Transforming Engineering Education: Project-Based Learning and Technology Integration in a Senior-Level Mechanisms Course

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Dr. Anurag Purwar is an Associate Professor of Mechanical Engineering at Stony Brook University. His research interests are in bringing together rigid body kinematics and machine learning for design of mechanisms and robots. He has published 109 peer-reviewed conference and journal papers and his research has been funded by National Science Foundation (NSF), NY-state SPIR, NY-state Center for Biotechnology, Sensor-CAT, SUNY Research Foundation, industry, Stony Brook University, and SUNY Office of Provost.

He received A.T. Yang award for the best paper in Theoretical Kinematics at the 2017 ASME Mechanisms and Robotics Conference and the MSC Software Simulation award for the best paper at the 2009 ASME International Design Engineering Technical Conferences (IDETC) . He is the recipient of the Presidential Award for Excellence in Teaching by Stony Brook University and the winner of the 2018 FACT2 award for Excellence in Instruction given to one professor from the entire SUNY system. He also received the 2021 Distinguished Teaching Award from the American Society of Engineering Education (ASEE) Mid-Atlantic Division.

He has been twice elected as a member of the ASME Mechanisms and Robotics committee and served as the Program Chair for the 2014 ASME Mechanisms and Robotics Conference, as the Conference Chair for the 2015 ASME Mechanisms and Robotics Conference and has served as symposium and session chairs for many ASME International Design Engineering Technical Conferences. He was the general Conference Co-Chair for the 2016 ASME International Design Engineering Technical Conferences (IDETC/CIE).

He won a SUNY Research Foundation Technology Accelerator Fund (TAF) award, which enabled him to develop a multifunctional Sit-to-Stand-Walker assistive device (http://www.mobilityassist.net) for people afflicted with neuromuscular degenerative diseases or disability. The technology and the patent behind the device has been licensed to Biodex Medical Systems for bringing the device to institutional market. The device won the SAE Top 100 Create the Future Award in 2016. Dr. Purwar gave a TEDx talk on Machine Design Innovation through Technology and Education which focused on enabling democratization of design capabilities, much needed for invention and innovation of machines by uniting the teaching of scientific and engineering principles with the new tools of technology. Five of his patented inventions have been successfully licensed to the companies world-wide.

Dr. Purwar is the Secretary and Chair-Elect of the the ASME Mechanisms and Robotics Committee and a senior member of the National Academy of Inventors (NAI). He is currently an Associate Editor of the ASME Journal of Mechanical Design.

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Transforming Engineering Education: Project-Based Learning and Technology Integration in a Senior-Level Mechanisms Course

Abstract. Engineering education faces the challenge of preparing students for a rapidly evolving, interdisciplinary field that demands a strong foundation in theoretical principles, practical skills, and the ability to solve real-world problems. This study describes a project-based learning (PBL) intervention implemented in a senior-level mechanical engineering course focused on mechanisms analysis and design. The intervention combined foundational coursework with bio-inspired design projects, where students developed walking end-effector robotic mechanisms for medical applications. Students utilized tools such as MotionGen software and SnappyXO kits to synthesize, simulate, prototype, and test their designs. Qualitative analysis of student evaluations and project reports revealed that the approach effectively reinforced theoretical concepts, fostered critical thinking, and promoted self-directed learning. Challenges identified included time management and balancing project demands with new material. Recommendations for improvement include earlier project introduction and structured lab-based assignments. The findings highlight the potential of project-based learning and technology integration to enhance interdisciplinary learning and prepare engineering students to address complex societal challenges.

Introduction

Engineering is becoming increasingly interdisciplinary, requiring engineers to demonstrate knowledge and experience in multiple disciplines (e.g., mechanical engineers working on a biomedical engineering project may have to understand the underlying biomechanics and acquire skills to work with electronics/computing hardware and coding related to the project). Further, engineers need to familiarize themselves with high-end modeling and simulation tools that support the engineering design process (e.g., brainstorming/conceptualization, synthesis, design, prototyping, analysis, redesign, etc.) of solving modern societal problems. Therefore, current engineering education faces the challenge of responding to a rapidly changing landscape of engineering by making advances that adequately prepare students with the skills and academic requirements of the next generation.

