacy and self-concept. They described self-concept as including both cognitive (thoughts about) and affective (feelings about) judgments about oneself. In fact, Parker et al. (Parker et al. 2014) found that while math self-efficacy was a good predictor of university entry math self-concept was a better predictor of entry into a STEM program. Math self-concept is connected to a person’s belief that specific actions will control the math assessment outcome (cognitive) and are based on the outcome’s value to their future. Both intrinsic and extrinsic value types are affective judgements. These will be discussed more in the section below titled “Connection between MA and Control Value Theory (CVT).” Figure 3 reflects where math self-efficacy fits within the conceptual framework that is structured around SET and the Control-Value Theory (CVT). The CVT will be discussed in greater detail in the next section.

6. Connection Between Math Anxiety and Control-Value Theory (CVT)

When a student is faced with a mathematical assessment, they start with a belief in their level of mathematical abilities (good or bad), but they will act on the situation based on two variables: 1) how much they perceive the outcome to be “worth” (value) and 2) the perceived potential of specific actions on the outcome (control). Pekrun's control-value theory (CVT) (2006) is a comprehensive theory that explains this relationship with three component parts: antecedents, self-concept, and achievement. These can be viewed in Figures 2 and 3 above as past (left side), present (right side), and future expected (middle) math relationships.

6.1 Antecedents: Past Relationship

The first component is the student’s appraisal of their antecedent experience with mathematics and retrospective positive or negative emotions. In relation to MA, this is their past interactions with mathematics. This can be represented by prior grades or some other quantitative data such as Likert scale questionnaires but should also include qualitative instruments such as semi structured open-ended interviews (SSOEI).
6.2 Self-concept: Future Expected Relationship

The second component is the student’s math self-concept, specifically, how confident they are with the subject, how much value they place in the math subject, and how much control they perceive they have over learning math. Prospective emotions are derived from the appraisal of their expectations. Self-efficacy was previously proposed to be assessed using MCS (Hendy, Schorschinsky, and Wade 2014). Control and value are measured different from self-efficacy.

Value is a construct relating to the power that math knowledge has over one’s future degree and career. Magana and colleagues (Magana et al. 2016) proposed a questionnaire for computational literacy that could be adapted to mathematical value. The four statements use a 5-point Likert scale. The MA-adapted statements are:

a. “I feel [specific mathematical concept] will be useful in my studies.”

b. “I feel [specific mathematical concept] will be useful in my career.”

c. “I intend to purposefully seek courses that will allow me to increase my knowledge about [specific mathematical concept].”

d. “I intend to use [specific mathematical concept] in my future career.”

To use this questionnaire a specific math subject must be included in the brackets that relates to a specific concept in a course, calculations of center of gravity, for example. This is more appropriate when conducting a test-retest intervention for MA. This method could become an alternate value test instrument when interventions for MA are tested. If a generalizable measurement of math value is wanted, it would be more appropriate to use the Math Value Scale (MVS) by Hendy and colleagues (2014) to assess perceived math value. The MVS test, like MCS, was internally validated and subsequently re-validated in independent studies by others (Moore 2018; Holm-Smith and Lee 2018; Schuh et al. 2023) seeking similar confirmative answers related to math value. In fact, the Holm-Smith and Lee study validated both the MCS and MVS tests in a community college population that varied widely by age, ethnicities, and socioeconomic groups. Figure 4 reflects where perceived math value fits within the conceptual framework that is structured around SET and CVT.

Control, on the other hand, is a construct of an individual’s perceived power to control the mathematical assessment outcome. Math self-concept was described by the OECD as “student’s beliefs in their own mathematics abilities (OECD 2013).” This perceived power to control is driven by how a student identifies themselves with the subject and the actions that can lead to success (Goings 2014). A statement like “I learn Mathematics quickly.” evaluates the students’ perception of power to control the mathematical outcome by defining how they perceive themselves within the subject. This statement comes from the Self-Description Questionnaire (SDQ II), a 5-item, 4-point Likert scale questionnaire based on a longitudinal study done by Parker and colleagues (Parker et al. 2014). The SDQ II is derived from the mathematics portion of earlier work done by Marsh that characterizes self-concept across multiple subject domains (Marsh 1990) with later validation and use by others (Wu et al. 2021; Marsh and O’Mara 2008).
This conceptual framework proposes to use the SDQ II, but reverse scored. This reverse scoring will allow for consistency with the implied directionality of control, low score equals low perceived control.

Figure 5 reflects where perceived control over math assessment outcome fits within the conceptual framework that is structured around SET and CVT.

6.3 Achievement: Present Relationship

The last component of CVT is evaluated through interventions using test-retest protocols. It should assess the student’s present emotional perspective relating to learning mathematics. Future research would need to identify appropriate intervention research. The relationship a population has with MA must be established quantitatively and qualitatively using mixed methods before an appropriate series of test-retest studies may be established. More discussion of these recommendations is synthesized below and illustrated in the final Figure 7.

CVT as it relates to MA predicts that students will experience MA (high AMAS score) if they 1) expect failure (SET) (low math self-efficacy score), 2) believe failure to be harmful to their future (low value appraisal score), and/or 3) are uncertain that they can prevent failure (low math control score). Figure 6 re-
reflects where math anxiety fits within the conceptual framework that is structured around SET and CVT.

The CVT has been used many times since Pekrun proposed it (2006). One notable study compares the learning styles of adult learners versus traditional college students (Jameson and Fusco 2014). Age is often a demographic difference between online versus on-campus students and between transfer versus non-transfer students. Jameson and Fusco found that adult learners scored lower on math self-efficacy the more time that had passed since their last math class. Solutions proposed by Jameson and Fusco included mastery testing which allows for retesting until the student has achieved mastery of the concept. Such a tool can offer students more control over the math assessment outcome.

Bhowmick and colleagues explored the mediating role that MA has on math performance in marketing students' math self-concept (Bhowmick et al. 2017), yet they considered math self-efficacy and perceived control, leaving out how perceived value impacts math performance. The Bhowmick study used a measure of math self-concept proposed by Lee (Lee 2009). It is a 4-item Likert scale test for math self-concept. The actual items are “I have always believed that mathematics is one of my best subjects,” “I learn mathematics quickly,” “In my mathematics class, I understand even the most difficult work,” “I get good grades in mathematics,” and “I am just not good at mathematics”. These statements do not address the value measures that this conceptual framework proposes. Bhowmick and colleagues did find that MA mediates the effects of math self-concept and math self-efficacy on math performance. They recommended math therapy exercises (a math assessment outcome control measure) that can reduce MA levels and increase math self-efficacy and math self-concept.

7. Synthesis and Critique
7.1 Conceptual Framework for Potential Research

The author proposes that the structure of future research adapt Pekrun’s CVT theoretical framework (2006) by including SET (Bandura 1977) as part of math self-concept. A student’s confidence in math will influence how they see themselves faring on a given math assessment. CVT evaluates emotionality and its success/failure predictors. The author included math self-efficacy as an additional affective component that defines math self-concept based on Bandura’s SET theoretical framework (1977). This is illustrated in Figure 7. The final additional boxes represent future intervention research phases. These are included because the related positive and negative reinforcement cycles are only completed using math assessment instruments.

Antecedent beliefs about control and value would be better informed by semi-structured open-ended interviews (SSOEI) and therefore will be among the recommendations for future research. Past GPA, and more specifically math-GPA, can initially serve as predictive data for these antecedent conditions.

Three factors form math self-concept (low self-efficacy, low perceived value, and low perceived control) leading to an increased risk for experiencing MA. Math self-concept forms the future expected...
relationship from math self-efficacy, math value beliefs, and math control beliefs. Past, present, and expected future together form a feedback loop; every math success or failure modifies the past relationship with math. These in turn influence math self-efficacy, math value beliefs, and math control beliefs, leading to an amplifying effect that either reduces or increases the existence and acuteness of math anxiety.

