Practical Skills for Students in Mechatronics and Robotics Education

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Abstract

In September 2019, the fourth and final workshop on the Future of Mechatronics and Robotics Education (FoMRE) was held at a Lawrence Technological University in Southfield, MI. This workshop was organized by faculty at several universities with financial support from industry partners and the National Science Foundation. The purpose of the workshops was to create a cohesive effort among mechatronics and robotics courses, minors and degree programs. Mechatronics and Robotics Engineering (MRE) is an integration of mechanics, controls, electronics, and software, which provides a unique opportunity for engineering students to function on multidisciplinary teams. Due to its multidisciplinary nature, it attracts diverse and innovative students, and graduates better-prepared professional engineers. In this fast growing field, there is a great need to standardize educational material and make MRE education more widely available and easier to adopt.   This can only be accomplished if the community comes together to speak with one clear voice about not only the benefits, but also the best ways to teach it. These efforts would also aid in establishing more of these degree programs and integrating minors or majors into existing computer science, mechanical engineering, or electrical engineering departments.

The final workshop was attended by approximately 50 practitioners from industry and academia. Participants identified many practical skills required for students to succeed in an MRE curriculum and as practicing engineers after graduation. These skills were then organized into the following categories: **professional, independent learning, controller design, numerical simulation and analysis, electronics, software development, and system design**. For example, professional skills include technical reports, presentations, and documentation. Independent learning includes reading data sheets, performing internet searches, doing a literature review, and having a maker mindset. Numerical simulation skills include understanding data, presenting data graphically, solving and simulating in software such as MATLAB, Simulink and Excel. Controller design involves selecting a controller, tuning a controller, designing to meet specifications, and understanding when the results are good enough. Electronics skills include selecting sensors, interfacing sensors, interfacing actuators, creating printed circuit boards, wiring on a breadboard, soldering, installing drivers, using integrated circuits, and using microcontrollers. Software development of embedded systems includes agile program design, state machines, analyzing and evaluating code results, commenting code, troubleshooting, debugging, AI and machine learning. Finally, system design includes prototyping, creating CAD models, design for manufacturing, breaking a system down into subsystems, integrating and interfacing subcomponents, having a multidisciplinary perspective, robustness, evaluating tradeoffs, testing, validation, and verification, failure, effect, and mode analysis.

A survey was prepared and sent out to the participants from all four workshops as well as other robotics faculty, researchers and industry personnel in order to elicit a broader community response. Because one of the biggest challenges in mechatronics and robotics education is the absence of standardized curricula, textbooks, platforms, syllabi, assignments, and learning outcomes, this was a vital part of the process to achieve some level of consensus. This paper presents an introduction to MRE education, related work on existing programs, methods, results of the practical skills survey, and then draws conclusions based upon these results. It aims to create the foundation for standardizing the development of student skills in mechatronics and

robotics curricula across institutions, disciplines, majors and minors. The survey was completed by 94 participants and it was clear that there is a consensus that the primary skills students should have upon completion of MRE courses or a program is a broader multidisciplinary systems-level perspective, an ability to problem solve, and an ability to design a system to meet specifications.

Key Words: Mechatronics, Robotics, Curriculum, Skills

Introduction

Mechatronics and Robotics Engineering (MRE) is experiencing enormous increases in interest among industry, university faculty, and students. Recognizing the need for preparing highly-educated MRE professionals, many universities and colleges are adopting MRE as a distinct degree program [1]. However, there is little agreement on the concepts and skills that such an MRE degree program should cover. This creates challenges for educators and future employers. For educators, the challenge is in defining the essential components of MRE curricula while providing flexibility to tailor those curricula to specific institutions and their needs. For employers, the challenges are to understand what to expect of MRE graduates and to contribute meaningfully to evolving MRE curricula. To overcome these challenges, a multi-university team of faculty has conducted a series of workshops on the Future of Mechatronics and Robotics Education, with financial support from industry partners and a government agency.

The purpose of the workshops was to create a cohesive effort among industry, government, and academia to develop MRE courses, minors and degree programs [2]. MRE is an integration of mechanics, controls, electronics, and software, which provides a unique opportunity for engineering students to function on multidisciplinary teams. Due to its multidisciplinary nature, it attracts a diverse set of innovative students, and graduates better-prepared professional engineers. In this fast-growing field, there is a great need to standardize educational material and make MRE education more widely available and easier to adopt.

In September 2019, the fourth and final workshop on the Future of Mechatronics and Robotics Education (FoMRE) was held at Lawrence Technological University in Southfield, MI. The workshop goal was to form partnerships among participants to ensure that future MRE professionals will have the appropriate knowledge and skills to create value, meet societal needs, and continue their professional development as challenges and technologies arise and evolve. The workshop was attended by approximately 50 practitioners from industry and academia. Participants addressed many issues in MRE education, including practical skills, fundamental concepts, diversity and inclusion, and branding. They identified many practical skills required for students to succeed in an MRE curriculum and as practicing engineers after graduation. These skills were then organized into the following categories: professional, independent learning, controller design, numerical simulation and analysis, electronics, software development, and system design.

