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Mechatronics and Robotics Education: Standardizing Foundational Key Concepts

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Before coming to Kenesaw State University, Dr. McFall lived abroad for more than ten years. His international experiences began with a study abroad for his entire undergraduate senior year at the Luleå University of Technology in Sweden 50 miles south of the Arctic Circle. After graduating with his B.S. in Mechanical Engineering from Virginia Tech, his international travels continued during masters studies at MIT with an appointment at the Japan Atomic Energy Research Institute in Japan. His work there involved heat transfer in the superconducting magnet systems for the International Thermonuclear Experimental Reactor project.

Such positive international experiences led to a research fellow position at Dalarna University in Sweden after graduation from MIT with his M.S. in Mechanical Engineering. His research shifted to artificial intelligence and image/signal processing where he was involved in developing an automated winter road condition sensor using artificial neural networks to classify road condition using image and sound input data. The research fellow position at Dalarna University quickly led to a permanent faculty position in the Department of Computer Engineering and Informatics.

In order to help advance his career in academia, he left Dalarna University to pursue a Ph.D. in Mechanical Engineering at Georgia Tech's European campus in Metz, France. He continued working in artificial intelligence by developing an alternative method for solving boundary value problems using artificial neural networks. After getting married soon after graduation, he moved his wife to France where he worked as a Visiting Assistant Professor at Georgia Tech for two years before accepting a tenure-track position Penn State's Lehigh Valley campus. His current position in mechatronics at KSU allows Dr. McFall to live closer to family and pursue his passion for scholarship at a student-centered technical university. His current research focuses on autonomous vehicles, directing numerous student teams to develop sensor systems and actuation control for self-driving cars.

Dr. Kevin Huang, Trinity College

Kevin Huang is an Assistant Professor of Engineering at Trinity College. He received the B.S. in Engineering and Mathematics from Trinity College, and the M.S. and Ph.D. in Electrical Engineering with concentration in Systems, Controls and Robotics at the University of Washington. He is a National Science Foundation Graduate Research Fellow and his research focuses on evaluating haptic feedback, virtual fixtures and usability in telerobotic tasks. He is interested in exploring human factors and human robot interaction.

Hunter B. Gilbert, Louisiana State University

Hunter B. Gilbert received the B.S. degree in mechanical engineering from Rice University, Houston, TX, USA in 2006 and the Ph.D. degree in mechanical engineering from Vanderbilt University in 2016. In 2016, he joined the department of Mechanical and Industrial Engineering at Louisiana State University, Baton Rouge, LA, USA, where he is currently an Assistant Professor of Mechanical Engineering and co-director of the iCORE lab. His research interests include medical robotics, continuum and soft robotics, and other applications of mechatronics in medicine. Dr. Gilbert won the NSF Graduate Research Fellowship in 2012 and was an Alexander von Humboldt Postdoctoral Fellow from 2016-2019 at the Max Planck Institute for Intelligent Systems, Stuttgart, Germany.

Prof. Musa K Jouaneh, University of Rhode Island

Musa Jouaneh is a Professor of Mechanical Engineering in the Department of Mechanical, Industrial, and Systems Engineering at the University of Rhode Island where he has been working since 1990. His research interests include mechatronics, robotics, and engineering education. Dr. Jouaneh founded the Mechatronics Laboratory at the University of Rhode Island, is the author of two text books on mechatronics, is the developer of mechatronics-based tools for engineering education, and is the recipient of several teaching and research excellence awards. He received his Master and Doctorate degrees in Mechanical Engineering from the University of California at Berkeley in 1986 and 1989 respectively. Dr. Jouaneh is a member of ASEE, a senior member of IEEE, and a Fellow member of ASME.

Dr. He Bai, Oklahoma State University

He Bai is an assistant professor in the School of Mechanical and Aerospace Engineering at Oklahoma State University. He received his B.Eng. degree from the Department of Automation at the University of Science and Technology of China, Hefei, China, in 2005, and the M.S. and Ph.D. degrees in Electrical Engineering from Rensselaer Polytechnic Institute in 2007 and 2009, respectively. From 2009 to 2010, he was a Post-doctoral Researcher at the Northwestern University, Evanston, IL. From 2010 to 2015, he was a Senior Research and Development Scientist at UtopiaCompression Corporation. He was the Principal Investigator for a number of research projects on sense-and-avoid, cooperative target tracking, and target handoff in GPS-denied environments. He has published over 70 peer-reviewed journal and conference papers related to control and robotics and a research monograph "Cooperative control design: a systematic passivity-based approach" in Springer. He holds one patent on monocular passive ranging. His research interests include multi-agent systems, nonlinear estimation and sensor fusion, path planning, intelligent control, and GPS-denied navigation.

Dr. David M. Auslander, University of California, Berkeley

David M. Auslander is Professor of the Graduate School, Mechanical Engineering, University of California at Berkeley. His interests include mechatronics, real time software, and mechanical control. Current projects are building energy control, satellite attitude control, mechanical system simulation, and engineering curriculum. He consults in control and computer applications and legal matters. He was a co-founder of Berkeley Process Control, which sold mechanical control products. His education was at Cooper Union and MIT. He has awards from several engineering organizations.