7.2 Math Self-Efficacy

Henry Ford once said, “Whether you think you can, or you think you can’t — you’re right. (Boomer 2014)” Students’ belief that they can or cannot succeed in math is the first predictive barrier. If they are confident of success, this should be reflected in a high MCS score with no negative emotions. On the other hand, if they reflect low self-efficacy (a low MCS score), then they are less confident and expect math failure. This predictive barrier requires interventions that target student confidence in math. Lack of confidence is not the only barrier. Students can be confident in math yet not care (low perceived value) and/or believe the math assessment outcome to be uncertain (low perceived control). These conditions could still lead to math anxiety. Therefore, students mentally process the next barriers, value, and control concurrently. They evaluate whether success on the math assessment is important to their course success (extrinsic value) or career success (intrinsic value).

7.3 Math Value Beliefs

Albert Einstein has been credited as saying “Not everything that can be counted counts and not everything that counts can be counted” (attributed to Albert Einstein) (Toye 2015). If a technology student does not believe the math they are taking “counts” for something they will relegate the subject to a check-the-box task that they do not care about. If the math is perceived to hold high value, this would be reflected in a high MVS score with no negative emotions because they choose to see the intrinsic value of the subject to their career. If a student perceives the math to only have extrinsic value (they only need it to get a good grade, pass the class, or complete a degree), they are likely to do just enough to get by, in other words, check the box. If they hold math to have intrinsic value to their future career, they will want to know how to apply the math to situations they expect to encounter beyond the classroom.

The value barrier requires interventions that prioritize students’ intrinsic value while still helping fortify the extrinsic value of the math. If instructors are successful in increasing students’ perceived value, students must still navigate the control barrier. Even if students consider math to have higher intrinsic or extrinsic value (a moderate to high MVS score), they still need to feel in control of the math assessment outcome by taking actions they believe will improve the outcome. The value and control barriers are navi-
7.4 Math Control Beliefs

“There are two ways to do great mathematics. The first is to be smarter than everybody else. The second way is to be stupider than everybody else — but persistent.” — Raoul Bott, a Hungarian-American mathematician (Quote.cc n.d.). Persistence is reflected in consistently taking action to control one’s learning environment. Math control beliefs stem from how much control over the outcome a student feels in the learning process. The mathematical achievement situation is established by the instructor of a given math assessment such as a test, quiz, or homework assignment. An instructor can also facilitate control options by offering solutions to similar problems, test review sessions, mastery testing, or providing clear and detailed constructive criticism on past performances. Students use this to evaluate their relative level of confidence in the subject, the value they perceive it to have, and their abilities to control the math assessment outcome through actions such as study, attendance in class, or use of the textbook. If they feel in control of the outcome (reflected by a high SDQ II score), then no negative emotions would be expected. If they do not feel in control (reflected by a low SDQ II score), they are likely to experience negative emotions leading to MA and are less likely to engage in moderating and mitigating behaviors such as class attendance, practice problems, study, and approaching the instructor for help.

7.5 Critique

There are several areas where this holistic review could be refined. The first would require a more in-depth look at the theoretical-applied spectrum proposed by Figure 1. There are also limitations from the way the database search was conducted. Finally, the subpopulation of STEM represented by T is itself more diverse as it relates to the required math. These math requirements may merit separation of the T students into two subsets.

As previously stated, the theoretical-applied spectrum was based on the degree requirements of a large, public, mid-western, R1 research university with many nationally ranked STEM degree programs. There are limitations with defining this spectrum with only one university. A more rigorous study should be conducted of multiple universities that reflect the diversity of foci such as public vs. private, research-focused vs. teaching-focused, minority serving, admissions selectivity, cost to attend, and geographic location within the US.

In the initial search for relevant research, perhaps the list could be separately refined using the additional refining term “self-concept” or control-value theory (CVT). This could provide some insight relating MA research on perceived math value, perceived control over math assessment outcomes, or CVT. By independently linking to research that includes MA connections to CVT, additional potentially testable interventions may be revealed. On the other hand, my efforts at constructing the “genealogy lineages” of MA may have found most of the salient research on MA that would relate to perceived math value and control. A later search using “‘math anxiety’ AND ‘self-concept’ NOT child NOT children NOT adolescent NOT elementary NOT primary” found 86 when reduced to peer-reviewed articles in English. A skim through the results found many of the same sources found through the “genealogy lineages” of the MA plus self-efficacy search described earlier.

Lumping technology and engineering technology students together presumes that these subpopulations of T students are sufficiently similar in their incidence and experience with MA. This literature review does not separate the type of T student in its final conclusions, yet it may play a role. As an example, anecdotal observations suggest that the Construction Management (CM) (technology) students have more difficulties in math-rich courses than the Architectural Engineering Technology (ArET) (engineering technology) students taking the same course. This may be because the minimum required math for the ArET degree is higher than for CM. This could be true of other technology degrees compared to engineering technology. Future studies may find that there is a significant MA difference when the population of T students is bifurcated.

8. Conclusions

The US has a national interest in increasing and maintaining the pipeline of STEM professionals entering the workforce. The US demonstrates its interest in STEM through funding research that aims to increase efforts to recruit and retain STEM professionals. Some of these professionals are finding MA to be a barrier to their success (Filer 2009; Moakler Jr and Kim 2014; Paschal 2017; Perez, Cromley, and Kaplan 2014; N. Ramirez 2017). The role of math in a STEM professional’s career extends beyond a testing event. MA can be experienced in the practice of their field.

The differences between math knowing and math doing can be represented on a continuum from theoretical to applied mathematics (Figure 1). Mathematicians (M), engineers (E), and natural scientists (S-Nat) depend more heavily on the theoretical application of the math. However, social scientists
(S-Soc) and technologists (T) depend on its practical application. Technologists also need more mathematical literacy than non-STEM professionals. While the theoretical-applied spectrum should be refined by conducting a broader review of university foci, the initial conclusions suggest that the required level of mathematics may be a significant deciding factor for choosing a STEM degree and for retention rates within each degree. Students’ math self-efficacy and experiences with MA within math-rich subjects can lead to a shift in matriculation within STEM (N. Ramirez 2017) and a hypothesized loss of technology STEM students who experience MA. This possible loss of technology students out of STEM needs conclusive evidence. It has been previously demonstrated that some engineering students matriculate out of engineering into technology degree programs because of the difficulty in the required math (N. Ramirez 2017). It is possible that the same can be said about technology majors matriculating out of a STEM career path. Technology professionals use math to predict safe outcomes from the products and processes that become tangible contributions to the US economy.

Past research has found that the study of MA has been far too dependent on convenience sampling, resulting in a dearth of quantitative research on populations that are science majors (mostly psychology), mathematics majors, or an undifferentiated population. Limited data on engineering majors and no data on technology majors have been identified. This population gap should be closed with a future mixed methods study of MA. There has also been limited exploration of the contributing factors to MA in these students. While Ramirez (N. Ramirez 2017) explored why some engineering majors chose to switch out, the study did not focus on the contributing factors to MA or study the engineering students’ experience with MA. A future mixed methods study should explore those reasons in technology students using a qualitative approach through semi-structured open-ended interviews (SSOEI).

To study MA in any population, it is important that an appropriate method for measuring it is used. It must be validated for use in postsecondary populations, and independently validated for differences in population, such as socioeconomic status, gender differences, and racial distinctions. The AMAS test instrument (Hopko et al. 2003) was found to be a well-documented test instrument meeting these criteria.

There is a demonstrated connection between MA and math self-efficacy, perceived math value, and perceived control over the math assessment outcome. The author proposes to use the control-value theory developed by Pekrun (2006) with modifications that are illustrated in Figure 7. Math self-efficacy (Math failure expected?) and Perceived math value (Math failure Harmful?) are incorporated using the test instruments, MCS and MVS respectively, both developed by Hendy and colleagues (2014). Perceived control over the math assessment outcome (Control action will be successful?) is incorporated using a test instrument, SDQ II, developed by Parker and colleagues (Parker et al. 2014).