This paper describes an exploratory intervention set out to address the aforementioned challenge through course curriculum changes and integration of new technologies in a mechanical engineering undergraduate class taught at a Mid-Atlantic university. In particular, a mechanical engineering faculty collaborated with a faculty (an international expert in the field of mechanisms) in the department of mechanical engineering at another Mid-Atlantic university to implement the intervention in a senior-level Mechanisms–Analysis & Design course taught at the university in Spring 2023 and Spring 2024. A project-based learning approach was adopted by engaging students in collaborative classroom projects to nurture their acquisition of deeper content knowledge through active exploration of real-world problems. Subsequently, the course project involved design of medical devices to promote ambulation by providing students with exposure to design and development of walking end-effector based robots as artifacts. The paper presents the details of the course curriculum design, technology integration/usage in the classroom, and the novel content/teaching tools implemented as a part of the intervention. Qualitative analysis of student course evaluations and instructors' assessment of the project materials was used to identify the benefits and challenges of participating in the project and evaluate the overall effectiveness of the intervention.

Extensive studies have shown benefits of project-based learning (PBL) as a method for enhancing student engagement and learning outcomes in engineering education, emphasizing its effectiveness in fostering deeper understanding, critical thinking, and problem-solving skills [1-3]. Through hands-on, real-world projects, students not only gain technical knowledge but also develop interdisciplinary collaboration and communication skills [4], which are essential for modern engineering challenges. Despite its benefits, PBL poses challenges, including time management, resource constraints, and the need for structured guidance [5, 6]. Hmelo-Silver [7] highlighted that without proper scaffolding, students may struggle to balance open-ended exploration with mastering core concepts. Furthermore, student feedback in PBL courses often emphasizes the need for clear project guidelines, rubrics, and early introduction of projects, as seen in studies by Dochy et al. [8]. The design of medical devices as a context for engineering projects has gained traction as an interdisciplinary approach to teaching, integrating concepts from mechanical engineering, electronics, and biomedical sciences, providing students with exposure to real-world healthcare applications [9]. This approach aligns with broader trends in engineering education to prepare students for interdisciplinary and socially impactful careers. In this work, student team projects involving design and development of walking end-effector based robots as artifacts were chosen as means to study design principles of medical devices. A related field is bio-inspired design, encouraging students to draw inspiration from natural systems to solve complex design problems [10-13]. The integration of bio-inspired themes in undergraduate projects has been shown to improve student motivation and provide practical experience in translating biological principles into engineering systems. Finally, the use of computational tools for modeling and simulation has been shown to significantly enhance students' understanding of engineering concepts [14]. More recently, domain-specific tools like MotionGen, used in this study, have gained attention for their ability to teach complex kinematic analysis through interactive simulations. Prior work has demonstrated the effectiveness of integrating such tools in project-based courses to reinforce theoretical knowledge and facilitate practical applications [15].

Methods

Participants and Context

The participants consisted of undergraduate engineering students enrolled in a 400-level senior elective course on Mechanisms–Analysis & Design taught at the university in Spring 2023 (29) and Spring 2024 (28). The course introduced students to the fundamental principles and applications of four-bar mechanisms, a fundamental topic in kinematics and mechanical system design. Students learned to analyze the motion of these mechanisms, classify their types using Grashof's criteria, and design systems to meet specific functional requirements through synthesis techniques. The curriculum integrated theoretical concepts with practical skills, including the use of modern CAD tools for modeling and simulation. By exploring real-world applications in robotics, automotive systems, and manufacturing, students gained the knowledge and skills to design efficient mechanical systems, preparing them for advanced studies or careers in mechanical engineering and automation.

To leverage the benefits of project-based learning (e.g., enhanced engagement, development of critical skills, deeper understanding of content, etc.), students were engaged in collaborative classroom projects involving design and development of walking end-effector based robotic artifacts. The overarching theme centered on creating medical devices to promote ambulation, combining engineering design principles with real-world healthcare applications. Students were provided with the following resources to support their project needs: 1) MotionGen (a web-based software application for synthesizing and simulating planar linkage mechanisms), 2) SnappyXO (an open-architecture robotics kit with linkage parts, sensors, actuators, and Arduino hardware), and 3) prototyping support from the university's maker space facility. These resources allowed a tight integration between simulations-based synthesis and physical implementations of the leg mechanisms designed by the students in their projects. The MotionGen software and the SnappyXO resources were developed with grant support from the National Science Foundation. The students were also provided with an opportunity to interact with the faculty expert over Zoom to clarify their questions on how to go about solving problems related to synthesis, modeling, and simulation of the leg mechanisms in the MotionGen software.