Literature Review

Previous studies have shared case studies and brief summaries of existing mechatronics and robotics programs. For example, in 1996 mechatronics programs in Europe, the United Kingdom, Australia, Hong Kong, and the USA were summarized [3]. The authors provided the curriculum from the University of Hull as a typical undergraduate curriculum for the growing

field of mechatronics. In 2003, a case study described the curriculum of the mechatronic engineering undergraduate degree at the City University of Hong Kong [4]. In 2018, a case study of the Robotics Engineering major at WPI shared details of the objectives, outcomes, and curriculum of the program [5]. Each of these studies listed courses in the program reviewed. From the course titles and additional information, some skills and/or topics can be inferred. There are also examples of master's degrees in mechatronics [6]. These skills and topics of the required courses are summarized and compared in Table 1.

Some universities offer mechatronics or robotics as an individual course for a different program. For example, ENSGSI (Ecole Nationale Supérieure en Génie des Systèmes et de l'Innovation) at the Université de Lorraine, France offers a first-year project-based course in mechatronics [7]. Other universities include mechatronics or robotics inspired projects in other courses within their curriculum [8]. Additionally, there are examples of robotics projects for K-16 courses [9]. Skills and topics listed for these additional courses or projects are compared in Table 1.

Table 1 - Skills and topics listed in other mechatronics education studies.

Skills/Topics	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Principles of Design	X	X	X		X		
Computer Programming	X	X	X	X	X	X	X
Materials	X	X					X
Mechanical Systems	X	X	X	X	X	X	
Project management	X						
Electronic design	X	X		X	X	X	X
Control Systems	X	X	X	X		X	X
Actuators, drives, and sensors	X	X	X	X		X	X
Report writing	X		X				
Business and finance	X						
Transducer technology	X						
Microprocessor systems	X	X					
Manufacturing	X	X					
Information systems	X						
Software engineering	X						
Computer Aided Engineering (CAE) / Computer Aided Design (CAD)	X	X			X		
Production management	X						

Digital systems	X		X				
Logic design and programming	X		X	X			
Navigation			X				X
Advanced Math (e.g. differential equations, linear algebra, probability)		X	X				
Embedded systems			X				
Program design			X				
Instrumentation		X					
Optimization				X			
Artificial intelligence				X			
Systems modeling				X			
Rapid prototyping					X		
Robots and society							X
Types of error							X

As shown in Table 1, there is a wide variety of required skills and topics among mechatronics and robotics programs and courses. There is only one common skill listed in all the papers: computer programming. Other differences could be attributed to the level and duration of the programs studied. Additionally, since these studies span over two decades, changes in technology and terminology could also explain some of the differences mentioned as a program should adapt and change over time.

While each program and course is unique, there are reasons to define a common set of skills for mechatronics and robotics programs and courses. The primary reason is to ensure 1) graduate employability, and 2) that students and employers understand the skills a graduate should possess [10, 11]. In 2014, a survey of employers and academics was conducted to identify gaps between STEM industry expectations and the education provided for students [11]. The goal of the survey was to highlight the skills gap. Some suggested solutions to bridge the gap are project-based learning, supporting research programs, developing curricula with industry input, supporting student projects, building student communities, learning through gamification, and a platform for dialog between industry and academia. Project-based learning [7] and student project teams [5, 8] are common in some mechatronics and robotics programs. Another reason to define common skills is to take advantage of standard and shared resources for courses and labs [12]. These shared resources will reduce the development time spent by faculty and staff. Given the multidisciplinary aspect of this field, students benefit when taking courses across programs that share resources.

Mechatronics and robotics are not the first disciplines to define common skills. There have been many case studies and surveys with similar goals. In 1998, academics, engineering students, and

industry professionals were surveyed about the importance of technical knowledge, intellectual skills, attitudes, standards of engineering practice, business practice, international culture, and foreign language proficiency for engineers [13]. The outcome of the survey was a comparison of the importance of specific topics in each area. However, the results are for engineers in general, not a specific discipline. In 2000, there was a case study of the relationship between the needs of industry and the curriculum of a communications systems engineering program in Israel [14]. The relationship was defined with results of a survey of 280 industry professionals with about 40% being graduates of the program being studied. The results include a ranked list of skills for communication systems engineers. In 2004, a joint ACM and IEEE task force met to define curricula guidelines for software engineering [15]. The outcome of the task force was to create a list of knowledge and skills that a software engineering program should include in its curriculum. Additionally, the task force provided guidelines for pedagogy and example curriculum outlines. In 2014, concepts, equipment, and learning objectives for control systems labs were defined via a multi-round Delphi survey panel and a follow-up survey of industry professionals and academics [16]. The outcome of this study provided a rank order of items in each category to guide the development of a control systems laboratory experience, which is an almost-universal component of a mechatronics or robotics program (See Table 1). Finally, in 2016, the PELARS project was started to define 21st Century STEM knowledge and skills in European Union high schools and colleges [17]. PELARS is a collaboration of universities, business, and non-profit organizations. The goal of this project is to create learning analytics of skills that are already defined for a course or program, rather than to define those skills. With each of these studies their respective disciplines were closer to defining common criteria that were shared among industry and academia.