Hembree’s findings suggest that MA would be higher in students whose highest required math course is lower in difficulty relative to the other STEM degree programs. Technology programs have lower minimum required math courses, as shown in Figure 1. If Figure 1 were considered together with Hembree’s conclusions, it implies that technology (T) students are predicted to experience MA at higher rates and severities compared to students in science (S), engineering (E), or mathematics (M) degree programs. This needs to be conclusively demonstrated. If T students are found to have higher rates of MA, then it is incumbent on the researcher to determine who experiences it most acutely and why. Quantitative data on MA, self-efficacy, perceived value, and perceived control should reveal students with the highest risk for retention in STEM. Who a high-risk student is should be defined, such as students meeting at least one of the following criteria:

a. a high math anxiety score (in the highest quartile of the AMAS (Hopko et al. 2003),
b. a low math self-efficacy score (in the lowest quartile of the MCS (Hendy, Schorschinsky, and Wade 2014),
c. a low math value score (in the lowest quartile of the MVS (Hendy, Schorschinsky, and Wade 2014), and/or
d. a low math outcome control score (in the lowest quartile of the SDQ II (Parker et al. 2014).

Future studies should interview these high-risk students to identify appropriate interventions to test. Knowing who is at higher risk for failure in math-rich coursework is only the beginning step in finding solutions, but it does help define the target population. Knowing why and how these high-risk T students learn to navigate MA will aid in better recruitment, retention, and instructional efforts through matching targeted solutions that may be tested for viability. Such qualitative research could also present an opportunity to study the effect of acute MA on degree choice which will reveal helpful insight into recruitment efforts. The first step is to quantitatively measure the prevalence and associa-
tions of MA then qualitatively explore the messier questions of what is really driving the problem in students.

Solving the problem of MA may require customization and consideration of equity in the solutions. If, for example, it was found that the weakness a subpopulation has with MA was correlated with low confidence and value perhaps problem-based learning (PBL) approaches could alleviate it. On the other hand, if the population exhibited a weakness for confidence and control then use of mastery tests could reduce MA. Bosman et al. found that service-learning projects that serve a need in a population elicited positive emotive responses such as desire to serve (value) and improve learning skills (control) leading to improved motivation (Bosman et al. 2020). Azad (Azad 2008) proposed relaxation techniques to alleviate anxieties, controlling the emotive response directly. Reducing the gaps for disadvantaged students (STEM minority (women), URM, first-generation college, part-time, and those who need financial aid) was investigated by Takai et al. (Takai, Barker, and Jacky 2023) who found that using equity-minded approaches reduced the performance gap. Instructor proactivity through direct intervention and accepting late assignments, for example adds a degree of student control that can help mitigate challenging life circumstances. A late assignment with penalty is better than no assignment allowing for the student to continue to progress. These and many other potential solutions should target the three constructs of math self-concept (confidence, value, and control) that influence students’ experience with MA. The STEM professions depend on us to mitigate MA in students.

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Development of a Smart Fuzzy–PID Active Control System Without the Need for Direct Muscle or Brain Command Signals

Ammar Alzaydi

Abstract

In an innovative approach to active prosthetic management, this paper introduces a method for intelligent control that circumvents the necessity of expensive sensory systems directly linked to user brain activity, such as muscle signals. The prosthesis autonomously determines the appropriate timing and nature of its movements, showcasing a unique control technique. The study also involves the development and evaluation of an advanced control system, alongside the establishment of a test platform for an Active Prosthetic Knee (APK). The scope of this research spans mechanical design, sensor integration, and motor control tailored to the APK. A noteworthy outcome of this study is the ability to fabricate a durable and cost-effective active prosthetic suitable for individuals with above-the-knee amputations. The resulting prosthesis demonstrates an enhanced capability to mimic the movement of a healthy limb with greater precision, all the while minimizing the physical strain on the patient’s muscles. In terms of movement decision-making, the APK relies on analyzing the motion of the unaffected leg, thus eliminating the requirement for high-priced sensory systems traditionally connected to human brain signals. The intelligent control system has shown a significant improvement in movement precision compared to conventional models, and a reduction in the strain experienced by the user, marking significant strides in active prosthetic technology.

1. Introduction

In the field of active prosthetics, where conventional methods have relied on expensive sensory systems to interpret and respond to signals from the user’s brain, this paper introduces a groundbreaking approach that sidesteps such complexities. Rather than seeking direct input from the brain or muscle signals, it has innovatively developed an intelligent control method that allows the prosthesis itself to decide when and how to move.

The research details a novel control technique that integrates intelligence into the prosthesis. This distinctive strategy facilitates autonomous determination of the timing and nature of movement by the prosthetic limb. In simple terms, the prosthetic "learns" to function in a manner that’s sensitive to the user’s natural gait and movements, without requiring a connection to the brain or muscles.

A significant portion of the paper is dedicated to the design, development, and rigorous testing of an intelligent control system specifically crafted for an Active Prosthetic Knee (APK). The development process involved multifaceted aspects, including the mechanical construction of the APK, its associated sensing system to perceive movements, and the motor controllers that drive its motion.

The mechanical design aimed to create a robust structure that would withstand daily wear and tear. The sensing system’s role was to capture and analyze the movements of the healthy leg, translating them into actionable information. The motor controllers then used this information to guide the APK’s movements in a way that mimicked the natural motion of a healthy limb.

One of the standout merits of this research lies in its potential to revolutionize the availability of active prosthetics for above-the-knee amputees. By eliminating the need for costly sensory systems that tap into human brain signals, it opens up possibilities for creating active prosthetics that are both robust and affordable. This technological advancement could make life-changing devices accessible to a broader population.

Another significant advantage is the ability of the developed prosthetic to accurately replicate the motion of a healthy limb without exerting any additional strain on the patient’s muscles. This achievement adds to the quality of life for the wearer by enabling smoother, more natural movement, enhancing both functionality and comfort.

The research heralds a significant leap in prosthetic technology by focusing on intelligent control that draws inspiration from the user’s healthy leg rather than directly connecting to their brain signals.
than relying on expensive and complex connections to the brain. This holistic approach, encompassing design, sensing, and control, not only promotes a more natural movement but also paves the way for a more accessible and affordable active prosthetic system for above-the-knee amputees.

The incorporation of this project into an engineering technology curriculum could offer a comprehensive learning experience for students, addressing various educational aspects crucial for their development. Below is a discussion on how this project aligns with the education of engineering technology students:

1. **Practical Application of Theoretical Knowledge**:
   - **Integration of Disciplines**: The project involves mechanics, electronics, control systems, and computer science. Students can see how different engineering domains interact in real-world applications, enhancing their interdisciplinary understanding.
   - **Hands-on Experience**: Designing and implementing a control system for an active prosthetic knee provides students with valuable practical skills, bridging the gap between theory and practice.

2. **Problem-Solving and Critical Thinking**:
   - **Design Challenges**: Students must navigate through various design challenges, such as choosing the appropriate sensors, designing the control algorithm, and ensuring the mechanical integrity of the prosthetic knee. This enhances their problem-solving skills.
   - **System Optimization**: The need to optimize the system for weight, efficiency, and accuracy fosters critical thinking and the ability to make informed decisions.

3. **Use of Modern Tools and Technology**:
   - **Exposure to Industry-Standard Software**: Utilizing software for simulations, CAD design, and programming provides students with skills that are directly transferable to the workplace.
   - **Hands-on with Emerging Technologies**: Working with modern sensors, microcontrollers, and wireless communication modules ensures that students are up-to-date with current technologies.

4. **Teamwork and Communication**:
   - **Collaborative Environment**: Engineering projects often require collaboration. This project can teach students the importance of effective communication and teamwork.
   - **Documentation and Reporting**: Preparing comprehensive reports, maintaining design documentation, and presenting their findings help in developing students’ technical writing and oral communication skills.

5. **Ethical Considerations and Social Impact**:
   - **Understanding Ethical Responsibility**: Designing prosthetic devices brings an inherent responsibility. Students must ensure that their design is safe, reliable, and accessible, reflecting on the ethical aspects of engineering.
   - **Awareness of Social Impact**: The project’s potential to positively affect the lives of amputees can instill a sense of social responsibility and the desire to contribute to community well-being.

6. **Project Management and Time Management**:
   - **Resource Allocation**: Learning how to allocate resources effectively, including time, money, and manpower, is a critical skill developed through project work.
   - **Deadline Adherence**: Managing the project within a given timeframe teaches students the importance of time management.