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Introduction

The field of Mechatronics [1] and Robotics [2] Engineering (MRE) is emerging as a distinct academic discipline. Previously, courses in this field have been housed in departments of Mechanical Engineering, Electrical Engineering, or Computer Science, instead of a standalone department or curriculum [3–5]. More recently, single, freestanding courses have increasingly grown into course sequences and concentrations, with entire baccalaureate and graduate degree programs now being offered [6–10]. The field has been legitimized in recent years with the National Center for Education Statistics creating the Classification of Instructional Programs (CIP) code 14.201 Mechatronics, Robotics, and Automation Engineering [11]. As of October 2019, ABET accredits a total of 9 B.S. programs in the field: 5 Mechatronics Engineering, 3 Robotics Engineering, 1 Mechatronics and Robotics Engineering, and none in Automation Engineering.

Despite recent tremendous and dynamic growth, MRE lacks a dedicated professional organization and has no discipline-specific ABET criteria. As the field grows more important and widespread, it becomes increasingly relevant to formalize and standardize the curricula of these programs. This paper begins a conversation about the contents of a cohesive list of key concepts for MRE. The impetus for this effort grew from a set of four industry and government sponsored workshops held around the country named the Future of Mechatronics and Robotics Engineering (FoMRE). These workshops brought together multidisciplinary academic professionals and industry leaders in the field, and ran from September 2018 to September 2019.

The goal of this current work is to survey the MRE community to understand what science, mathematics, and engineering concepts are most vital to the burgeoning field of MRE. Like most engineering curricula, the limits of a typical 120 credit baccalaureate program constrain the amount of content that can be delivered in a program. And MRE programs especially, with their content ranging across mechanics, electronics, and computing, must make judicious decisions about which concepts are included and which are left out. The survey used in this study was designed to identify the relative importance of the many topics important to MRE in order to identify the fundamental key concepts that should be included in all MRE programs. While the study presented here focuses primarily on programs at the baccalaureate level, it also informs discussion at the graduate level as well.

Methods

Survey Distribution

A survey was created in Google Forms and distributed via email and word-of-mouth. The survey was completely voluntary and no compensation was provided to participants. Potential self-selection bias should be noted; respondents who took the time to answer the survey are invested in mechatronics education in some way, and may be more or less inclined to believe change is necessary. Responses were collected for a period of 35 days, starting from the 19^{th} of December, 2019 and closing on the 22^{nd} of January, 2020. The study was approved by the Trinity College Institutional Review Board, and in total, 83 subjects responded to the survey.

As part of the survey, respondents were asked to identify their primary role. These roles are shown below in order of descending number of respondents. The relative percentage of respondents who identified with said role are also shown:

- Faculty, 50/50 Research and Teaching **26** (31.3%)
- Industry **18** (21.7%)
- Undergraduate Student **15** (18.1%)
- Graduate Student **11** (13.3%)
- Faculty, Primary Focus is Teaching **10** (12%)
- Faculty, Primary Focus is Research **6** (7.2%)
- Academic Administrator **1** (1.2%)
- Adjunct Faculty **1** (1.2%)
- Alumnus **1** (1.2%)
- Researcher at Research Center **1** (1.2%)
- Staff 50/50 Teaching and Maintaining Lab **1** (1.2%)

The respondents identified their primary fields of expertise as shown below in Fig. 1

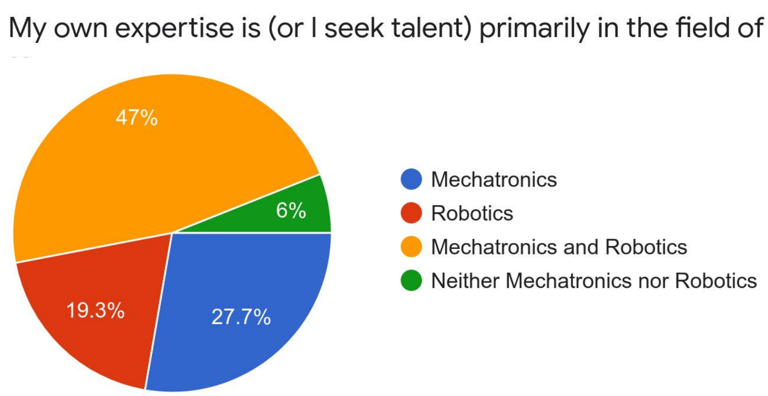

Figure 1: Respondents' fields of expertise. 39 respondents identified with both Mechatronics and Robotics, 23 with Mechatronics, 16 with Robotics, and 5 with Neither Mechatronics nor Robotics.

Survey Questions

Several types of questions were posed in the survey. Beyond the two questions requesting background details (role and area of expertise), we asked participants in sequence four classes of queries. The classes targeted (we also show the number of questions within each class):

i) computational vs. analytical approaches **1**
ii) relative importance of course items **54**
iii) relative importance of concepts within course items **180**
iv) additional comments **2**

The question classes were presented to participants in the order shown above, for a total of 239 questions asked per participant – respondents were not required to answer all questions. The questions in classes i) - iii) were presented as likert rating tasks. The question in class i) was shown as below in Fig. 2.