Method
A two-phase process was used to gather information from stakeholders on the practical skills necessary for students in mechatronics and robotics education. The stakeholders included industry professionals, administrators, faculty, and students. In the first phase, breakout sessions were held at the four FoMRE workshops in order to prepare a list of the practical skills a student should have upon completion of a mechatronics or robotics program. The results of these discussions were used to create an online survey that was sent to key stakeholders between October 2019 and January 2020 (see Appendix). The survey questions were organized into seven categories: professional skills, independent learning, numerical simulation and analysis, controller design, electronics skills, software development, and system design. The survey participants ranked each skill in each category on a Likert scale from 1 (least important) to 5 (extremely important).

The survey was also posted to LinkedIn, Twitter, Facebook and listservs such as robotics-worldwide, ASEE Multidisciplinary Division, ASEE Computers in Education Division, ASEE Women in Engineering Division, the Mechatronics Education Community, AA-Robotics, Academic Research and Leadership Network, ASME Dynamic Systems and Control Division, KEEN MRE Subnet, and the industrial advisory board, students, and faculty at some authors' institutions. The survey was completed by 94 participants. The next section summarizes those results in order to identify commonalities that will aid in the development of a cohesive MRE curriculum.

Results

The 90 survey participants had a diversity of roles related to mechatronics and robotics education. Figure 1 presents a summary of their affiliations and shows that the majority of the respondents were academia and industry representatives.
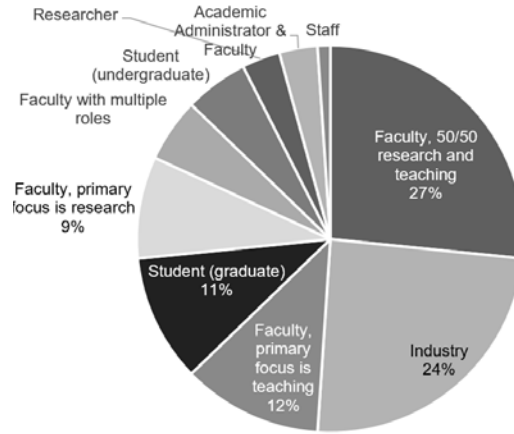

Figure 1: A summary of the roles of the survey respondents

Professional Skills

The workshop participants identified the following professional skills as key for a student completing a mechatronics and/or robotics curriculum: giving a technical presentation, properly documenting a technical project, and writing a technical report. Figure 2 presents a summary of the professional skills responses from the survey participants. It is evident that proper project documentation is extremely important, although writing a report and giving a technical presentation also have merit. Several participants also provided additional skills that they considered vital, such as working well on teams, good communication skills, collaborative work ethic, and networking. There were also a couple of project management skills highlighted, such as task and risk estimation, planning and scheduling a project, and delegating responsibilities.
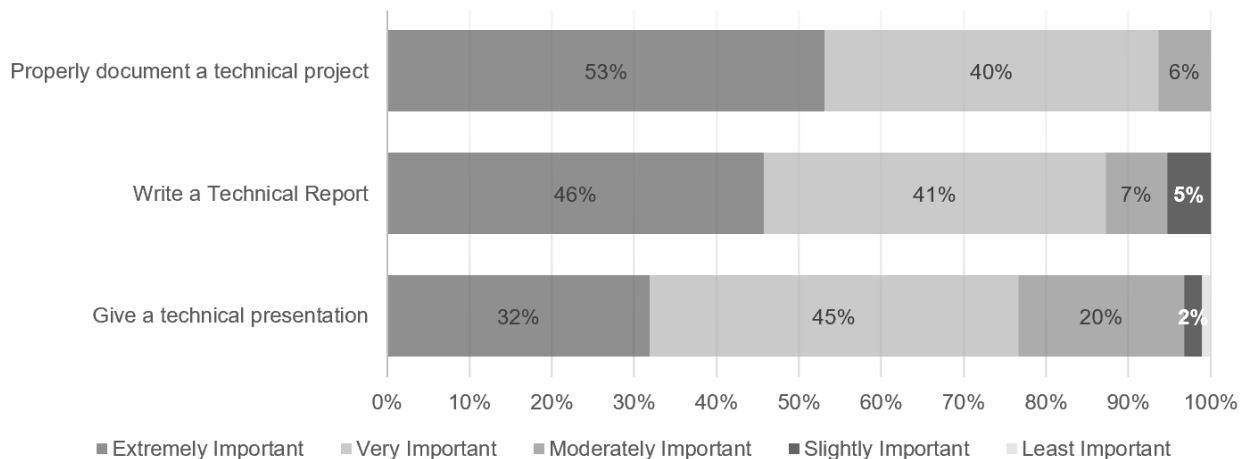