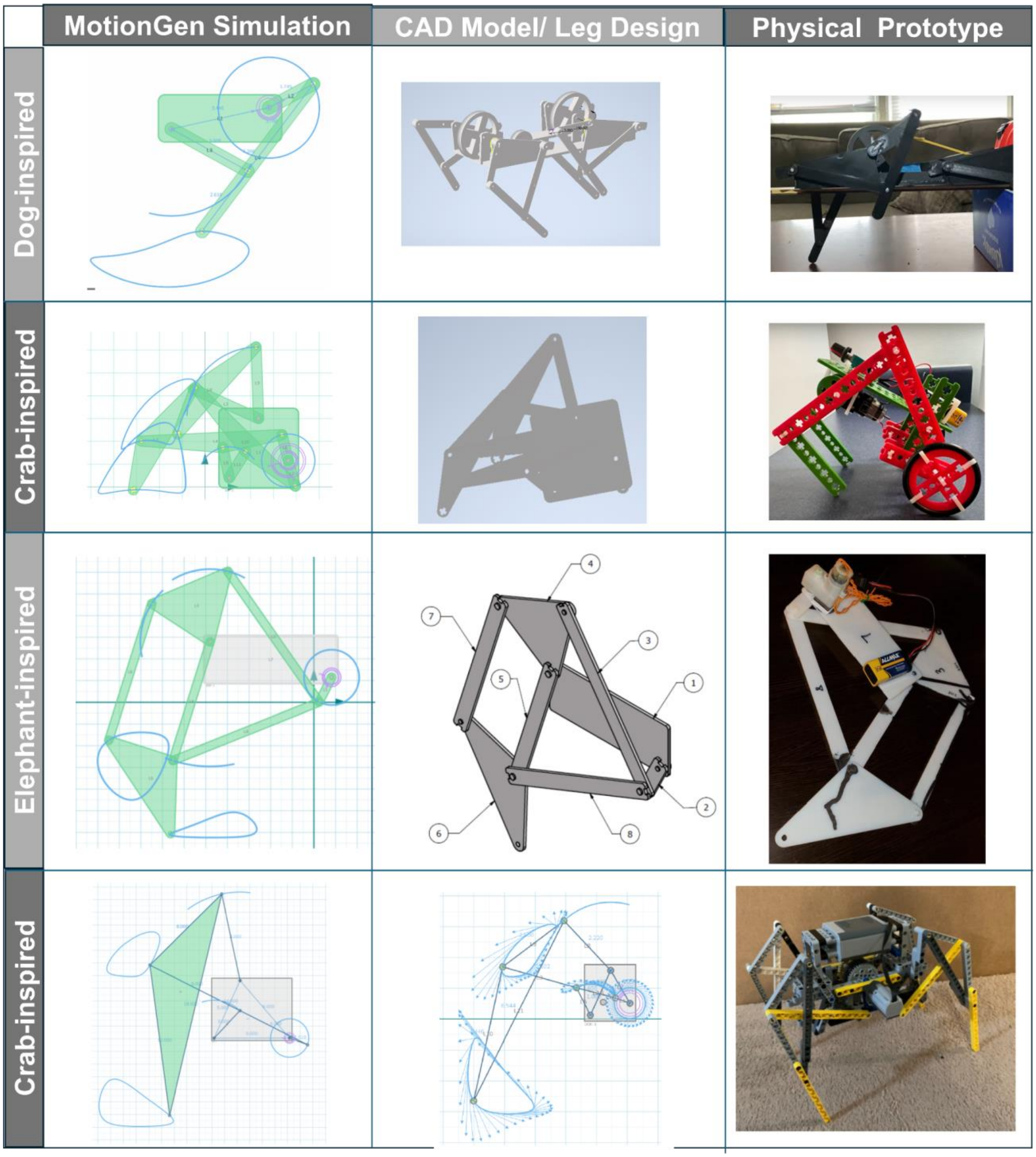

Figure 1. Sample projects ranging from dog-inspired to crab-inspired and elephant-inspired leg mechanisms, showing the MotionGen simulation snapshots, CAD models, and physical prototypes in each project.

Measures

A total of 57 engineering students (29 from Spring 2023 and 28 from Spring 2024) enrolled in the course participated in this intervention. Data consisting of student course evaluations, mechanism simulations, physical prototype demonstrations, and project reports collected at the conclusion of the semester were analyzed for this study. Open-ended prompts directed students to describe the factors that contributed the most to their learning, the factors that helped them to learn to think critically, and the changes to the class that would have helped them learn more. Students submitted videos of mechanism simulations and demonstrations of their physical prototypes. A project report template was provided to the students that served as a guideline to to help students write different sections of the report, while emphasizing important aspects like animal inspiration used for their project, leg motion specifications, linkage mechanism synthesis, MotionGen simulation, description of the physical prototype construction (use of Snappy kit or 3D-printing, etc), and presentation of the testing results.