7. **Lifelong Learning and Adaptability**:
   - **Staying Current**: The fast-paced evolution of technology necessitates a commitment to lifelong learning, which this project can instill in students.
   - **Adaptability**: Encountering and overcoming unforeseen challenges during the project prepares students to be adaptable and resilient in their future careers.

8. **Industry Relevance and Career Preparedness**:
   - **Alignment with Industry Needs**: Engaging in projects that reflect real-world applications ensures that students are prepared to meet the demands of the workforce.
   - **Portfolio Building**: Successfully completing such a complex and relevant project provides students with a tangible outcome that can be showcased to potential employers, enhancing their employability.

Incorporating a project like the development of an active prosthetic knee into the engineering technology curriculum aligns well with educational objectives, providing students with a holistic learning experience. It not only enhances their technical proficiency but also fosters soft skills such as teamwork, communication, and ethical reasoning, all of which are crucial for their future careers.

1.1 Brief Background
The history of prosthetics dates back to ancient civilizations, with evidence of rudimentary devices crafted by Romans, Egyptians, and Greeks (Aberle,
Powlett, and Cozart 2020). Modern prosthetic technology is broadly categorized into passive and active devices. Passive prosthetics, while more affordable, are limited in movement, often leading to challenges in daily activities. Active prosthetics, equipped with power sources and sensors, allow for more natural motion but come at a higher cost, rendering them inaccessible in lower-income regions like Afghanistan (Hobara 2014; Shepherd et al. 2022; Furuya et al. 2013; Shepherd et al. 2022; Ono and Katsumata 2007).

A significant global population, especially landmine injury victims, face leg amputations, making the need for affordable active prosthetics (priced between $30,000 and $45,000) pressing (Mondal et al. 2023; Subramanian, Shunmugam, and Srinivasan 2023; Kinra and Black 2003; Ryken et al. 2017; Smailytė, Lendraitienė, and Žemaitienė 2023). This paper aims to develop a cost-effective active prosthetic knee (APK) that uses sensors mounted on the healthy leg to control the prosthetic knee’s torque. The project encompasses designing a sensor system to track the healthy leg’s motion, programming a responsive controller, and creating a test platform for performance evaluation.

The project’s novelty lies in its affordability, addressing the urgent need for practical prosthetic solutions globally. It seeks to replicate human gait accurately, control knee motion within a natural range, ensure minimal calibration, maintain user comfort, and utilize precise wireless sensors (Hermez et al. 2023). The test platform simulates realistic walking patterns, with specific speed and motion requirements (Hales et al. 2022). The APK aims to be cost-efficient, versatile, and aesthetically pleasing, setting new standards in prosthetic design that balance functionality, affordability, and user comfort.

2. Brief Literature Review

The control of prosthetic limbs represents a convergence of multiple scientific and engineering domains. Conventional methods often rely on costly sensory systems, posing challenges due to their complexity, cost, and invasiveness.

2.1 Active Prosthetic Systems

Brain-Machine Interfaces (BMIs): Lebedev and Nicolelis, pioneered research on BMIs, providing insight into their vast potential (Lebedev and Nicolelis 2006). Hochberg et al., successfully applied BMI to control robotic arms by paralyzed patients (Hochberg et al. 2012). Wolpaw et al., reviewed the history and current state of BMIs, focusing on direct brain control (Wolpaw et al. 2002).

Muscle-Signal Controlled Prosthetics: Fougner et al., detailed EMG-based control (Saito et al. 2023; Fougner et al. 2012). Parker et al., discussed targeted muscle reinnervation (TMR) (Parker et al. 2006). Englehart and Hudgins, analyzed adaptive classifiers for multifunction myoelectric control (Chang et al. 2023; Englehart and Hudgins 2003; Pradhan et al. 2020).

2.2 Passive and Active Prosthetic Knees

Popovic et al., provided an overview of passive and active prosthetic advantages and limitations (Hochberg et al. 2012). Sup et al., outlined the creation of the Vanderbilt Powered Knee-Ankle Prosthesis (Sup et al. 2009). Varol et al., discussed the control of active prosthetics for rehabilitation purposes (Varol et al. 2010).

2.3 Affordability and Accessibility

Seymour, focused on the challenges of prosthetic cost and accessibility (Seymour 2002; Pasquina et al. 2017; Putri et al. 2023; Baghbanbashi et al. 2022). Ziegler-Graham et al., investigated long-term cost-effectiveness (Ziegler-Graham et al. 2008). Peerdeman et al., outlined the need for lower-cost prosthetic solutions (Peerdeman et al. 2011).

2.4 Sensing Technologies

Dillingham et al., analyzed sensing technologies for prosthetics, including optical and inertial sensors (Dillingham et al. 2001). Biddiss and Chau, Conducted a review of upper-limb prosthetics, focusing on available technologies and their efficacy (Frölke et al. 2023; Pomares et al. 2018; Biddiss and Chau 2007).

2.5 Integration of Movement Control

Hargrove et al., investigated pattern recognition and control strategies for powered lower-limb prosthetics (Hargrove et al. 2007). Dollar and Herr, examined the passive dynamic walking approach to reduce complexity and cost (Hu et al. 2020; Li et al. 2023; Dollar and Herr 2008).

Uniqueness of This Work: This paper presents an innovative departure from the existing body of work in the field of prosthetic control. While BMI, EMG, and traditional sensor technologies have provided valuable insights and advancements, they also come with inherent limitations. This research uniquely integrates intelligent control that draws from the natural movement of the unaffected limb, bridging the gap between sophisticated control mechanisms and affordable, accessible prosthetics.

By avoiding the need for complex, expensive sensory systems, and providing a robust solution for
above-the-knee amputees, this work offers a promising pathway to democratize advanced prosthetic care.

In summarizing the literature, it’s clear that prosthetic limb control intersects numerous scientific and engineering fields, presenting both advancements and challenges. While Brain-Machine Interfaces and Muscle-Signal Controlled Prosthetics have shown potential, they also carry high costs and complexity. The study of passive and active prosthetic knees has advanced, yet there remains a crucial need for affordable and accessible solutions, as highlighted in discussions about prosthetic cost and accessibility.

Sensing technologies have diversified, with optical and inertial sensors being thoroughly analyzed, but the quest for practical and effective solutions continues. Strategies like pattern recognition and passive dynamic walking have emerged for better movement control.

This work sets itself apart by leveraging intelligent control based on the unaffected limb’s natural movement, avoiding costly sensory systems and aiming for accessible prosthetic care for above-the-knee amputees. The findings from the literature survey underscore the significance and potential impact of this research in the field of prosthetic development.

3. Conceptual Overview

In this paper, the already fabricated mechanical prototype of the Active Prosthetic Knee will be thoroughly examined. The focus of this section will be on exploring the various design and implementation alternatives considered for elements such as the sensor system, wireless angle measurement techniques, fuzzy logic control mechanisms, and the testing platform for the APK.

3.1 Sensing Mechanism

To align with the phases of the human gait cycle (Pirker and Katzenschlager 2016), input sensors are employed to ascertain the leg’s position. These sensors form part of a feedback control system, allowing it to recognize the user’s current state and predict subsequent states based on prior information (Coates and Asaki 2019).

This paper considers two types of sensors: electromyography (EMG) sensors and accelerometers. These will be mounted on the unaffected leg to guide the prosthetic knee through the various phases, drawing on readings from the healthy leg.

EMG is a process for measuring and recording the electrical potential generated by muscle cells when they contract or are at rest. Accelerometers, on the other hand, calculate the angle of the healthy femur and tibia throughout the gait cycle. This angle is pivotal for determining the user’s movement and predicting the timing for upcoming phases (Tuuri et al. 2005).

3.2 Communication through Wireless Sensor System

The communication between sensors and microprocessor can be either wired or wireless. The wired method offers relatively rapid data transmission via a dedicated channel, less prone to interference compared to a wireless approach. However, its limitation lies in the cable length connecting the sensors to the microprocessor. To enhance the practicality of the APK, emphasis has been placed on the wireless approach after successfully validating the wired system. Various wireless solutions, such as WiFi, Bluetooth, and Zigbee, along with non-standardized methods operating at unique frequencies, have been explored (Aurégan and Tellier 2019).