Figure 2: Professional Skills for Mechatronics and Robotics students

Independent Learning

The workshop participants identified the following independent learning skills as key for a student completing an MRE curriculum: perform an internet search for technical information, read and interpret a data sheet, perform a literature review, debug and troubleshoot a system. Figure 3 presents a summary of the independent learning skills responses of the survey participants. It is evident that respondents overwhelmingly believe that students should be able to debug and troubleshoot a system. One respondent opined that a literature review was more for a research-oriented career than actual development, although other respondents felt that the literature review was important. Respondents also generally agreed that students should be able to read and understand research articles, discuss works and results, and properly cite sources. Also important was being able to search for, read and interpret technical information and data. Some other skills identified by participants as important were becoming a technical expert by staying abreast of industry and technological developments, finding and employing industry standards, doing domain research and defining requirements and being able to work with something new with which they have no prior experience.
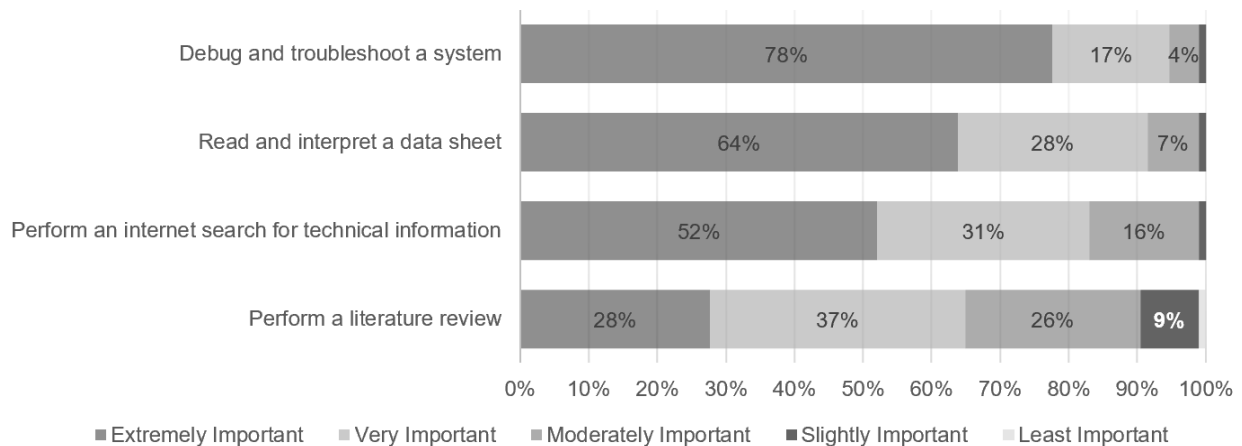

Figure 3: Independent Learning Skills for Mechatronics and Robotics students

Numerical Simulation and Analysis

Numerical simulation and analysis was found to be an important skill in MRE education, in particular being able to interpret data from a system, present data graphically, and solve and simulate a system in software. Figure 4 presents a summary of the numerical simulation and analysis responses of the survey participants. It is evident that interpreting data from a system was universally thought to be extremely important, although opinions were split on presenting data graphically, and solving and simulating a system in software. One respondent felt that these skills were more important for mechatronics than for robotics. Some respondents felt that knowledge of software such as CAD/CAM, LabVIEW, MATLAB, and Simulink was important. Several respondents also felt that some math skills were important such as a basic understanding of probability and statistics, understanding and interpreting statistical process control, and turning math into code. A few other skills were highlighted such as collecting data from a system, designing an experiment to determine the efficacy of a system, evaluating the fidelity of simulations, and reading and presenting data.
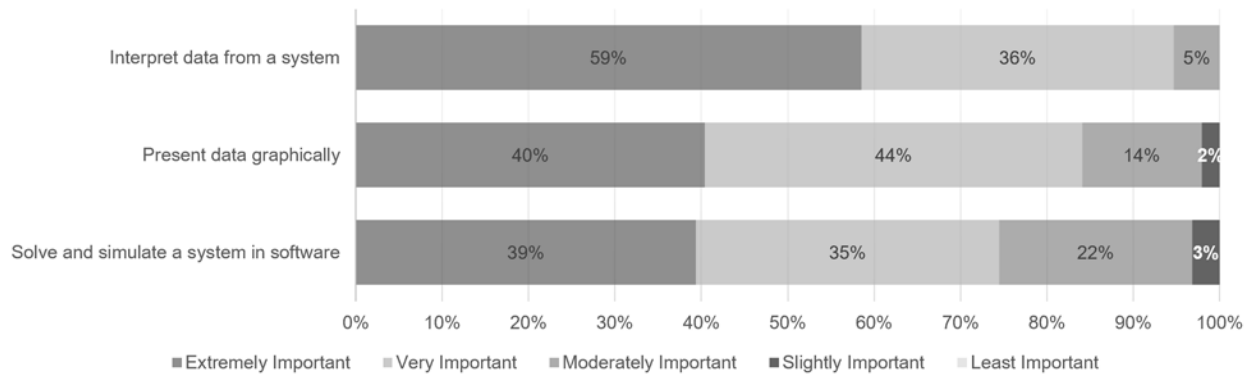
Figure 4: Numerical Simulation and Analysis Skills for Mechatronics and Robotics students

