Bridging Disciplines: Developing an Undergraduate Modeling and Simulation Course for Multidisciplinary Engineering Applications

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ABSTRACT

In the context of evolving technological demands and interdisciplinary challenges faced by modern engineers, this paper presents the development of an undergraduate course in Modeling and Simulation tailored for multidisciplinary engineering applications. The course addresses the critical need for engineers to employ simulation tools to solve complex engineering problems across various domains. By integrating theoretical principles with practical application, the curriculum fosters a comprehensive understanding of modeling techniques. Students engage in hands-on projects utilizing industry-standard software and tools, encouraging experiential learning and skill acquisition. Collaborative team-based assignments foster an interdisciplinary approach, enhancing communication and problem-solving skills. Pilot studies demonstrate that students who completed the course exhibit improved capability in designing and analyzing simulation models, enabling them to address real-world engineering problems efficiently and effectively. This course represents a step towards integrating modeling and simulation across engineering disciplines, preparing graduates to meet the multifaceted demands of future engineering roles and driving innovation in engineering education.

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INTRODUCTION

The evolving landscape of engineering increasingly demands a multidisciplinary approach to problem-solving, characterized by the integration of various domains such as mechanical, hydraulic, thermal, and electrical. This complexity is fueled by the advent of new technologies and the pressing global challenges that require innovative solutions. Modeling and simulation (M&S) have emerged as vital methodologies within this context, providing a framework for analyzing, predicting, and optimizing systems across a multitude of engineering applications (Banks et al, 2010). This paper presents the development of an undergraduate course designed to fortify engineering students' competencies in M&S, specifically targeting applications that span multiple disciplines. The aim is to cultivate graduates who are not only technically proficient but also capable of tackling multifaceted problems with an integrated approach.

Today's engineering challenges are rarely confined to single-discipline solutions. Whether it is designing complex machinery, electromechanical systems, a smart city infrastructure, or developing sustainable energy systems, engineers are necessitated to synergize various fields to achieve optimal outcomes (Friedman and Friedman, 2015). Multidisciplinary education fosters this integrative skill set, encouraging students to transcend traditional boundaries and collaborate effectively. Modeling and simulation techniques serve as critical tools to facilitate this education, allowing students to visualize complex interactions and simulate scenarios that would be difficult or costly to replicate physically (Winsberg, 2010). These virtual environments enable learners to experiment, test hypotheses, and comprehend interdependencies within system components, thereby deepening their understanding of interdisciplinary integration.

The course centers around harnessing advanced computational tools such as MATLAB, Simulink, and Simscape, which are prevalent in both academic and professional settings (Attaway, 2013; Langtangen, 2017). These platforms enable students to construct detailed models, conduct simulations, and analyze data efficiently. Incorporating hands-on lab sessions and projects with these tools lays a foundation for experiential learning, positing that knowledge is optimally acquired through direct experience (Kotb, 1984). By engaging with these tools, students enhance not only their technical proficiency but also their algorithmic thinking and problem-solving capabilities. Such skills are indispensable for tackling complex, multidisciplinary challenges and form an essential part of the modern engineer's toolkit. The development of this course requires thoughtful integration of pedagogical strategies to ensure student engagement and comprehension. A blended approach incorporating traditional lectures, interactive workshops, and team-based projects caters to diverse learning preferences, enhancing the educational impact (Bransford et al, 2000). The adoption of a flipped classroom model—where foundational course material is reviewed outside of class, reserving in-class time for applied learning—can further optimize student engagement and deepen understanding (Gao and Yu, 2021). Continuous assessments including quizzes, peer reviews, and collaborative projects serve as feedback mechanisms that help refine course content and adapt to student needs.

Real-world applications are a cornerstone of the proposed course, linking theoretical knowledge with practical implementation. Through case studies and projects that reflect current industry challenges, such as cyber-physical and electromechanical systems, or intelligent manufacturing systems, students witness the practical application of M&S in addressing real-world needs (Prince, 2004). These projects foster a learning environment where students can iterate solutions, assess risks, and understand the constraints of simulation models. Moreover, collaborating with industry partners to develop these applications provides students with insights into prevailing industry practices and future trends (Jonassen, 1996).