3.3 Controller Design

As delineated in section 1.3 Problem Formulation, the paper’s objective is to devise an active prosthetic knee guided by the unaffected leg’s position. Tracking human locomotion within a gait cycle is inherently uncertain and complex due to ever-changing dynamics like variable ground reaction forces. This uncertainty has sparked an interest in artificial neural networks or fuzzy logic-based controllers, each with unique features:

- Neural network systems are robust interpolators, while fuzzy logic systems are modular and handle uncertainty well.
- Unlike neural networks, fuzzy logic systems do not necessitate training.
- Neural networks are computationally expensive due to continuous online training.
- Neural networks must be retrained if disturbances occur, while fuzzy logic can make intelligent choices even with vague input data.
- Utilizing fuzzy logic allows for cheaper sensors, reducing overall costs.

Both methods are viable for building the intelligent control system, yet cost and efficiency must guide the final selection.

3.4 Test Platform Design

The test platform is aimed at emulating the human gait cycle during a steady walk, ensuring the APK mirrors the tibia’s position as in (Kibushi et al. 2018). It necessitates 3 degrees of freedom (DOF) for accurate representation of vertical, horizontal, and angular movements.

Three different designs for the test platform have been examined:

- **Angled Piston Design**: Utilizes three pneu-
matic pistons for 3 DOF, with each piston representing one DOF. They simulate different aspects of the leg’s movement.

• **Cartesian Piston Design**: A more conventional arrangement where three pistons still provide 3 DOF but are installed in a straightforward way.

• **Single Piston Design**: This design simulates only the angular movement of the femur using one piston and springs. Horizontal movement is achieved by making the APK walk on a treadmill in the platform base. This design is to be demonstrated later in the paper.

This segmentation of the paper details the complex considerations in the design and implementation of the APK, from the nuances of sensor selection to the challenges of controller design, highlighting the innovative approaches taken in each area.

4. Proposed Solution

The Active Prosthetic Knee is a knee prosthetic device governed by a microcontroller and equipped with one degree of freedom (DOF) within the knee joint itself. This device employs a DC motor that’s linked to a pulley mechanism, propelling a nut. As the nut shifts along a ball screw, it generates a pivoting motion around the knee joint. An illustration of the prototype, including its essential components, can be found in Figure 1a and Figure 1b.

Composed of aluminum 6061 alloy, the entire assembly exhibits enhanced attributes of weight and strength. The prototype has been engineered to endure a peak dynamic load of 2000 N, corresponding to a 70 kg individual’s weight, and includes a safety multiplier of three. Equipped with a high-torque, high-velocity DC brushed motor, the system achieves a maximum operational speed of 7468 RPM. Although the main focus of this paper is dedicated to the sensor design, control system, and test platform, the subsequent sections will elucidate the proposed solutions for these elements rather than the comprehensive design of the APK itself.

Continuing the experimental work with the DC motor despite its weight and potential noise was due to its cost-effectiveness, simplicity in control, and reliability. Prioritizing these factors over the drawbacks, especially if the primary goal was to develop an affordable and robust solution.

4.1 Proposed Sensing System Solution

The sensing system’s two considered methods exhibit several distinctions, with the primary difference lying in the control system’s electronic facet. In the case of the EMG signal, there is a necessity to amplify and filter it to render a data set that the micro-

![Figure 1a. Schematic of the Active Prosthetic Knee mechanical design.](image-url)
processor can utilize. Conversely, the angular model demands supplementary inputs like foot contacts to more comprehensively accomplish the different phases of the gait cycle. By comparing these methods based on ease of implementation, accelerometers emerge as the preferred option for the sensing system.

4.2 Wireless Sensor System

The selected approach for the solution leverages the Bluetooth protocol integrated within the Nintendo Wiimote, serving as the principal transceiver. This choice offers the advantage of employing the accelerometers to gauge the angles of the human femur and tibia bones, values that are vital inputs for the control system.

In sifting through design options, the focus was limited to wireless solutions that adhere to a collection of standardized communication protocols, as the crafting of new protocols fell outside the purview of this project’s objectives. Additionally, a thorough examination of the technical characteristics of these protocols was undertaken to identify those incompatible with the project’s specific requirements.

Ultimately, an evaluation was performed on the protocols whose specifications closely aligned with the project’s operational conditions. Among these, Bluetooth emerged as the sole wireless protocol that met all criteria. To facilitate a more streamlined implementation, commercially available units like the Nintendo Wiimote and the Sony Playstation SixAxis controllers were examined. Both these devices employ Bluetooth for their communication and come equipped with integrated accelerometers.

A comparative assessment of the two controllers resulted in selecting the most suitable wireless protocol and hardware, tailored to the specific demands of the project.

The selection of the Nintendo Wiimote as the optimal choice is grounded in its superior support system and more economical price point. When assessed for community backing in hardware and the scope of functionalities that align with the project’s prerequisites, the Nintendo Wiimote stands out. Its extensive hardware community is equipped to offer essential support during the various phases of the project’s lifecycle, as well as ensuring that it satisfies all necessary functionalities.

4.3 Control System Proposed Solution

Due to the inherent complexities in tracking the variable patterns of human walking gait, the control system necessitates a framework based on fuzzy logic or an artificial neural network. While the neural network methodology mandates online supervised training to accommodate the system’s changing dynamics, this approach suffers from a need for augmented processing time, possibly impeding system responsiveness and curtailing controller performance.

Although mitigating this issue with a more robust and faster processor is feasible, it conflicts with the underlying goal of creating a budget-friendly solution. Therefore, a control system founded on fuzzy...
logic is identified as the preferred option. Such a structure facilitates the infusion of human-like reasoning into the control mechanism while concurrently minimizing the computational demands linked with online training. The preliminary diagram of this fuzzy logic-centric controller is depicted in Figure 2.

4.4 Test Platform Proposed Solution

As previously outlined, the main function of the test platform is to offer an environment for assessing the APK’s performance within a constant walking gait cycle. Therefore, the selected design must align with the performance requirements intrinsic to a steady walking gait and adhere to a budget constraint of $1000. In this context, the design encompassing a single piston emerges as the unambiguous winner, thanks to its straightforward construction, ability to emulate vertical and angular movements, replication of the gait cycle, and cost-efficiency.

5. Design

This section builds on the foundational solutions set forth earlier, delving into the intricate design of the sensing system, control framework, and test platform.

5.1 Sensing System Design

Accelerometer Setup: The devised sensing arrangement employs two sets of three-axis accelerometers, strategically positioned on each axis of the healthy human leg, as illustrated in Figure 3.

To clarify, two accelerometers are affixed to the healthy femur, and an additional pair is mounted on the tibia. While a solitary accelerometer is sufficient for recording a static angle, capturing a dynamic angle becomes more challenging.

This issue can be circumvented by implementing two accelerometers in conjunction with a single-axis method. The proposed algorithm utilizes two accelerometers, spaced a specific distance D apart, to compute both angular acceleration and velocity.
These values can subsequently be integrated to ascertain the angle traversed. A potential drawback of this methodology is the periodic need for calibration. The conceptual framework involves two accelerometers positioned at a distance \(D (r_2 - r_1)\) from one another, as demonstrated in Figure 3.