Controller Design

Workshop participants felt that controller design was an important practical skill for MRE, in particular, the ability to select the appropriate controller, tune a controller, and recognize when results are good enough. Figure 5 provides a summary of the responses and indicates that all skills were found to be very to extremely important. It was evident that recognizing when results from a controller were good enough was the most important. Some additional skills that were added by the survey respondents included understanding feedback control, PID control, and a wide range of available controller types. Other participants focused on software such as low-cost controller design, model-based design, using LabView and MATLAB to model the system before applying controls on hardware, programming a controller, and recognizing when simulated results were possible. One respondent felt that understanding measures of success is an integral part of the engineering design process. Although another respondent stated that good enough was never enough. Another response was that tuning a controller was important in linear control but not as relevant in mechatronics because sometimes a state machine or other form of control is important. Finally, one respondent stated that an MRE student should be able to conduct time- and frequency-domain analysis and integrate a chosen controller into a system.
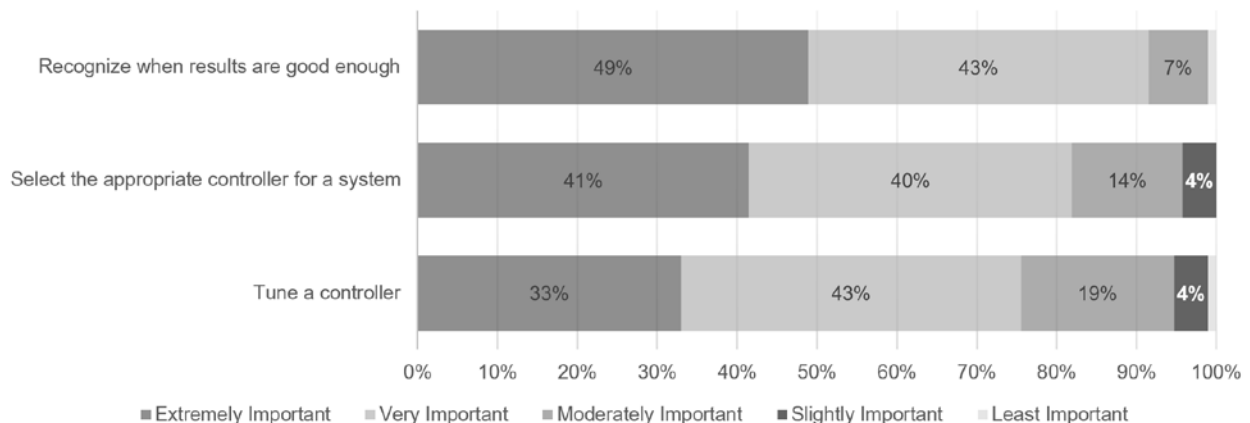

Figure 5: Controller Design Skills for Mechatronics and Robotics students

Electronics Skills
The workshop participants responded that many electronics skills are necessary for students including:

- Select sensors for a system
- Interface sensors
- Interface actuators
- Created a printed circuit board
- Wire a circuit on a breadboard
- Solder
- Use integrated circuits
- Design a board with a microcontroller
- Troubleshoot and debug a circuit