Results

Teams developed diverse robot designs ranging from dog-inspired leg mechanisms designed for stability and gait replication to crab-inspired claw mechanisms emphasizing lateral mobility. Additionally, some teams developed elephant-inspired mechanisms, focusing on load-bearing and adaptability to various terrains. Examples of such projects showing the MotionGen simulation snapshots, CAD models, and physical prototypes of each design are shown in Figure 1. By drawing inspiration from nature, these projects not only advanced the students' understanding of bio-inspired design but also provided valuable insights into developing next-generation robotic systems for healthcare applications.

Findings from a qualitative analysis of the student course evaluations and instructors' assessment of the project materials revealed benefits such as students' perceived reinforcement of engineering concepts learned in the class and helped evaluate the overall effectiveness of the intervention. The project reports revealed that students were able to effectively apply theoretical principles and simulation tools for the synthesis, analysis, construction, and testing of their designs. Challenges such as time management and resource limitations were frequently cited by the student teams in the discussion section of their project reports.

Sample quotes of students in response to the course evaluation survey that were primarily related to their team projects and the resources provided to them can be classified into three categories:

1. **Factors contributing to students' learning and critical thinking.** Students highlighted several factors that contributed to their learning and development of critical thinking skills. The initial focus on foundational topics, such as graphing and sketching four-bar linkages, provided an accessible starting point, fostering a strong conceptual understanding. Tools like MotionGen software played a crucial role in bridging theory

and practice, enabling students to visualize mechanisms and apply concepts to real-world projects. The hands-on approach, including in-class activities and the instructor's project assignment and physical demonstrations, reinforced the material effectively. The culminating project was particularly impactful, allowing students to explore complex mechanisms in depth and apply their knowledge creatively. However, some noted challenges in balancing project demands with understanding new concepts introduced later in the semester.

2. **Self-directed learning.** Students identified several self-directed efforts that contributed to their learning. Engaging with resources provided by the professor, such as homework problems, class materials, and MotionGen software, was a key factor in reinforcing their understanding. Many emphasized the value of dedicating significant time outside class to studying, practicing examples, and working on the final project. The hands-on use of software and kits helped students visualize mechanisms and connect theoretical concepts to practical applications. Collectively, these efforts enabled a deeper comprehension of the course material and strengthened their grasp of key topics.

3. **Feedback for improvement.** Students suggested incorporating lab-based assignments utilizing MotionGen earlier in the semester to better prepare for the project and aid in visualizing mechanisms. Additionally, they recommended assigning the project during the initial weeks of the class and providing the rubric upfront. These changes would allow for more time to plan and complete the project, accommodating the demands of other classes and commitments while enhancing their overall learning experience.

Table 1. Sample quotes from participating students in response to questions from the course evaluation survey results

What factors about this class contributed the most to your learning? What aspects of this class helped you to learn to think critically?
The initial topics of graphing and sketching four-bar linkages were insightful and fairly simple concepts to grasp. Later in the semester, as more concentration and emphasis were put into the project it became more difficult to allocate time to understand the concepts being presented. MotionGen software was very helpful in developing more of an understanding of mechanisms and the practical applications through our projects. *Professor Z's project assignment and physical demonstrations reinforce the material the most.* *The project helped reinforce and explore more complex mechanisms* *The project at the end of the class.* *Hands on work during class*
What factors about your own performance helped you learn the most? What did you do to facilitate your learning?
Simply utilizing the resources given by the professor and doing homework problems as well as working on the project allowed for better learning of the course topics *Studying and working on the project outside of class.* *the software and the kits use to know more about this subject* *Practicing examples/homeworks and visualizing mechanisms through MotionGen.* *I spent significant time working on homework, studying for exams, and creating the end-of-the-year project. This allowed me to better understand the content discussed during class time.*
What changes, if any, could be made to the class that would have helped you to learn more?
Lab-based assignments utilizing MotionGen would be great for preparing for the project and visualizing mechanisms. *I think the project should be assigned the very first weeks of class and the rubric should be uploaded from the very beginning so as to give people more time to work on the project. Because of other classes and work, there is just not enough time for most people to work on it even if they use up most of their free time.*

Discussion and Conclusions

This study explored the implementation of a project-based learning (PBL) intervention in a senior-level mechanical engineering course focused on mechanisms analysis and design. The intervention aimed to address the growing interdisciplinary demands of engineering education by integrating bio-inspired design projects, advanced simulation tools, and hands-on prototyping. Through collaborative projects, students were challenged to design and develop walking end-effector robotic mechanisms inspired by animal biomechanics, with applications in medical devices promoting ambulation. Findings from qualitative analysis of student evaluations, project reports, and instructor assessments demonstrate the effectiveness of the intervention in reinforcing theoretical concepts, fostering critical thinking, and promoting interdisciplinary learning. Students reported that foundational topics like graphing and sketching four-bar linkages provided an accessible entry point into the subject matter, while tools like MotionGen enabled them to bridge theory and practice effectively. The hands-on use of MotionGen and SnappyXO kits was particularly impactful in helping students visualize mechanisms and connect abstract principles to tangible outcomes. The culminating project, focused on the design and prototyping of bio-inspired mechanisms, emerged as a key element of the course, allowing students to creatively apply their knowledge to real-world challenges. Students' self-directed learning efforts, including extensive engagement with provided resources and consistent project work, played a significant role in their success. However, challenges such as time management and balancing the project with other coursework were frequently noted. Suggestions for improvement included incorporating lab-based assignments earlier in the semester to provide more structured preparation and assigning the project during the first weeks of class with an upfront rubric to allow sufficient planning and execution time. Overall, the study underscores the potential of project based learning and technology integration to foster creativity, innovation, and practical problem-solving skills in engineering education, aligning with the evolving demands of the field.

References

[1] Kokotsaki, D., Menzies, V., & Wiggins, A. (2016). Project-based learning: A review of the literature. *Improving schools*, *19*(3), 267-277.

[2] Prince, M. J., & Felder, R. M. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education, 95*(2), 123–138.

[3] Mills, J. E., & Treagust, D. F. (2003). Engineering education—Is problem-based or project-based learning the answer? *Australasian Journal of Engineering Education, 3*(2), 2–16.

[4] Kaipa, K., & Kidd, J. J., & Kumi, I. K., & Ringleb, S. I., & Ayala, O. M., & Gutierrez, K., & Pazos, P., & Cima, F., & Rhemer, D. M. (2024, June), Reflections of undergraduate engineering students completing a cross-disciplinary robotics project with preservice teachers and fifth

graders in an electromechanical systems course, In *Proceedings of ASEE Annual Conference & Exposition*, Portland, Oregon.

[5] Aldabbus, S. (2018). Project-based learning: Implementation & challenges. *International journal of education, learning and development*, *6*(3), 71-79.

[6] Meng, N., Dong, Y., Roehrs, D. *et al.* Tackle implementation challenges in project-based learning: a survey study of PBL e-learning platforms. *Education Tech Research Dev* **71**, 1179–1207 (2023).

[7] Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review, 16*(3), 235–266.

[8] Dochy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based learning: A meta-analysis. *Learning and Instruction, 13*(5), 533–568.

[9] Böhmer, A. I., Zöllner, A. M., Kuhl, E., & Lindemann, U. (2014). Medical device design process: a medical engineering perspective. In *13th International Design Conference* (pp. 749-758).

[10] Kaipa, K., Onal, C., Jovanovic, V., Djuric, A., Luo, M., Bowers, M., & Popovic, M. Bio-inspired robotics, *Biomechatronics*, Elsevier, 2019, M. Popovic, ed.

[11] Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A.-K. (2006). Biomimetics: Its practice and theory. *Journal of the Royal Society Interface, 3*(9), 471–482.

[12] Nagel, J.K.S., Rose, C., Beverly, C., Pidaparti, R. (2019). Bio-inspired design pedagogy in engineering. In: Schaefer, D., Coates, G., Eckert, C. (eds) *Design Education Today*. Springer, Cham., 149-178.

[13] Shu, L. H., Ueda, K., Chiu, I., & Cheong, H. (2011). Biologically inspired design. *CIRP Annals*, *60*(2), 673-693.

[14] Magana, A. J. (2017). Modeling and simulation in engineering education: A learning progression. *Journal of Professional Issues in Engineering Education and Practice*, *143*(4), 04017008.

[15] Sola-Guirado, R. R., Guerrero-Vacas, G., & Rodríguez-Alabanda, Ó. (2022). Teaching CAD/CAM/CAE tools with project-based learning in virtual distance education. *Education and Information Technologies*, *27*(4), 5051-5073.