This paper outlines the development of an undergraduate modeling and simulation course tailored for multidisciplinary engineering applications. Through the integration of computational tools and real-world projects, the course aims to build technical proficiency while fostering critical thinking and collaboration—a dual capability essential for modern engineering challenges. As technology and industry needs continue to evolve, ongoing course refinement will be crucial to sustaining its relevance and effectiveness in shaping future engineering professionals.

CURRICULUM DEVELOPMENT

The development of an undergraduate modeling and simulation course requires a thoughtful approach that incorporates best practices in curriculum design, leverages advanced educational tools, and fosters high levels of student engagement. This methodology outlines the systematic process employed to design and implement the course, focusing on curriculum development, integration of educational tools, and strategies to enhance student engagement. The curriculum was designed following Bloom's Taxonomy to ensure that learning objectives catered to different cognitive levels, from basic understanding to advanced application and analysis (Bloom, 1956). The course content is divided into theoretical instruction, hands-on practice, and project-based learning. The theoretical instruction covers fundamental modeling and simulation concepts, ensuring a solid foundation in mathematical models and system dynamics (Banks et al, 2010). Bloom's Taxonomy has long been considered as a framework for designing educational curricula that cater to different levels of cognitive skills, facilitating structured and hierarchical learning. In developing an undergraduate modeling and simulation course, Bloom's Taxonomy serves as a vital tool in structuring content, creating assessments, and ensuring that students achieve comprehensive mastery of the subject matter. This section outlines learning objectives, instructional methods, and assessments within the modeling and simulation course

Designing Learning Objectives

The cognitive domains articulated by Bloom's Taxonomy, ranging from remembering and understanding to applying, analyzing, evaluating, and creating, provide a scaffold for crafting precise learning objectives. The course is designed to guide students from foundational knowledge to advanced application, ensuring a thorough understanding and capability in modeling and simulation.

a. Remembering: The initial stage involves grounding students in essential terminologies and concepts of modeling and simulation. This includes understanding key definitions, recognizing the types of models, and recalling fundamental mathematical principles used in modeling.
b. Understanding: Students progress to grasping relationships within systems and interpreting simulation results. This involves learning to explain the function of different components in a model and identifying the purposes of various simulation techniques (Anderson et al, 2001).
c. Applying: At this stage, students demonstrate their ability to apply theories and techniques to solve practical problems. Laboratory sessions and assignments focus on utilizing computational tools like MATLAB to build and simulate simple models.
d. Analyzing: Students are tasked with dissecting complex models, identifying variables, and understanding system dynamics. Analytical skills are honed through case studies that require students to disassemble model constructs, explore causal relationships, and conduct sensitivity analyses.
e. Evaluating: Here, students assess the efficacy of their models and suggest improvements based on simulation outcomes. Critiques, peer-reviews, and group discussions are employed to evaluate models, challenging students to defend methodologies and outcomes, and propose optimizations.
f. Creating: The pinnacle of Bloom's Taxonomy involves students synthesizing knowledge to design and develop innovative models addressing novel issues. Final projects require students to assimilate course learning to construct original models and simulate complex systems, demonstrating creativity and interdisciplinary application (Krathwohl, 2002).

Instructional Methods

Bloom's Taxonomy also informs the selection of instructional methods. Lectures and readings cater predominantly to the lower-order cognitive skills, while collaborative projects and labs emphasize higher-order processes such as analysis, evaluation, and creation. The flipped classroom model effectively supports this structure by pre-loading students with foundational content, reserving in-class time for active problem-solving and discussion, thereby enhancing comprehension and engagement.

Assessment Design

Assessment within the course is meticulously aligned with Bloom's Taxonomy to ensure a multidimensional evaluation of student learning. Initial quizzes test recalling and understanding of concepts, while assignments and lab reports require application and analysis. Peer reviews and reflective essays foster evaluation skills, encouraging constructive feedback and self-assessment. The capstone project represents the course culmination and demands integrative and innovative application of content. The course represents a robust framework that drives progressive learning and intellectual growth. By carefully structuring learning objectives, instructional methods, and assessments, the course not only aims to develop technical proficiency but also to cultivate critical thinking and creativity, equipping students with the skills necessary for multidisciplinary engineering challenges.