The survey results indicate that there is no strong consensus regarding designing a board with a microcontroller, using integrated circuits, soldering parts, wiring a circuit on a breadboard, or creating a printed circuit board. However skills that were deemed very to extremely important included troubleshooting and debugging a circuit, interfacing with actuators and sensors, and selecting sensors for a system. Figure 6 provides a summary of the results for electronics skills.
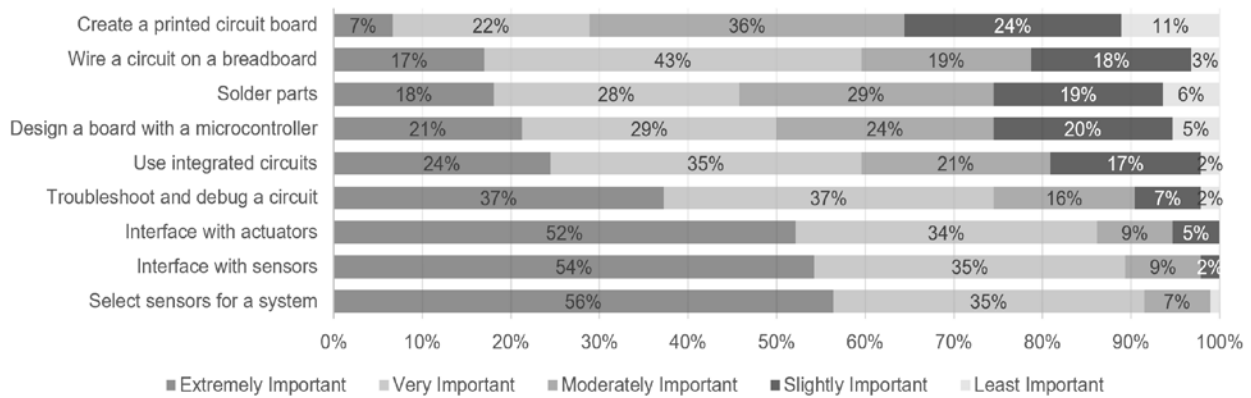

Figure 6: Electronics Skills for Mechatronics and Robotics students

Respondents provided some other electronics skills that they deemed important. One consistent theme is that troubleshooting skills and knowledge of possible hardware problems is key for all students. Respondents felt that using microcontrollers, such as Arduino and Raspberry PI, was more important than designing a circuit from scratch, because most engineers will purchase COTS parts. Students also need to know how to use lab instrumentation and electrical test equipment, such as oscilloscopes, power supplies, programmable loads, etc. It is also necessary to be able to simulate electric circuits in software. In order to protect their devices, students needed to be able to design fuses and circuit breakers and protect a circuit from noise and damage such as overcurrent. There were a few respondents who felt PLC programming, circuit optimization, and selecting actuators for a system were important. One respondent felt that the importance of these skills was dependent upon whether there was manpower in a lab and if the person was a generalist or a specialist.

Software Development

The workshop participants responded that many software development skills are necessary for students including:

- Program a microcontroller
- Install drivers
- Do agile program design
- Create a state machine
- Analyze and evaluate code results
- Properly organize and comment code
- Troubleshoot and debug code
- Use AI and machine learning

Based on the results, the related coding skills of troubleshooting and debugging / organizing and commenting / analyzing and evaluating results were deemed to be extremely important. Almost as important is the ability to program a microcontroller. Beyond that there was no clear consensus regarding doing agile program design, using AI and machine learning and installing drivers. Figure 7 provides an overview of the software development skills responses.
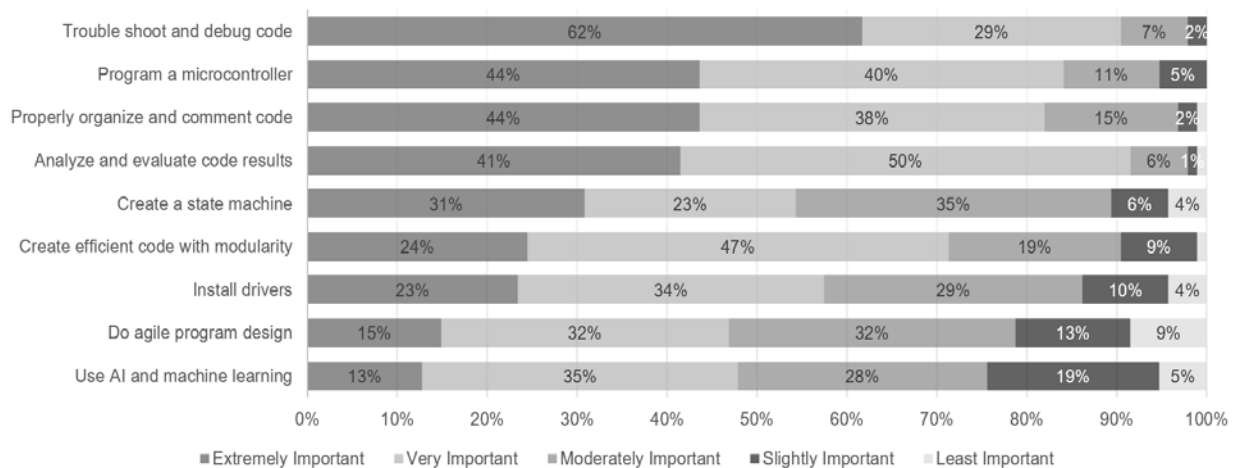

Figure 7: Software Development Skills for Mechatronics and Robotics students

One survey participant felt that many of the skills needed were highly dependent on the type of job that the student would seek after graduation. One participant suggested that a student should know Python, while another felt that more broadly being able to select an appropriate programming language and environment is a necessary skill. A few other skills included being able to connect to a network, interface with other systems, and integrate libraries. Finally, with respect to software system design and maintenance, students should be able to establish ISO design principles, perform unit testing, and perform software lifecycle management.