The radial acceleration measured by each accelerometer in the \(x\) direction is:

\[
a_{x1} = \omega^2 r_1
\]  

Where \(\omega\) is the angular velocity. The radial acceleration measured by accelerometer 2 is:

\[
a_{x2} = \omega^2 r_2
\]  

The difference of the two accelerometers yields the result below:

\[
a_{x2} - a_{x1} = \omega^2 (r_2 - r_1) = \omega^2 D
\]  

\[
\omega = \frac{a_{x2} - a_{x1}}{D}
\]  

Also, the tangential acceleration (\(y\)-direction) can be measured by the equation:

\[
a_{y1} = \alpha r_1
\]  

Where \(\alpha\) is the angular acceleration. The tangential acceleration measured at accelerometer 2 is:

\[
a_{y2} = \alpha r_2
\]  

Again, taking the difference:

\[
a_{y2} - a_{y1} = \alpha (r_2 - r_1) = \alpha D
\]  

\[
\alpha = \frac{a_{y2} - a_{y1}}{D}
\]  

In this study, the pivotal factor for measuring angular rotation is the distance, \(D\), between two accelerometers. Their readings, captured by a microcontroller, enable calculation of angular movement through time interval \(\Delta t\), inferring angle and motion direction from velocity and acceleration data. This method, effective for rapid rotations with significant angular accelerations, minimizes errors and drift, although its efficacy decreases with very small angular accelerations due to reliance on accurately determining the direction of movement. To address sensor discrepancies, initial calibration is necessary, and threshold selection (\(\omega_t\)) is dependent on sensor performance.

Circuit Development involves subtracting readings from the accelerometers and using an operational amplifier circuit to boost signal gain. The voltage from a DC-DC converter, initially at 7.2 V, is regulated to 5 V and inverted to -7.2 V, employing a 7805 voltage regulator and DC-DC converter. This setup, optimized for high-quality accelerometer output, does not require capacitors for noise filtering.

### 5.2 Wireless Sensor System Design

The development of wireless communications software for this project is structured into three phases, transitioning from C++ to specialized C code for a specific microprocessor.

1. **Phase 1**: Involves developing a C++ utility for connecting to the Wiimote via a USB Bluetooth dongle, allowing for the acquisition of accelerometer data from the Wiimote and Nunchuck controller.

2. **Phase 2**: Entails converting the C++ code into C and making necessary modifications for compatibility with the designated microprocessor. This phase continues to utilize the Nintendo Wiimote’s communication with the computer through USB Bluetooth.

3. **Phase 3**: Completes the software development, shifting the Wiimote’s connection from the computer to a Bluetooth module connected to the microprocessor. This module facilitates communication between the Wiimote and the microprocessor through a serial port connection.

### 5.3 Control System Design

The controller based on fuzzy logic utilizes a feed-forward design, derived from standard empirical data. However, a feed-forward approach is adequate only in typical conditions and becomes ineffective with significant system disturbances. As a result, enhancements to the original controller architecture have been made, integrating a feedback loop that includes a Proportional-Integral-Derivative (PID) controller. This controller tracks the real-time position of the APK. An error signal, resulting from the difference between the actual and desired positions of the APK, is input into the PID controller. This controller then produces a control signal, or torque instruction, that complements the fuzzy logic controller’s output. The fuzzy logic controller determines the current phase of the APK’s gait cycle and provides a corresponding torque output. Simultaneously, the PID controller...
controller adjusts for heightened ground reaction forces by delivering extra torque, ensuring the APK reaches its intended position. The concluding control system is a combination of fuzzy and PID controls, as illustrated in Figure 4.

**Fuzzy Logic Overview:** As touched upon earlier, angle data from the unaffected leg guides the fuzzy logic controller. This data helps identify the APK’s present phase, subsequently instructing the motor with a torque command. The Fuzzy Inference System (FIS) is split into two main parts: a group of input membership functions translating angular data to specific gait cycle phases, and a collection of “if-then” rules that emulate human reasoning within the FIS. Each of the seven gait cycle phases possesses a linked membership function tied to the angle of the healthy leg’s femur and tibia. The corresponding functions for these angular data points can be seen in Figure 5.

The firing of specific rules in the system activates associated output membership functions, drawing parallels to how angular data is mapped via input membership functions. The derived fuzzy output is combined and subsequently translated into a definitive value using a center of heights technique. Figure 6 offers a streamlined visualization of the entire FIS process.

**Fuzzy Rule Framework:** Highlighted below are foundational rules forming the knowledge base for the fuzzy inference process. Here, X1 and X2 represent angular readings from the femur and tibia. The seven phases, namely LR, MST, TST, PSW, ISW, MSW, and TSW, are representative of various stages in the gait, ranging from loading response to terminal swing.

IF X1 is LR AND X2 is LR Then Y is LR
IF X1 is MST AND X2 is MST Then Y is MST
IF X1 is TST AND X2 is TST Then Y is TST

---

Figure 4. Fuzzy-PID control architecture.

Figure 5. Input membership functions.
IF X1 is PSW AND X2 is PSW Then Y is PSW
IF X1 is ISW AND X2 is ISW Then Y is ISW
IF X1 is MSW AND X2 is MSW Then Y is MSW
IF X1 is TSW AND X2 is TSW Then Y is TSW

In any control system, it’s essential to fine-tune it for optimal performance, which is a crucial part of the controller’s design. For the fuzzy logic controller, certain parameters, like the mean and standard deviation associated with the input and output membership functions (based on the Gaussian distribution), demand tuning. The “adaptive network-based fuzzy inference system” (ANFIS) is the technique employed for this adjustment. This method resembles the training process of an artificial neural network where training data is provided to the ANFIS. It, in turn, delivers a refined set of fuzzy parameters for the primary fuzzy logic controller.

The use of Fuzzy Gaussian analysis in this study is motivated by its several advantageous properties:

1. **Smoothness and Symmetry**: The Gaussian distribution’s smooth and symmetric nature facilitates efficient computations, essential for the complex calculations involved in prosthetic control.

3. **Uncertainty Management**: Combining fuzzy logic with a Gaussian distribution enables robust handling of data uncertainty and variability in human movement.
4. **Ease of Integration**: Gaussian functions are mathematically tractable, simplifying their integration into control algorithms and computational models.
5. **Enhanced Decision-Making**: The Fuzzy Gaussian approach allows for smoother transitions in prosthetic movement, providing a more natural user experience.
6. **Probabilistic Reasoning**: This method supports probabilistic reasoning, crucial for making inferences and decisions in the presence of uncertainty.

In essence, the Fuzzy Gaussian method is selected for its computational efficiency, its ability to accurately represent human biomechanics, its robustness in handling uncertainty, and its facilitation of smooth and responsive prosthetic control.

In the case where the motion is completely different from what the fuzzy logic system has been trained on, it may struggle to accurately interpret and respond to the input. However, thanks to the inherent flexibility and tolerance for uncertainty within fuzzy logic systems, it should still be able to generate a safe output, possibly defaulting to a neutral or safe state to prevent any potential harm. Ensuring this safe response under unexpected condi-
tions would be a critical aspect of the system’s design and testing phase.

**Embedded Configuration:** The fused fuzzy-PID controller operates on a 16-bit PICMicro microcontroller (MCU) with a speed of 32MHz, sourced from an 8MHz inbuilt clock amplified by a 4x-phase-locked-loop (PLL) (Malčík and Drhanský 2019). An 80-pin MCU is selected because it meets all I/O and serial communication necessities, offers ample embedded flash storage, and permits external memory extension affordably. The embedded system connects to external peripherals, such as the motor driver, angle detectors, and a Bluetooth module. The software inside this system is built to be interrupt-driven, serving various functions:

- Gathering encoder pulses to fetch speed and position details.
- Guaranteeing proper reception and storage of incoming serial data in a processing buffer.
- Timer disruptions applied in functions necessitating integration, like the PID’s integral control.

Beyond the aforementioned interrupts, the primary software routine involves polling the ADC channels to derive accelerometer readings from the femur and tibia, using four ADC channels in total. This ADC data gets transformed into an angular speed. Recognizing the initial leg position, this speed is integrated to derive the angular position. This angle data then inputs into the run_fuzzyControl function, which yields the required torque instruction and the APK’s intended knee stance. The run_PIDControl function processes this intended position, determining the proportional, integral, and derivative components of the PID control signal. This is then turned into another torque directive and relayed to the motor driver through the Digital-to-Analog Converter (DAC).

5.4 Test Platform Design

According to anthropometric evaluations, the femur’s length is identical to the tibia’s length. With the APK prototype’s tibial length being 0.36 meters, the artificial femur’s length is also set at 0.36 meters. A pneumatic piston, positioned at the midpoint of the femur, actuates it. Given the necessary range of motion from -20° to 30°, the piston’s requisite length is computed to be 152 mm. The pneumatic mechanism will move back and forth at a speed defined by the user to mimic the femur’s movement. The piston’s speed can be altered, allowing for the APK’s testing at increased velocities in the future. The piston’s bore is established by taking into account the femur’s maximum acceleration. With the entire leg assembly weighing 6 kg and having an acceleration of 230 m/s², the needed bore diameter is determined to be 0.020 meters:

\[
\text{bore diameter } d = \sqrt{\frac{4m(\omega r)}{\pi P}} = \sqrt{\frac{4(6 \text{ kg})(230 \text{ rad/s})(0.105 \text{ m})}{\pi(500 \text{ kPa})}} = 0.020 \text{ m}
\]

\[
\omega = 5.08 \text{ rad/s}
\]

\[
\nu = \nu r = 5.08 \times 0.18 = 0.9144 \text{ m/s}
\]

\[
Q = V A = 0.9144 + 4.9087 \times 10^{-4} = 0.44885 \text{ l/s}
\]

A piston with a bore diameter of 0.025 m is selected, including a slight safety margin. Given the need for a swing speed of 5.08 rad/s, the piston must be capable of extending at a velocity of 0.9144 m/s and manage a flow rate of 0.449 l/s, corresponding to the 0.025 m bore. As a result, the pneumatic mechanism must incorporate a double-acting piston that has a 0.025 m bore and can handle a flow rate of 0.449 l/s.

The final expenditure for the original design is calculated at $798.62. However, as the budget allocated for the testing platform is constrained to $1000, a more streamlined circuit must be conceived. A simplified redesign reduces the overall cost to a mere $326.72.

The design includes a top plate that supports the hip joint and pneumatic piston, allowing vertical movement along 1” diameter linear shafts to mimic the hip’s vertical oscillation. The APK will ambulate on a small treadmill positioned at the platform’s base. Additionally, the top plate offers an area where weights can be affixed to imitate a human’s mass. A detailed illustration, complete with labels, of the test platform is depicted in Figure 7. It is important to note that the diagram does not include the foot attachment.

6. Design Analysis

This section will detail if the design presented in the prior segment fulfills the stipulated specifications and requirements.

6.1 Sensing System Design Analysis

Take into account the positioning of two three-
axis accelerometers that are apart by a distance denoted as D, with their X-axes aligned in the orientation illustrated in Figure 8. This arrangement should enable the measurement of radial and tangential accelerations, which, in turn, will determine the angular velocity around the Y-axis (signified as ωy and referred to as the roll rate) and the Z-axis (notated as ωz, known as the yaw rate).

For calculating the rotational rates, the accelerations of the X, Y, and Z-axes are taken from both accelerometer #1 and accelerometer #2. By maintaining a running average of the accelerations (typically around 5 samples at a frequency of 60 Hz), the potential noise can be minimized. The overall magnitude of the rotation rate (ω) is computed directly from the radial acceleration, as depicted in Eqn. 9. If any value of ω falls below a specific threshold (marked as ωt), it is designated as 0 (Kao et al. 2020).

\[ \omega = \frac{\sqrt{|a_{x2} - a_{x1}|}}{D} \]  

(9)

When ω is equal to or greater than ωt, then ω remains as it is. However, if ω is less than ωt, then ω is set to 0. The full magnitude of the rotation rate, as calculated using Equation 9, can be observed in Figure 9.

While the total rotation rate is now identified, there remains ambiguity regarding its direction (indicated by its sign) and the specific rates of rotation about the Y-axis (termed as roll) and the Z-axis (referred to as yaw). To compute these, the angular accelerations concerning the z-axis and y-axis are derived from the accelerations along the Y-axis and Z-axis, respectively, utilizing Equation 8:

\[ \alpha_z = \frac{a_{z2} - a_{z1}}{D} \]  

(10)

\[ \alpha_y = \frac{a_{y2} - a_{y1}}{D} \]  

(11)

When ω is not equal to zero, the values of ωy and ωz can be ascertained by performing the integration of αy and αz. As a result, both the relative magnitude and the orientation of the rotation are derived from the integrated values of the tangential accelerations.
Given that the angular accelerations, \( \alpha_y \) and \( \alpha_z \), increase before \( \omega \), it becomes essential to include the integral of \( \alpha_y \) and \( \alpha_z \) from several preceding time steps before \( \omega \) reaches the \( \omega_t \) threshold. The illustration of this timing is provided in Figure 10.

The combined vector sum of \( \omega_y \) and \( \omega_z \), as derived from Equations 12 and 13, corresponds to the magnitude of the total angular rotation rate, denoted as \( \omega_{total} \).

\[
\omega_{total} = \sqrt{\omega_y^2 + \omega_z^2} \quad (14)
\]

Through utilizing the total rotation rate magnitude computed via Eqn. 9, and by analyzing the relative magnitude and rotation direction determined by Eqn. 12, we are able to derive the yaw and roll.

\[
yaw = \omega * \left( \frac{\omega_z}{\omega_{total}} \right) \quad (15)
\]

\[
roll = \omega * \left( \frac{\omega_y}{\omega_{total}} \right) \quad (16)
\]

An illustrative example showcasing the calculated yaw and roll rates can be found in Figure 11.
training data) is fed into the controller. Figure 12 displays the normalized knee torque against % stride, with vertical lines indicating torque variation. As depicted in Figure 13, the ANFIS output, drawn from the training data, corresponds with the desired knee torque pattern shown in Figure 12. This theoretical examination in Matlab confirms the fuzzy logic controller’s precision under standard conditions.

6.4 Testing Platform Design Analysis

The testing platform has been crafted to imitate a motion range between -20° and 30°, as evidenced in Figure 14. The reciprocating pneumatic’s extension and retraction speeds have also been corroborated as correct.

7. Manufacturing, Testing, And Commissioning

This segment elucidates the outcomes of the completed prototype and its adherence to the designated design prerequisites. Overall, the system aligns with the stipulated design criteria.

7.1 Sensing System

The procedure was tested by affixing two accelerometers to a rigid body, separated by 9.2cm, along with a gyro for comparing angular rates. Figures 15 and 16 exhibit the testing results.

Measurements indicate the method is highly effective for brief, medium-magnitude motions, while encountering issues with very low or high magnitudes or during prolonged motions.

7.2 Wireless Sensor System

Tests involving Wiimote and Nunchuck during the early software development phases concentrated on successful data acquisition. Calibration was performed to rectify minor discrepancies, and subsequent testing ensured proper serial communication setup. The process culminated in successful data transmission, including the conversion of accelerometer readings to angle measurements.

7.3 Controller

Changes to the final control system design were necessary due to certain limitations. Consequently, position control replaced torque control, leading to modifications in the control system architecture. The overly aggressive compensation for overshoot was carefully managed to ensure motion smoothness. The final architecture is revealed in Figure 4.

7.4 Test Platform

Figure 17 displays the completed test platform design for the APK. Constructed from aluminum extrusions, the platform offers two degrees of freedom (DOF). The pneumatic piston supplies one DOF, while the other comes from a set of springs in the hip joint, enabling vertical movement.
8. Recommendations

From the study presented in this document, several strategic recommendations are drawn:

Weight Reduction: The current Active Prosthetic Knee weighs around 6 kg, a substantial part of which stems from the existing DC motor. Substituting this motor with a lighter variant would contribute to a significant reduction in the device’s overall weight.

Safety Enhancements: To enhance the safety of the APK, it would be prudent to incorporate limit switches into the design. These would serve to restrain the knee joint from surpassing the permissible range of motion, thus preventing potential damage or injury.

Alternative Controller Examination: It is suggested to explore the Sony Playstation SixAxis controller for possible integration. The gyroscopes within this controller may offer superior measurements for APK control compared to the current usage of the Wiimote and Nunchuck. This might lead to a reduction in the number of controllers needed, possibly simplifying the process of gauging the phase of the gait cycle.

Further Exploration of Accelerometers: Continued examination and development should be conducted on the implementation of four three-axis accelerometers. The aim would be to ensure that vertical and horizontal accelerations can be negated, leading to an unadulterated angular input for the control mechanism. Currently, the simplified system deploys only two sets of three-axis accelerometers, which may lead to errors when significant vertical and horizontal accelerations are detected. For a comprehensive assessment of the control system, these extraneous accelerations must be eliminated from the control system input.

9. Summary

The increasing global demand for robust and economical active prosthetics underscores the impor-
tance of this project, which aims to create an APK that leverages the healthy leg’s position to determine the necessary torque for knee actuation.

The objectives of this paper encompass the creation of a cost-efficient, durable, and easily calibrated prosthetic knee for above-the-knee amputees. Specifically, the work detailed here includes the design and realization of a sensor system to gauge the position of the healthy leg. The use of a Wiimote, which improves the potential of these strategies in creating more intuitive control of prosthetic devices. It leverages the natural movements of the unaffected limb.

While the use of contralateral control in prosthetic devices has been explored in various studies, the field is continually evolving. Innovations in machine learning, sensor technologies, and biomechanics are consistently pushing the boundaries of what is possible, aiming to create more natural, efficient, and user-friendly prosthetic solutions.

This study marks a major advancement in affordable and efficient prosthetic solutions, introducing an Active Prosthetic Knee (APK) that synchronizes with the natural movements of the unaffected leg for intuitive knee actuation. It encompasses the development of a sensor system, implementation of a Wiimote for positional data, and a fuzzy logic control system, all evaluated on a comprehensive test platform. Prioritizing cost-effectiveness, durability, and ease of calibration, the prototype successfully mimics a consistent walking pattern, demonstrating the feasibility of this innovative approach. Distinctively, this research sidesteps the need for expensive and complex sensory systems, offering a groundbreaking and accessible solution for above-the-knee amputees, and laying the groundwork for future enhancements in prosthetic technology.

10. Suggestions to Further Improve This Project

Given the extensive and thorough nature of your project, there are a few potential areas in which Artificial Intelligence (AI) can be incorporated or leveraged to enhance the functionality, efficiency, and user experience of the APK:

1. **Predictive Modeling with AI:**
   - **Adaptive Learning:** By using machine learning models, the APK can observe, learn, and adapt to unique walking styles, terrains, or special movements (like dancing or running) by analyzing the data from the healthy limb over time (Russell and Norvig 2016).
   - **Predictive Analytics:** AI can predict the intended motion by analyzing patterns from past data. For instance, if a person is always taking a step up with their healthy leg after reaching a certain angle, the pros-
thetic can be ready to replicate that motion without delay (Wang et al. 2016).

2. **Enhanced Feedback Systems:**
   - **Haptic Feedback:** Integrate AI-driven haptic feedback mechanisms that offer users tactile or vibration-based feedback to help them understand the movement of the prosthesis. This can improve the learning curve for new users and provide them with an enhanced sense of control and awareness (Culbertson et al. 2018).

3. **User Interface and Interaction:**
   - **Voice Commands:** Incorporate AI voice recognition systems, allowing users to give verbal commands to their prosthesis for specific movements or calibrations (Hinton et al. 2012).
   - **Gesture Recognition:** By analyzing movements of the upper body or other parts of the user’s body, AI can interpret intended motions for the APK. For example, a certain hand gesture could signify the desire to transition from walking to running (Mitra and Acharya 2007).

4. **Safety and Anomaly Detection:**
   - **Anomaly Detection:** AI can monitor the user’s gait and movement patterns to detect any irregularities or potential issues, notifying users in real-time of any potential problems or malfunctions (Chandola et al. 2009).

5. **Customization and Personalization:**
   - **Personalized Profiles:** Based on user data and AI-driven insights, create personalized movement profiles that can be switched between, depending on activity (e.g., a "jogging mode" or a "stairs climbing mode") (Domingos 2012).

6. **Enhanced Calibration:**
   - **Self-calibrating Systems:** Using AI, the APK can self-calibrate by assessing the environment and its own performance metrics to optimize movement without needing human intervention (Sutton and Barto 2018).

7. **Training and Onboarding:**
   - **Virtual Assistant:** Integrate an AI-driven virtual assistant that guides the user during the initial setup, ongoing usage, and any troubleshooting, making the onboarding process seamless (Milgram and Kishino 1994).
   - **AR Integration:** Pair the APK with Augmented Reality (AR) glasses or apps that visualize the movement, training users on how to walk, climb stairs, or perform other activities with the APK more effectively (Wang et al. 2017).

8. **Maintenance Predictions:**
   - **Predictive Maintenance:** AI can predict when parts of the APK may need maintenance or replacement based on usage patterns, ensuring prolonged effective usage and reducing unexpected breakdowns (Hashem et al. 2015).

9. **Data Collection and User Feedback:**
   - **User Feedback Loop:** Implement AI-driven surveys or feedback systems that learn from user inputs and continuously improve the APK’s performance (Atzori, Iera, and Morabito 2010).
   - **Cloud Integration:** Store and analyze data on cloud platforms, enabling researchers to continuously update and optimize the APK’s algorithms based on large datasets (Jiang et al. 2014).

10. **Collaboration with External Devices:**
    - **IoT Integration:** Connect the APK with other smart devices, like smartwatches, for enhanced monitoring, control, and user feedback (Cordella et al. 2016; Godfrey et al. 2016).

Incorporating some or all these AI-driven enhancements will not only improve the functionality and user experience of the APK but can also contribute to its overall efficiency, making it even more competitive and beneficial for the intended users.

Furthermore, the fuzzy logic systems, produce outputs that can be somewhat opaque, especially when compared to more transparent rule-based or algorithmic approaches. This characteristic can pose challenges in troubleshooting and maintenance, particularly in critical applications like prosthetics. If a part of the system fails or doesn’t behave as expected, addressing the issue can be complex for several reasons:

1. **Lack of Transparency:** The inherent imprecision and lack of clear boundaries in fuzzy logic systems make it difficult to pinpoint the exact source of an issue or understand how specific input changes affect the output.

2. **Complex Interactions:** Fuzzy logic systems often involve complex interactions between multiple rules and input variables. A failure in one part of the system can have cascading effects, complicating the diagnosis and repair process.

3. **Adaptability Challenges:** Fuzzy logic systems are designed to be adaptive and handle ambiguity, which is beneficial for operation
but can make it challenging to isolate problems when they arise.

To mitigate these challenges and facilitate maintenance and repairs, several strategies can be adopted:

1. **Detailed Logging**: Implement comprehensive logging of system inputs, outputs, and internal states. This can help in retracing the steps leading to a failure and identifying the root cause.

2. **Modular Design**: Design the system in a modular fashion, allowing for isolated testing and replacement of individual components.

3. **Diagnostic Tools**: Develop specialized diagnostic tools that can interpret the fuzzy logic system’s behavior and provide insights into potential issues.

4. **User-Friendly Interface**: Create a user-friendly interface that can translate the fuzzy system’s outputs into more understandable terms, helping technicians and end-users to identify and address issues.

5. **Training and Documentation**: Invest in thorough training for maintenance personnel and provide comprehensive documentation, ensuring that they have the necessary knowledge and resources to troubleshoot and fix issues.

6. **Redundancy and Safety Mechanisms**: Implement redundancy and safety mechanisms that can take over or shut down the system safely in case of a failure, preventing further damage and facilitating repairs.

By adopting these strategies, the challenges posed by the opacity of fuzzy logic systems can be mitigated, ensuring that the prosthetic device remains safe, reliable, and maintainable, even when issues arise.

**References**


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A native of Columbus, Ohio, Dr. Ammar Alzaydi has cultivated a notable career in Mechatronics Engineering, culminating in a BASc., MASc., and Ph.D. from the University of Waterloo, Ontario, Canada. His research, characterized by a keen focus on the integration of Artificial Intelligence and Machine Learning, centers on Autonomous Robotics and the enhancement of manufacturing processes. With a balanced approach towards innovation and sustainability, Dr. Alzaydi is dedicated to advancing product design and manufacturing techniques aiming to make a lasting impact on the efficiency and durability of modern manufacturing practices. His work reflects a commitment to the continual improvement and evolution of engineering technology.
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