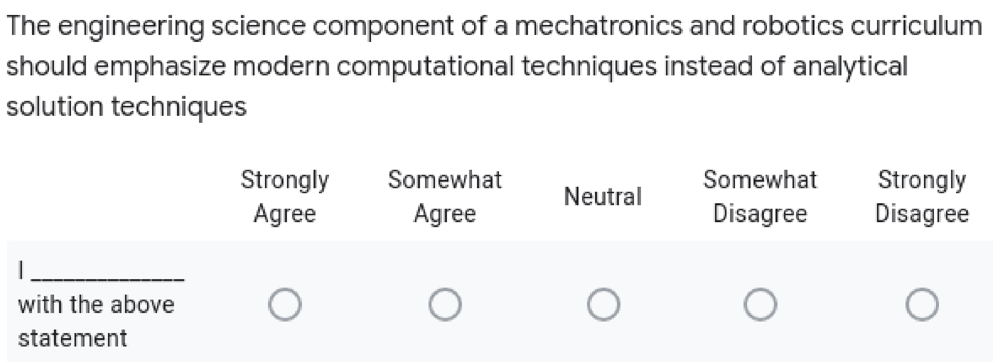

Figure 2: Question asked to participants regarding the relative importance of computational vs. analytical approaches that should be emphasized in mechatronics and robotics curriculum.

For questions in class ii), participants were tasked to "Please rank on a likert scale the importance to mechatronics/robotics education of each of the following course items (1 least to 5 most important)". A sampling of the survey question format is shown below in Fig. 3.

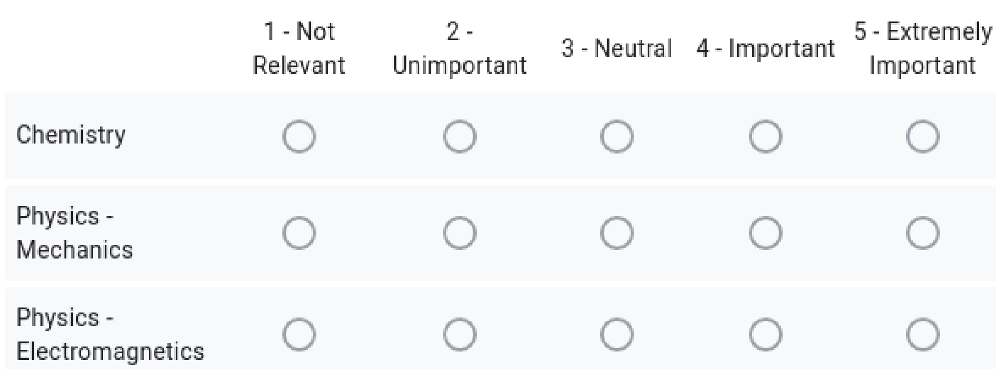

Figure 3: Example likert rating tasks presented to users for evaluating importance of course items in mechatronics/robotics education.

Class iii) questions asked participants to rank importance of concepts within course items on a likert scale. Users were requested: “For each of the below course items you deem important, please rank on a likert scale the importance of the listed concepts (1 least to 5 most important)". A sample of the concept likert scale response format for a particular course item is shown below in Fig. 4.

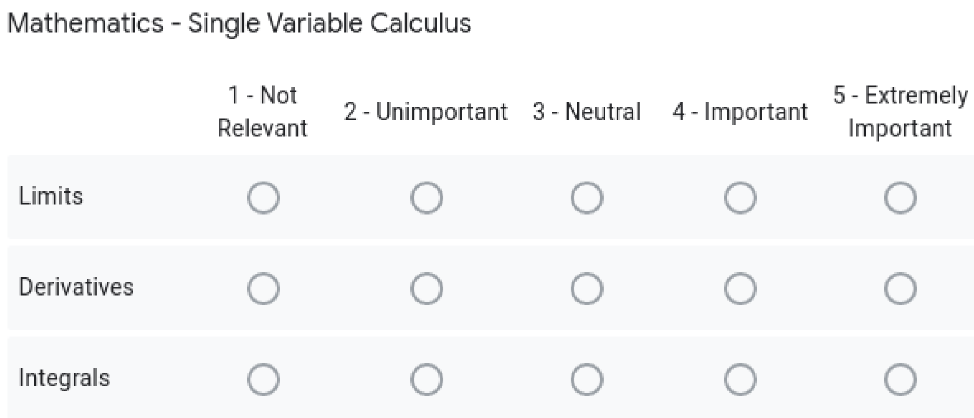

Figure 4: Example likert rating tasks presented to users for evaluating importance of concepts within a course item in mechatronics/robotics education.

Finally respondents were asked to provide any additional comments or insight in the two class iv) type questions. These included:

1. “Are there any other concepts that you think we missed? How would you rank them?"
2. “Any additional thoughts about compiling key concepts for mechatronics and robotics education that you would like to share?"

Results and Analysis

Course Items That Were Rated Important or Extremely Important

The ten course topics that received the highest combined rating by all the respondents as a percentage of the five available choices for each topic were collected. Table 1 and Fig. 5 show these data for all respondents.

The data for the administrator group are not shown in Table 1 since there was only one respondent in that group. In general, there was not a substantial difference in the percentage rating among the different groups. In total (n = 83), the highest rated topic was rated highly by 99% of respondents, while the tenth ranked topic was rated highly by only 94%. The highest ranked topic (PID control) was rated as important or extremely important by

i) 100% of the faculty group (total n = 39);
ii) 100% of the industry group (total n = 18);
iii) 92% of the undergraduate student group (total n =15);
iv) 100% of the graduate student group (total n =10);

while the tenth highest ranked topic (Serial Mechanisms) was rated as important or extremely important by

i) 91% of the faculty group (total n = 39);
ii) 94% of the industry group (total n = 18);
iii) 100% of the undergraduate student group (total n =15);
iv) 100% of the graduate student group (total n =10).

Course[Topic]	% of Respondents Who Identify the Topic as Either Extremely Important or Important				
	All (n = 83)	Faculty (n= 39)	Industry (n = 18)	Graduate Students (n= 10)	Undergraduate Students (n = 15)
Control Systems [PID control]	99	100	100	100	92
Kinematics [Forward Kinematics]	99	100	94	100	100
Control Systems [Feedback Control]	99	100	100	100	91
Kinematics [Gears]	97	97	100	100	92
Kinematics [Inverse Kinematics]	97	97	94	100	100
Control Systems [Frequency Response]	96	94	100	100	91
Mathematics - Linear Algebra [Systems of Linear Equations]	95	100	88	100	85
Dynamics [Rigid Body Kinetics]	95	97	94	90	93
Control Systems [Stability Criteria]	94	95	87	100	100
Kinematics [Serial Mechanisms]	94	91	94	100	100

Table 1: Important Course Topics

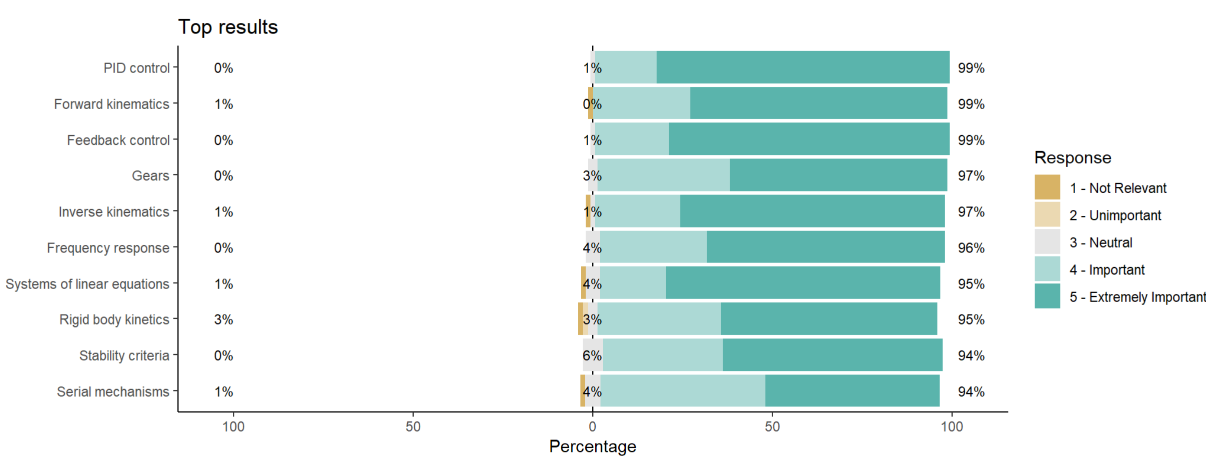

Figure 5: Stacked Bar Chart of Top Rated Course Topics

The total ranking followed the trends of Faculty and Industry (57 out of 83 total respondents). Undergraduate student perceptions stood out for some course topics, e.g., PID, feedback, kinematics, frequency response, and linear algebra were all rated lower. In contrast, the graduate student group found most topics in the top-ten very important – nine of the top ten topics were important or very important by 100% of graduate student respondents. It should be noted that the top ten course topics come from just four course items: Control Systems (4 topics), Kinematics (4 topics), Dynamics (1 topic), and Linear Algebra (1 topic).

The top-forty ranked course topics that had received the highest combined rating of either 'extremely important' or 'important' by all respondents as a percentage of the five available choices for each topic are shown in Table 2. The courses are listed in decreasing order of the number of important topics in each course item. For each course listed in the table, the topics are listed in order of importance from left to right as ranked by the survey. The results show that twelve courses cover these forty topics; just three courses (Control Systems, Kinematics, and Instrumentation and Measurement) cover nineteen of these topics. While the analysis was limited to the top forty topics in this paper, more detailed analysis can help identify important courses to include in MRE curriculum.

Course	Topics listed in order of importance (left to right) for each course							
Control Systems	PID control	Feedback control	Frequency response	Stability criteria	Block diagrams	LTI Sys.	Freq. domain comp.	Cont. and discrete time sys.
Kinematics	Forward kinematics	Gears	Inverse Kinematics	Serial mech.	Machinery	Parallel mech.		
Instrument. & Measurement	Data acquisition	Error Estimation	Signal conditioning	Handling digital data	Error propagation			
Dynamics	Rigid body kinetics	Rigid body Kinematics	Constraints	3D dynamics				
Linear Algebra	Systems of linear equations	Linear transf.	Matrix operations, matrix inverse	Eigenvalues and eigenvectors				
Ordinary Differential Eq.	Linear & nonlinear diff. eqns.	Laplace Transform	First order equations					
Signals, Systems, & Comm. Sys.	Fourier Transform	Filtering & filter design	Sampling theory					
Single Variable Calculus	Integrals	Derivatives						
Statics	Friction	Center of gravity						
Numerical Methods	Interpolation							
Physics Mechanics	Fixed axis rotations							
Machine Vision	Motion detection and object tracking							

Table 2: Topics Listed in Order of Importance

Course Items That Were Rated Least Important

Respondents ranked the following course topics as unimportant (in descending order of mean importance score; 5 is highest, 1 is lowest): ceramics, combustion, periodic table, power and refrigeration cycles, phases and phase diagrams, chemical bonding, intermolecular forces, water-vapor mixtures, atomice structure, and stoichiometry. These results are depicted in Fig. 6. These topics are typically covered in Chemistry, Material Science, and Thermodynamics courses.

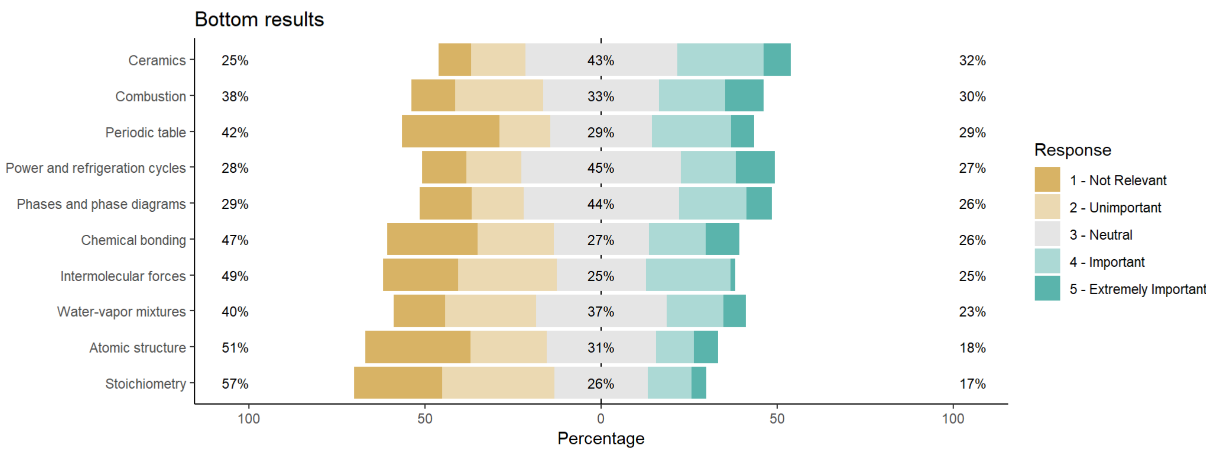

Figure 6: Course Topics Ranked Least Important

Computational vs. Analytical Approaches

Subjects were asked to rate the following statement:

> "The engineering science component of a mechatronics and robotics curriculum should emphasize modern computation techniques instead of analytical solution techniques."

The responses to this statement are graphically depicted below in Fig. 7.

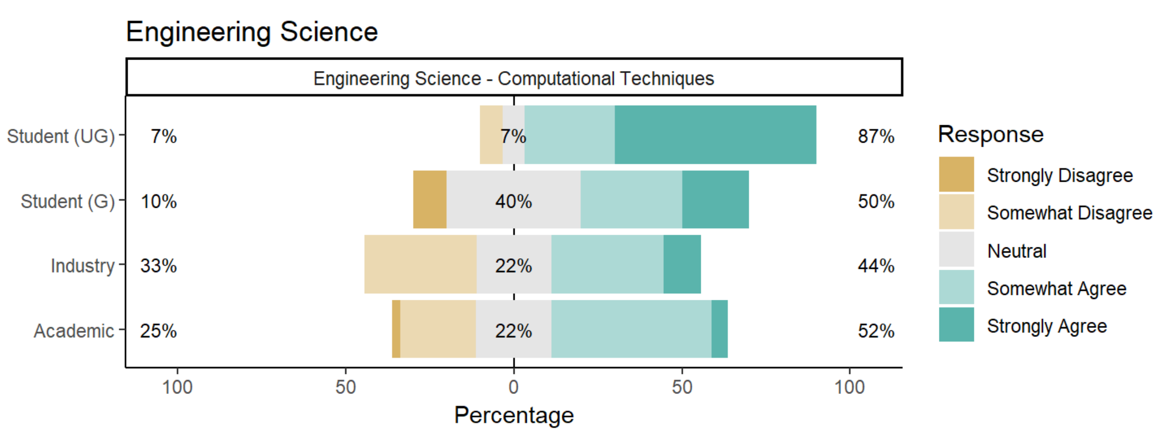

Figure 7: Importance of Computational vs. Analytical Techniques

The undergraduate students answered the question about engineering science and computational techniques with a statistically significant difference (multiple linear regression, $p = 0.003137$) from the remaining participant types. The undergraduate mean response is 1.1 points (on the 5-point likert scale) more in favor of the statement than academics. The survey failed to establish a significant difference between academics, industry members, and graduate students on this question, with the mean response of academics at 3.3, which is almost neutral. These results are perhaps not surprising as undergraduate students, who are likely digital natives, may recognize the increasing necessity of computational techniques over survey participants with a traditional perspective having more experience in academia.

Survey Respondent Comments

In addition to scoring mechatronics concepts, the survey asked the following two questions to the respondents:

1. "Are there any other concepts that you think we missed? How would you rank them?"
2. "Any additional thoughts about compiling key concepts for mechatronics and robotics education that you would like to share?"

Regarding the first question, the respondents provided these additional concepts and areas:

- manufacturing (rapid prototyping)
- electromagnetic capability
- modeling and simulation
- state-space control
- robotic concepts
- digital image processing
- laser technology
- virtual reality
- algorithm design and debugging
- discrete mathematics
- sensor properties and selection
- industrial standards
- CAD & CAM
- Internet of Things
- pneumatics and hydraulics control
- interfacing with and programming microcontrollers
- onboard communication (i2C, SPI, etc)
- mechatronics system design
- autonomous systems
- project management
- social privacy
- ethics & social implications

The concepts provided by the respondents expand our mechatronics key concepts in multiple directions, including manufacturing, advanced robotic, control and signal processing techniques, discrete mathematics, critical skills for microcontrollers and mechatronic system designs, and professional skills such as project management. Some of the provided concepts, such as onboard communication (i2C, SPI, etc), were expected to be covered by the "asynchronous serial communication" and "synchronous communication" concepts in the survey, although we did not make "i2C" and "SPI" explicit. Similarly, concepts involved in "interfacing with and programming microcontrollers" were expected to be covered in the "Embedded systems" and programming-related topics in the survey.

Respondents also commented on the relevance of mechatronic concepts to different specific application domains. For example, it was mentioned that various robot applications may require different or specialized mechatronics concepts. Cycle time and economics are huge driving factors for effective robotic applications.

Below are some insightful responses to the second question:

- “The trouble with Mechatronics/Robotics is that they are interdisciplinary, but a student shouldn’t be expected to complete more credit hours than a traditional engineering degree. I think the core competency of a mechatronics/robotics engineer should be system design, including the selection of components and interfaces as well as the design of a control system. The remainder of their curriculum should be the core classes of mechanical, electrical, computer, and software engineering”
- “Emphasis should be on the education and theory with with laboratory practice and internships for practical applications”
- “Focus on advanced programming knowledge and coding skills (e.g., C++) and provide a better introduction to linux and ROS (Robotic Operating Systems)"
- “A closer tie to industry is beneficial to mechatronics programs as it will bring in more participation and projects from companies"
- “Understanding safety features and standards of different industrial robots is also very relevant"

Survey Results by Course Item

Figures 8 - 12 show the likert response results from the various course items. The aggregate likert responses are also provided in the Appendix in Fig. 13.

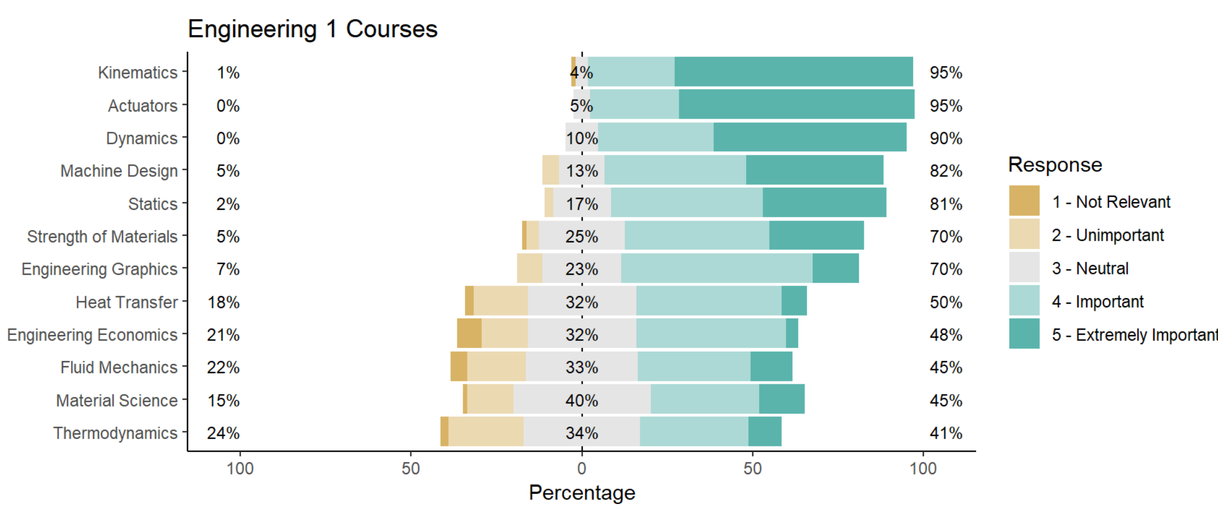

Figure 8: Engineering Courses Part 1

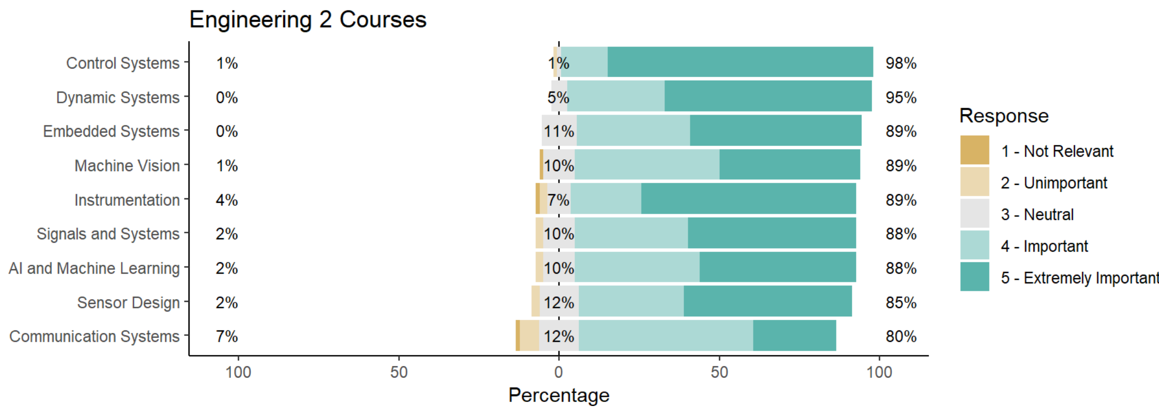

Figure 9: Engineering Courses Part 2

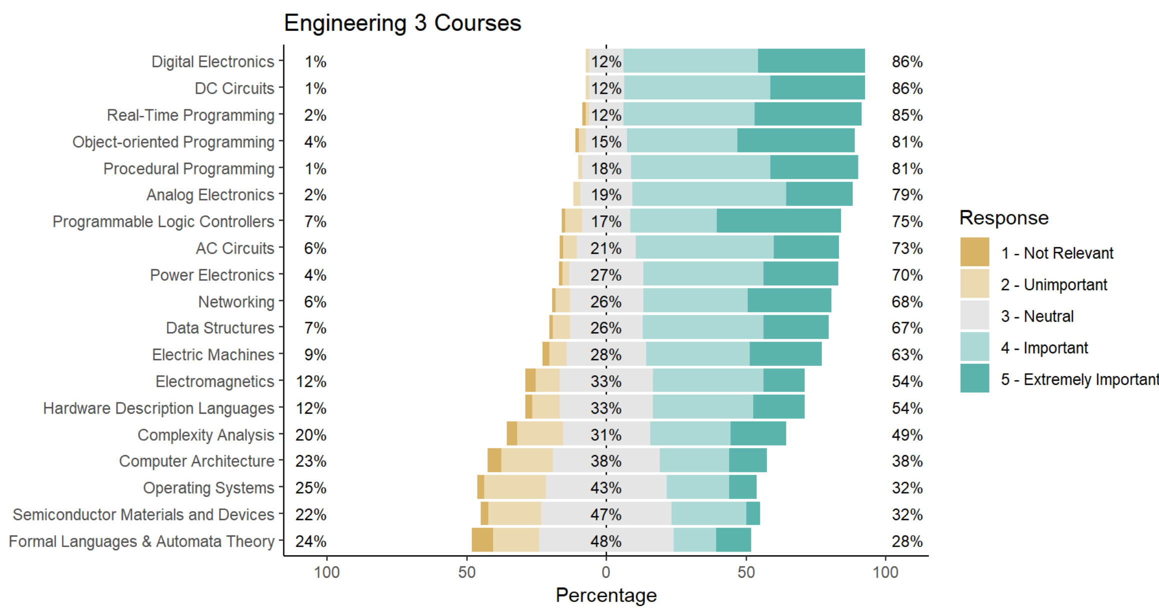

Figure 10: Engineering Courses Part 3

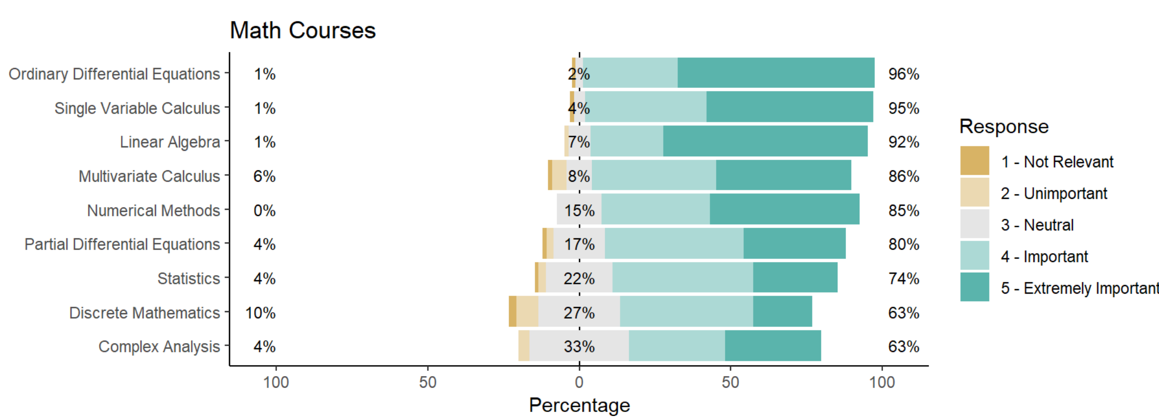

Figure 11: Basic Mathematics

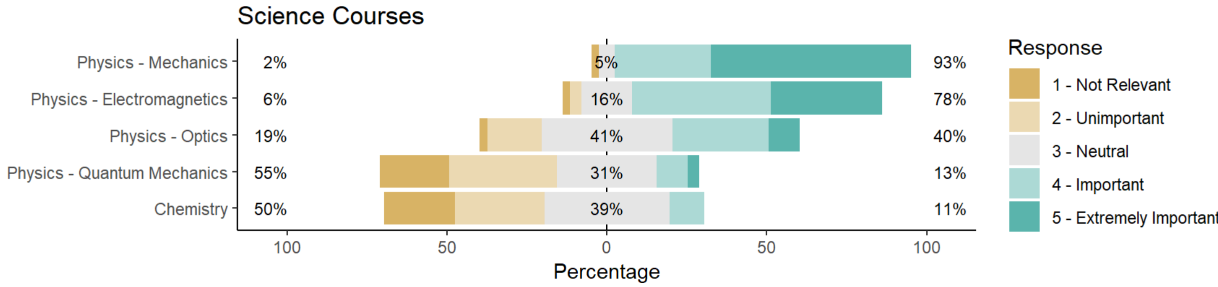

Figure 12: Basic Science

Discussion

The survey collected input from important stakeholders (faculty, industry, and graduate/undergraduate students) regarding courses and course items important for an MRE curriculum. As expected for an interdisciplinary field like MRE, a great many course items were rated important by respondents. This makes developing MRE curricula including all the requisite content challenging within the constraints of a typical baccalaureate engineering degree. The central tenants of the MRE curriculum are summarized by an astute respondent who commented: “the core competency of a mechatronics/robotics engineer should be system design, including the selection of components and interfaces as well as the design of a control system.”

At least for the ten top-rated course items in Fig. 5, which heavily emphasize control systems and kinematics, there was not a substantial difference in the percentage rating among the different groups taking the survey, indicating an agreement on the importance of these topics. Control Systems and Kinematics courses therefore rank as the most important in MRE curricula. In fact 19 of the top 40 highest ranked course items are typically covered in these two courses and Instrumentation and Measurement. An additional nine courses (see Table 2) comprise all of the top 40 course items, rounding out the central core of MRE curricula. On the other hand, chemistry, material science, and thermodynamics topics were found to be the least relevant for inclusion in MRE programs.

The results of this survey shed light on the important (and less important) courses and/or course items to include in MRE curricula. This serves as a foundation from which to inform the discussion surrounding creation of new MRE programs and modification of existing ones. Note that the survey used in this work did not distinguish between mechatronics and robotics, rather lumping them together as a single field. How to differentiate the two is itself an ongoing discussion, and developing key concepts for each separately may arrive at different conclusions. The MRE community will certainly explore and debate such questions as programs in mechatronics and robotics become increasingly widespread.

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Appendix

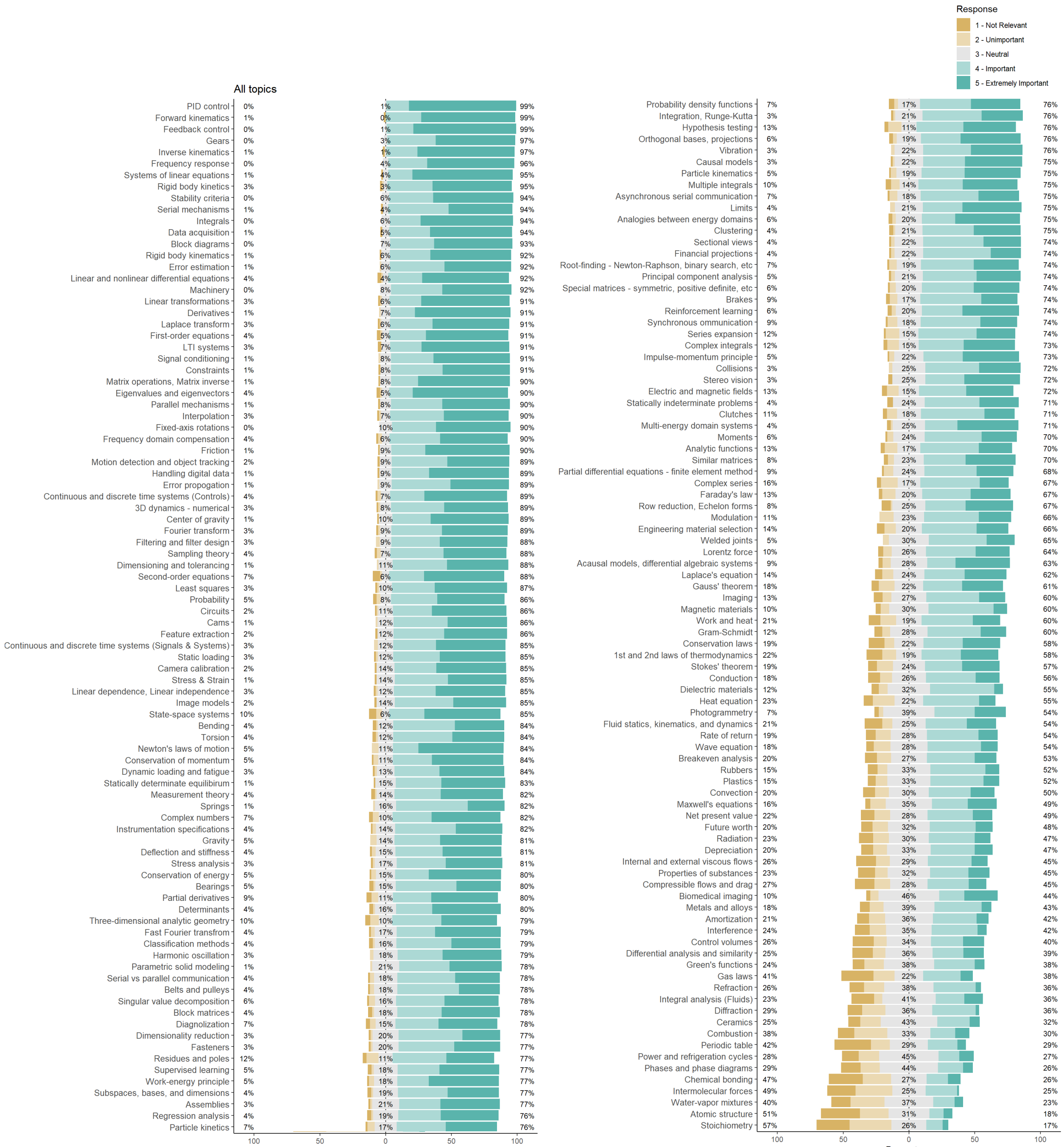

Figure 13: Aggregate likert responses for all course topics from all respondents.