System Design

The workshop participants responded that many system design skills are necessary for students including:

- Design a system to meet specifications
- Break a system down into subsystems
- Create a prototype for a system
- Create CAD models
- Design for manufacturing
- Integrate and interface subcomponents
- Have a multidisciplinary perspective
- Design for robustness
- Evaluate tradeoffs
- Design tests for a system
- Perform validation and verification
- Conduct failure mode, effect analysis

This category was another one where opinions were split over many of the skills. However, there were a few that had a consensus as extremely important to very important. Most participants agreed that students needed to have a multidisciplinary perspective, be able to break down a system into subsystems, and design a system to meet specifications. There was also some agreement, although not as overwhelming, that students should be able to perform the rest of the skills as well. Figure 8 presents the results of the responses to the system design skills.
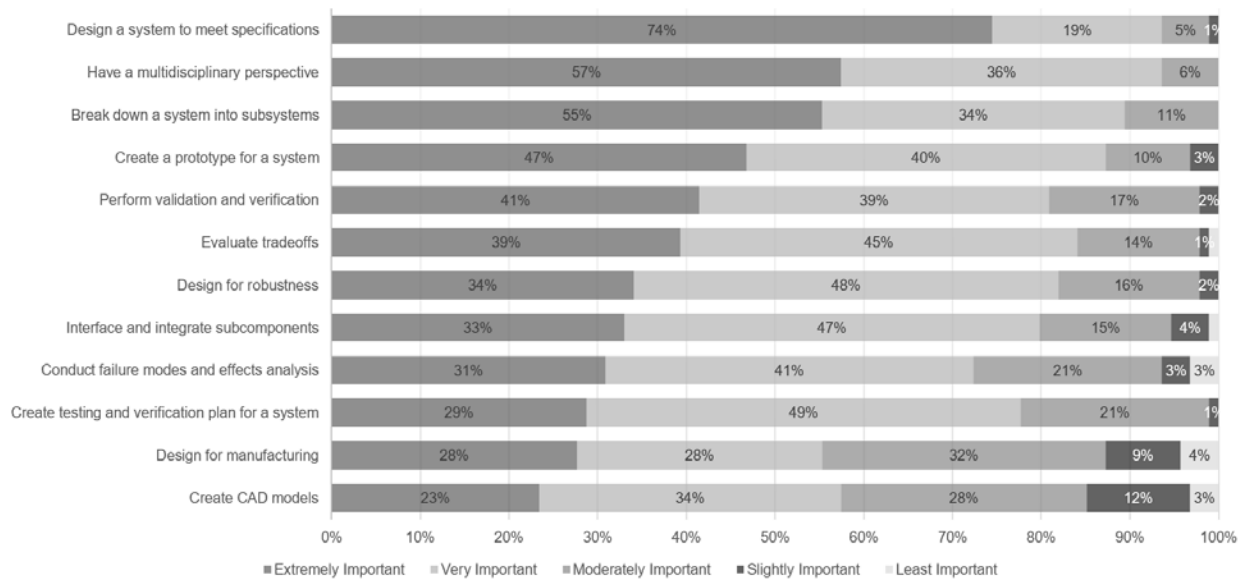

Figure 8: System Design Skills for Mechatronics and Robotics students

One respondent felt that the importance of these skills was dependent upon whether the person was a generalist or a specialist, which was a common theme for many skills. Other skills that respondents felt were important are designing a system that could handle errors and be adaptive. It is also important to extract system requirements based upon customer needs and being able to discuss capabilities of a system with customers. After completing a requirements analysis, participants felt that students should be able to create a system block diagram, create multiple prototypes, and learn how to develop built-in tests throughout the project.

Most Important Practical Skills
Table 2 presents a summary of the most important practical skills over all the categories. It is evident that there is a common thread among them and they are problem solving, systems-level perspective, and design. It is universally agreed that students should be able to debug and troubleshoot hardware and software. Students should also be able to have a multidisciplinary perspective, design to meet specifications, break a system down into subsystems, and properly document their work. Finally, at a technical level they should be able to select sensors and actuators for a system, interface with sensors and actuators, and be able to interpret data from a system.