Student Engagement Strategies

To maximize student engagement, the course adopts a flipped classroom model where foundational content is explored through pre-class assignments and reading materials. This approach reserves classroom time for interactive discussions, hands-on labs, and collaborative problem-solving activities, thus fostering a more engaging learning environment (Gao and You, 2021). Active learning strategies, including peer instruction and group-based projects, are employed to encourage participation and deepen understanding (Prince, 2004). These strategies are designed to promote critical thinking, communication, and teamwork—skills essential for modern engineering practice. Continuous feedback is a key component of the student engagement strategy. Regular formative assessments, including quizzes and peer reviews, provide immediate feedback, helping students identify areas for improvement early in the course (Bransford et al, 2000).

INTEGRATION OF EDUCATIONAL TOOLS

Central to the course is the use of advanced computational tools such as MATLAB, Simulink, and Simscape, which enable students to perform complex simulations and data analyses (Attaway, 2013; Langtangen, 2017). These tools are integrated throughout the course to facilitate experiential learning, where students apply theoretical concepts to practical problems (Kolb, 1984). In contemporary engineering education, the use of advanced software tools such as MATLAB, Simulink, and Simscape is pivotal for teaching students how to effectively model, simulate, and analyze complex systems. MATLAB has established itself as one of the leading computational tools widely used in both academia and industry due to its versatility in handling complex mathematical operations, matrix manipulations, and algorithm development. In the context of an undergraduate modeling and simulation course, MATLAB serves as a cornerstone for enabling students to carry out sophisticated numerical simulations and develop models that closely mimic real-world systems. These tools collectively provide a comprehensive platform for understanding system dynamics and performing realistic simulations, which are critical for bridging the gap between theoretical knowledge and practical applications. This section delineates how MATLAB, Simulink, and Simscape are integrated into the curriculum of a modeling and simulation course to enhance learning outcomes and prepare students for multidisciplinary engineering challenges.

Matlab: The Computational Foundation

MATLAB serves as the computational backbone of the course, providing a robust environment for numerical analysis, algorithm development, and data visualization [4]. Initial coursework involves familiarizing students with MATLAB's syntax and capabilities through basic programming exercises focusing on matrix operations and procedural scripting. These activities lay the groundwork for understanding more complex simulations and data processing tasks. Students then progress to utilizing MATLAB for solving engineering problems involving Simulink and Simscape. Through these applications, students develop skills in constructing mathematical models and performing simulations that reflect real-world scenarios (Chapman, 2019).

Simulink: Visualizing and Simulating Dynamic Systems

Simulink, an extension of MATLAB, offers a graphical interface for modeling and simulating dynamic systems. It is particularly effective for students who benefit from visual learning, as it allows them to construct models using block diagrams that represent system components and their interactions (Mathworks, 2020).

The course incorporates Simulink for projects involving system dynamics and control systems. Students learn to simulate time-variant behaviors of systems and evaluate their responses to different inputs. By working on projects like developing feedback control systems, students gain hands-on experience that reinforces theoretical concepts covered in lectures.

Simscape: Simulating Physical Systems

Simscape extends Simulink's capabilities by providing tools to model and simulate physical systems across various engineering domains such as mechanical, hydraulic, thermal, and electrical systems. It allows students to incorporate real-world physical connections and constraints into their simulations (Mathworks, 2020). Incorporating Simscape into the curriculum enables students to model more realistic systems by utilizing pre-built components that mimic actual physical behaviors, such as motors, gears, thermal, and fluid systems. For example, in a project on renewable energy systems, students can use Simscape to simulate the interaction between photovoltaic cells and power grids, gaining insights into system efficiencies and potential improvements. This exposure to complex system modeling fosters critical thinking, as students must understand underlying physical principles and how they translate into computational models. Simscape's multidomain simulation capabilities encourage interdisciplinary thinking, crucial for modern engineering tasks that do not fit neatly into single-discipline boundaries.

COURSE CONTENT

The course content is divided into key thematic modules, each focusing on distinct aspects of modeling and simulation. These modules are designed to build upon each other, starting with fundamental principles and advancing towards complex system modeling and innovative applications. This sequential structure ensures that students develop a well-rounded understanding, enabling them to integrate knowledge across disciplines and apply it effectively in professional settings.

Course Description

The course provides foundations, principles, methods, and tools for modeling and simulation of electro-mechanical components and systems using appropriate modeling techniques. The course is focused on the multi-body dynamics systems, fluid, hydraulic, and electrical systems.

Course Objectives and Expectations

After completing this course, student should be able to apply MATLAB software to:

a. Perform basic MATLAB operations and create scripts.
b. Model and simulate basic mechanical systems. Interpret simulation results and perform appropriate modifications to the system to achieve desired function.
c. Model and simulate basic electrical systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.
d. Model and simulate electro-mechanical systems. Interpret simulation results and perform appropriate modifications to the system to achieve desired function.
e. Model and simulate basic hydraulic systems. Interpret the simulation results and perform appropriate modifications to the system as to achieve desired function.
f. Model and simulate multibody systems. Interpret simulation results and perform appropriate modifications to the system to achieve desired function.

Course topics include:

a. Introduction to MATLAB, Simulink, and Simscape
b. Modeling and simulation of mechanical systems
c. Modeling and simulation of electrical systems
d. Modeling and simulation of electro-mechanical systems
e. Modeling and simulation of hydraulic systems
f. Modeling and simulation of multi-body systems - SimMechanics

Integrated Projects: Real-World Problem Solving

The integration of MATLAB, Simulink, and Simscape culminates in capstone projects where students are required to tackle comprehensive real-world problems. These projects challenge students to synthesize their learning into complete solutions, encouraging creativity, and innovation. Such projects highlight the interplay between theoretical principles and practical challenges, preparing students for future roles in industry where such integrations are common. The strategic application of MATLAB, Simulink, and Simscape throughout the modeling and simulation course curriculum equips students with the technical skills necessary for analyzing and solving complex engineering problems. By providing a platform for both theoretical exploration and practical application, these tools not only enhance students' understanding of multidisciplinary systems but also foster the development of critical thinking, problem-solving, and innovative capabilities crucial for their professional careers.

Example of Student Projects

The course offers number of different projects that students need to address. Several of those projects are listed and described in the further text.

Four-Bar Linkage

Four-bar linkages, Fig. 1, are mechanisms commonly used in mechanical engineering as part of complex machines to provide the desired motion of end effectors. Students are asked to apply MATLAB to model four-bar linkage mechanism, Fig. 2, including electric motor that drives link AB, and to design controller that will provide desired motion, i.e. specified angular velocity of link AB, Fig. 3, and to determine required torque and power that will result in desired motion, Fig. 4. Exercise provides students with insight in the system behavior with respect to various values of proportional (P), integral (I), and derivative (D) gains. The results indicate the required power of electrical motor and resulting forces in joints. This information is essential during design process when sizing different system components, including link geometry, joints' size, and electric motor power.

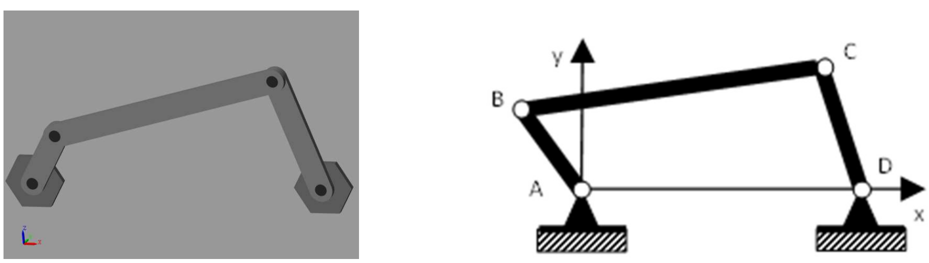


Figure 1. Four-bar linkage

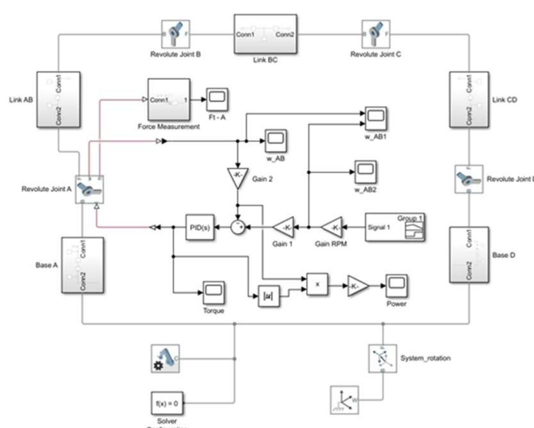
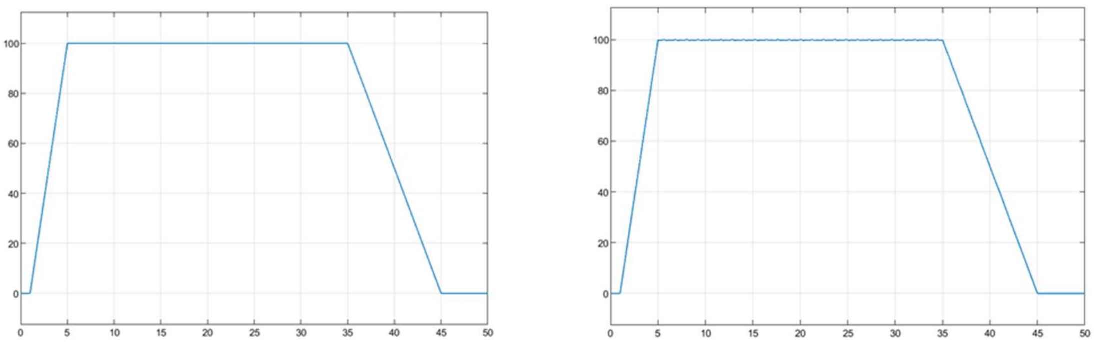
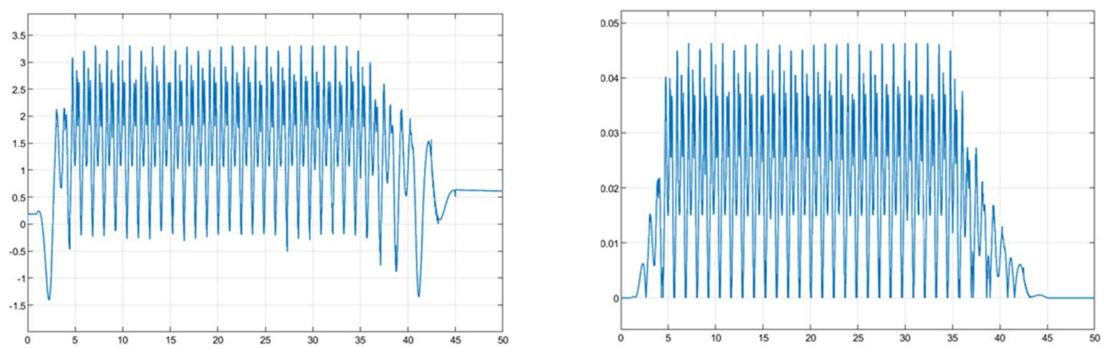


Figure 2. MATLAB model of a four-bar linkage



(a) **(b)**

Figure 3. (a) Histogram of desired angular velocity of linkage AB. (b) Histogram of actual angular velocity of linkage AB when PID controller is applied.



(a) **(b)**

Figure 4. (a) Histogram of torque in joint A required to produce desired angular velocity of link AB. (b) Histogram of power required to move link AB.

EVALUATION AND FEEDBACK

The course effectiveness is evaluated through student feedback, performance metrics, and assessment outcomes. The iterative refinement process involves adjusting course material and teaching methods based on evaluation results, ensuring the course continuously evolves to meet educational and industry needs. The course evaluation was performed based on department's adopted ABET method for course evaluation and results are presented in Table 1 and 2. The class performance with respect to course objective results, Table 1, indicate that the course is exceeding performance expectations, i.e. the average of all five course objectives is above 85, which is above the average for all course in the program. There are indicators (class average) that point to the need for further development of models of electro-mechanical systems and complex rigid-multi-body systems.

Table 1. Class performance with respect to course objectives.

Course Objective	**Class Average**	**Performance Indicator**			
		1a	1b	2a	2b
Solve basic mathematical problems using MATLAB and Simulink	90.0	x	x		
Develop model and simulate behavior of basic mechanical systems.	87.3	x	x	x	x
Develop model and simulate behavior of basic electrical systems.	86.0	x	x	x	x
Develop model and simulate behavior of basic electro-mechanical systems.	81.3	x	x	x	x
Develop model and simulate behavior of multibody systems.	82.0	x	x	x	x

The class performance with respect to student outcomes results, Table 2, indicate that students are able to apply knowledge, techniques, skills, and modern tools of mathematics, science, engineering, and technology to solve broadly-defined engineering problems appropriate to discipline. Specifically, 78.6% of students “meet” or “exceed expectations.” This is one of the essential areas that industry is expecting of engineering graduates, and results show that the course meets industry expectations. In addition, Table 2, indicates that students are able to design systems, components, or processes meeting specified needs for broadly-defined engineering problems appropriate to the discipline. Specifically, 71.4% of students “meet” or “exceed expectations.” This is another one of the essential areas that industry is expecting of engineering graduates, and the results show that the course meets industry expectations.

Table 2. Class performance with respect to student outcomes.

Student Outcomes (ABET)	Performance Indicator	Bellow Expectation	Progressing	Meet Expectation	Exceeds Expectation
1. An ability to apply knowledge, techniques, skills, and modern tools of mathematics, science, engineering, and technology to solve broadly-defined engineering problems appropriate to discipline	1a. Ability to select and identify the appropriate engineering tools to evaluate and analyze problems	7.1%	14.3%	28.6%	50.0%
	1b. Apply mathematics and science principles to solve broadly-defined engineering problems	7.1%	14.3%	28.6%	50.0%
2. An ability to design systems, components, or processes meeting specified needs for broadly-defined engineering problems appropriate to the discipline	2a. Identify the problem using engineering design	7.1%	21.4%	21.4%	50.0%
	2b. Design solution(s) to meet the needs of broadly-defined engineering problems	7.1%	21.4%	21.4%	50.0%

The numerical examples of student feedback, on the 5.0 scale, are shown in Table 3. The results indicate that students are very satisfied with the course content and are of the opinion that the course requires them to think critically, which is another requirement stated by the industry. The results also indicate that the projects are relevant and that they have learned and benefited from the class. Some of the descriptive student feedback is provided in Table 4.

Table 3. Student course evaluation

Question	Score
The course materials, exams, projects and/or papers in this class required me to think critically	4.75
The exercises, labs and written assignments used in this course are well-constructed	4.88
The exams and projects used to assign grades in the course are relevant	5.00
Overall, I have learned or benefited from the class	4.63

Table 4. Example of written student feedback

Comment
The teacher provided relevant examples.
Teacher gives ample and cognitive examples which correlate to the material being taught.
The ease of the problems is in relation to the examples provided. All problems were based on material and required you to use the material to solve each situation differently.
The wealth of information and exercise examples.

CONCLUSION

Traditional undergraduate courses are highly disciplinary, e.g. fluid mechanics courses deal only with fluid mechanics problems, and they neglect dynamics of the mechanical structures within the flow field which can have substantial impact on the flow patterns, which, alternately, can have impact on dynamics of the mechanical structure. In essence, real world systems and problems are complex multidisciplinary systems that require bridges between different disciplines. The interaction between different domains of complex mechatronic systems requires tools that can provide results that would capture physics of the interaction and enable engineers to make appropriate conclusions and decisions. An effective way to accomplish this complex task is to apply modern tools for modeling and simulation.

The "Modeling and Simulation of Mechatronic Systems" course was developed for the undergraduate program in Mechanical Engineering Technology at Old Dominion University. It is unique in the sense that it bridges several disciplines commonly present in mechatronic systems and provides students with tools to perform what-if analysis which can lead to optimal design and performance of physical systems. The course is intended to prepare students to solve complex real-world problems.

The student feedback indicates that the students find that the course is preparing them to solve the real-world problems that they will deal with upon graduation. They also find that the course is well structured and provides them with modern tools and requires them to critically think when dealing with complex multidisciplinary problems.

The future work will focus on the longitudinal study of the impact of course modifications on student success in understanding the material and their ability to apply their knowledge to solve increasingly complex real-world problems. Efforts will be made to reach out to alumni and seek feedback on the impact of the course on their everyday job responsibilities related to the design of complex mechatronic systems. The future work will also include interaction with industry to include more realistic problems that are relevant to practicing engineers. In addition, future work will focus on dissemination of developed curricula and modern tools for design and analysis of mechatronic systems.

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