Table 2 - Most important practical skills over all categories

Category	Skill	Extremely Important	Very Important	Moderately Important	Slightly Important	Least Important
Independent Learning	Debug and troubleshoot a system	77.66%	17.02%	4.26%	1.06%	0.00%
System Design	Design a system to meet specifications	74.47%	19.15%	5.32%	1.06%	0.00%
Independent Learning	Read and interpret a data sheet	63.83%	27.66%	7.45%	1.06%	0.00%
Software Development	Trouble shoot and debug code	61.70%	28.72%	7.45%	2.13%	0.00%
Numerical Simulation and Analysis	Interpret data from a system	58.51%	36.17%	5.32%	0.00%	0.00%
System Design	Have a multidisciplinary perspective	57.45%	36.17%	6.38%	0.00%	0.00%
Electronics Skills	Select sensors for a system	56.38%	35.11%	7.45%	0.00%	1.06%
System Design	Break down a system into subsystems	55.32%	34.04%	10.64%	0.00%	0.00%
Electronics Skills	Interface with sensors	54.26%	35.11%	8.51%	2.13%	0.00%
Professional Skills	Properly document a technical project	53.19%	40.43%	6.38%	0.00%	0.00%
Electronics Skills	Interface with actuators	52.13%	34.04%	8.51%	5.32%	0.00%

There were two respondents who provided an overall perspective on what they thought a student who obtains an MRE degree should be able to do. It adequately summarizes some of the key points made in this section and they are quoted directly below.

"Designing for specifications is integral to mechatronics/robotics design. Have a multidisciplinary outlook and ensuring the design meets specifications is the purpose of a mechatronics/robotics engineer. Some more specific elements like design for manufacturing are more relevant for a development engineer than someone doing more research tasks."

"...I see a mechatronics degree more geared towards the design of automation hardware components (which is what the questionnaire above relates to primarily), while a robotics degree relates more to the overall field of robotics, from the design of robotic hardware (to a lesser degree) to the application of robotics in real life (to a larger degree)."

Conclusions
The purpose of this paper was to work toward creating a standardized MRE curriculum by obtaining feedback from key stakeholders. If this community can come to a general consensus on the practical skills required for any student who completes MRE courses or graduates from an MRE program, then these can be used to inform courses, syllabi and assignments. This will then achieve the goal of making MRE education more widely available and easier to adopt. The survey was completed by 94 participants and there were several consistent themes found among

the respondents. System integration skills and design are the priority, as opposed to very specialized skills. These specialized skills may be dependent upon the particular degree or where the student seeks to work in the future. Some of the general skills that most students were expected to have included having a multidisciplinary perspective, being able to extract system requirements, being able to design to meet specifications, integrate subsystems, and properly document their work. Finally, it is evident that a small sample size of 94 may not be sufficient to inform future curriculum development which will require subsequent surveys and feedback from key constituents. The next steps in this work would then be to use these results to draft necessary course content in an MRE minor or major, which should be helpful for faculty, students, employers, and accreditors.

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Appendix:
Mechatronics and Robotics Practical Skill Survey
Background Information
Please provide the following information about yourself.
Role
_Academic Administrator
_Faculty, primary focus is research
_Faculty, primary focus is teaching
_Faculty, 50/50 research and teaching
_Industry
_Student (undergraduate)
_Student (graduate)
_Other
Professional Skills
Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).
_Give a technical presentation
_Properly document a technical project
_Write a technical report
_Other:
Independent Learning
Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).
   _ Perform an internet search for technical information
   _ Read and interpret a data sheet
   _ Perform a literature review

    _   Debug and troubleshoot a system
    _   Other:

Numerical Simulation and Analysis

Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).

    _   Interpret data from a system
    _   Present data graphically
    _   Solve and simulate a system in software
    _   Other:

Controller Design

Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).

    _   Select the appropriate controller for a system
    _   Tune a controller
    _   Recognize when results are good enough
    _   Other:

Electronics Skills

Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).

    _   Select sensors for a system
    _   Interface with sensors
    _   Interface with actuators
    _   Create a printed circuit board
    _   Wire a circuit on a breadboard
    _   Solder parts
    _   Use integrated circuits
    _   Design a board with a microcontroller
    _   Troubleshoot and debug a circuit
    _   Other:

Software Development

Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).

    _   Program a microcontroller
    _   Install drivers
    _   Do agile program design
    _   Create a state machine
    _   Analyze and evaluate code results
    _   Properly organize and comment code
    _   Troubleshoot and debug code
    _   Use AI and machine learning
    _   Create efficient code with modularity
    _   Other:

System Design

Please rank on a Likert scale the importance of the following skills in mechatronics/robotics education (1 least important to 5 extremely important).

- Design a system to meet specifications
- Break down a system into subsystems
- Create a prototype for a system
- Create CAD models
- Design for manufacturing
- Interface and Integrate subcomponents
- Have a multidisciplinary perspective
- Design for robustness
- Evaluate tradeoffs
- Create testing and verification plan for a system
- Perform validation and verification
- Conduct failure modes and effects analysis
- Other: