Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025 ASEE
Paper ID #46459

Development of Virtual Labs for Soft Robotics Courses to Enhance Student Learning and Support Faculty Teaching

Fahim Dorsey, Kennesaw State University
Connor Joseph Talley, Kennesaw State University
Dr. Razvan Cristian Voicu, Kennesaw State University

Dr. Razvan Cristian Voicu is a faculty member in the Department of Robotics and Mechatronics Engineering at Kennesaw State University. His research interests include artificial intelligence, robotics, and the development of AI-driven systems for knowledge transfer and adaptive learning. Dr. Voicu is dedicated to exploring innovative applications of AI to enhance learning and problem-solving in complex environments.

Dr. Ayse Tekes, Kennesaw State University

Ayse Tekes is an Associate in the Mechanical Engineering Department at Kennesaw State University. She received her B.S., M.S. and Ph.D. in Mechanical Engineering from Istanbul Technical University, Turkey.

Development of Virtual Labs for Soft Robotics Courses to Enhance Student Learning and Support Faculty Teaching

Abstract.

Soft robotics is an emerging field that deals with the design, modeling, and fabrication of robotic systems made of soft and compliant materials mimicking the motion in nature. Since soft robotics will revolutionize the safe interaction of humans and robots due to the application of soft materials in the robot's structure, the next generation of robotics will yield more soft robotics. Engineering programs should introduce this cutting-edge technology in their curriculum that is designed to satisfy societal challenges, provide a template for the advances in soft robotics, and support students to learn and explore these revolutionary changes to prepare the U.S. workforce for advanced robotics careers. However, despite the rapid growth of soft robotics, the resources available to the engineering faculty and students are very limited. To meet the needs of developing technological solutions in soft robotics courses by visualizing complex concepts, improving students' core understanding of the material, and growing their confidence for emerging engineering careers, we developed an open-source and user-friendly virtual lab using MATLAB Simscape for soft robotics and compliant mechanisms courses to simulate and visualize the core concepts.

The virtual lab enables students and faculty to visualize and simulate complex concepts in soft robotics, which are often challenging to grasp through traditional teaching methods. By integrating teaching methodologies with interactive simulations, our virtual lab simplifies the learning process and enriches the teaching experience. The virtual lab includes a comprehensive library of compliant components, such as flexure hinges and flexible beams (e.g., fixed-fixed, fixed-free, and initially curved). It also features a variety of compliant mechanisms like double-dwell, bistable, parallel-arm, four-bar, and five-bar systems. Furthermore, it offers detailed comparisons between theoretical models, such as the pseudo-rigid-body model (PRBM), MATLAB Simscape simulations, Ansys results, and experimental data obtained from 3D-printed lab kits and machine vision measurements. To support active learning, the virtual lab is complemented by a set of example activities that can be used as homework or in-class demonstrations.

Motivation.

When we think of robots, we often envision machines with rigid components and joints specifically designed to accomplish user-defined tasks. In contrast, nature follows an entirely different approach, where plant and animal movements rely on softness and flexibility to adapt and perform tasks that rigid machines cannot. For example, consider an octopus navigating in a coral reef. Its limbs squeeze through narrow crevices, bend around obstacles, and adapt to their surroundings with remarkable deformation. In contrast, a rigid robot attempting the same task would require advanced programming and manufacturing techniques to navigate such irregular spaces and risk damaging itself or the fragile reef due to its rigidity. Soft robotics seeks to imitate the motion inspired by nature and incorporates flexible materials that allow robots to bend, stretch, and adjust to their surroundings. These attributes make soft robots safer and more versatile, allowing them to navigate through unpredictable environments and overcome the limitations of rigid systems [1-5]. Similarly, compliant mechanisms, which are considered the core of soft robotics, consist of bendable links to deform and large-deflecting hinges to create relative motion between two adjacent members. They offer several advantages, including increased precision, reduced cost, single-piece manufacturing, and the elimination of assembly requirements [6-8].

Projections indicate that the U.S. soft robotics market is expected to reach $8.7 billion by 2030, with applications spanning diverse fields such as healthcare, manufacturing, bio-inspired design, and environmental exploration [9]. However, the challenges for both soft robotics and compliant mechanisms lie in meeting user experience requirements and deriving their mathematical models, particularly for control purposes. Designing soft robots requires a deep understanding of their nonlinear and deformable dynamics—concepts that are challenging to teach within a standard undergraduate curriculum. Unlike rigid robotics, soft robotics lacks undergraduate-level reference textbooks, structured teaching frameworks, and educational tools, making it challenging for instructors to teach the fundamentals and for students to master its applications. Owing to the advantages of soft robots and compliant mechanisms over traditionally designed rigid systems, the future of robotics is likely to shift increasingly toward soft robotics due to their versatile applications and ability to enable safe human-robot interactions [10-12]. Despite the rapid growth of this field, accessible educational resources for both students and faculty remain limited. To meet the evolving demands of U.S. companies and government agencies, the engineering workforce must be equipped with advanced skills and knowledge that support economic growth and sustain competitive advantages. Engineering education, therefore, must evolve alongside rapid technological advancements, especially in next-generation disciplines like soft robotics where traditional rigid-body assumptions no longer apply. Soft robotics presents unique challenges in dynamics, material properties, and control systems, requiring an educational approach that bridges theoretical concepts with practical applications.

Traditional engineering courses often emphasize theoretical concepts without incorporating hands-on practice. As a result, students struggle to connect fundamental concepts to real-world applications. The primary causes of this issue are time constraints in the curriculum, as well as financial and logistical challenges in providing hands-on learning opportunities with commercially available equipment. Additionally, while virtual labs have gained popularity in K-12 and college-level science programs, there is still a notable lack of accessible and advanced virtual labs specifically designed for engineering courses [13-15]. Virtual labs provide several benefits by complementing hands-on practice and reinforcing theoretical knowledge in traditional engineering courses. Virtual labs offer engaging learning activities to deepen understanding of complex concepts by enabling students to explore simulations at their own pace and anywhere.

Although the presented virtual lab simulations are primarily designed for undergraduate-level soft robotics and compliant mechanisms courses, they can be incorporated into other engineering courses, such as Introduction to Engineering, Machine Dynamics, Mechanical Vibrations, Fundamentals of Biomechanics, and Introduction to Robotics as a homework, class project, or only for five to ten minutes in-class demonstrations. These virtual lab simulations provide a platform for students at various academic levels to engage with fundamental and advanced engineering concepts in a hands-on, interactive manner. Freshman students can explore the simulations by modifying key parameters such as material properties, link dimensions, force magnitude, and force type. Through these modifications, they can observe the direct impact on output motion and develop an intuitive understanding of the relationship between input parameters and system behavior. On the other hand, junior and senior students enrolled in advanced engineering courses can use the simulations to validate theoretical models and gain deeper insights into emerging topics like soft robotics and compliant mechanisms. By combining parameter exploration with theory validation, these simulations serve as a valuable tool for reinforcing foundational knowledge and preparing students for research or industry applications in these rapidly evolving fields.

Background on Soft Robots and Compliant Mechanisms.

Compliant mechanisms use flexible members that bend or deform under input force, displacement, or torque to generate output motion. The ability of compliant mechanisms to bend or undergo large deformations simplifies designs by reducing the number of required parts, eliminating the need for assembly in monolithic structures created through additive manufacturing, and enabling reduced weight and simpler manufacturing, even for complex designs. The ability of compliant mechanisms to precisely generate motion makes them ideal for applications such as precision instruments, energy harvesters, medical devices, and microelectromechanical systems (MEMS). Compliant members store and release energy during motion, similar to translational springs (e.g., pinned-pinned flexible beams) and rotational springs (e.g., flexure hinges), making them suitable for the design of bistable, multistable, and dwell mechanisms. They are also widely used in robotics and displacement amplification systems, such as grippers [16-18].

Soft robotics marks a significant shift in robotic design, drawing inspiration from the flexibility and adaptability of biological systems. Unlike traditional robots made of rigid materials, soft robots use compliant and deformable components to perform complex motions while ensuring safe interactions with humans and the environment. This emerging field combines principles from engineering and material science to develop systems that are lightweight, capable of navigating unstructured environments, and designed to follow a larger workspace. Soft robotics has applications across various domains, including healthcare, where they are used as surgical robots [19], and industrial automation, such as pick-and-place robots for handling delicate objects, enabling safer human-robot collaboration [20,21]. Figure 1 shows some examples of our previously designed compliant mechanisms and soft robots and their virtual lab simulations to give the reader an overall idea of these mechanisms.

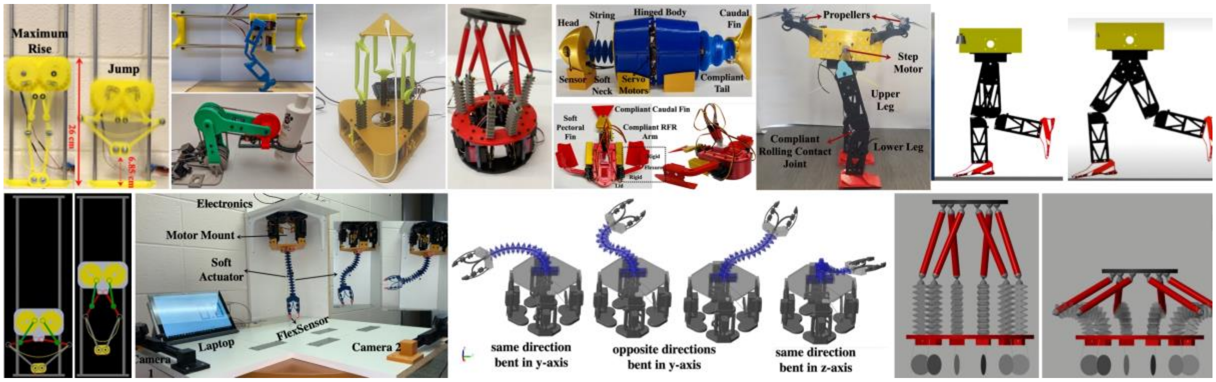

Figure 1. Examples of our compliant mechanism and soft robot designs and their virtual simulations

Development of Virtual Lab Simulations in MATLAB, Simulink, and Simscape.

The development of complex-shaped rigid or compliant/soft mechanisms in MATLAB Simulink presents significant challenges for undergraduate students. While some engineering programs incorporate MATLAB into introductory programming courses, some disciplines, such as computer engineering, robotics, and mechatronics, do not offer dedicated programming courses. Nevertheless, students are often assigned homework and laboratory exercises requiring MATLAB proficiency. As a result, by engaging with MATLAB across sophomore to senior-level courses, many students gradually develop competence.

In mechanical engineering, students are introduced to programming during their freshman year. However, programming remains a persistent challenge for these students, as upper-level courses typically do not emphasize programming skills. For instance, in the Fall 2024 semester, a 3D-printed single degree-of-freedom pendulum was assigned as homework in two sections of system dynamics and control theory courses taught by the corresponding author, involving 76 students in total. Teams of four were tasked with collecting free-response data from hands-on equipment using rotary encoders and Arduino systems and performing system identification using the logarithmic decrement method. Students were permitted to utilize AI tools to support Arduino coding and wiring. While many students acknowledged the value of using MATLAB and MATLAB Simulink in creating models to compare theoretical model with experimental data, several reported difficulties with wiring and coding. This observation highlights the programming challenges mechanical engineering students face due to their limited exposure to coding beyond the freshman year.

We developed a virtual lab simulation for soft robotics and compliant mechanisms courses to address the need to visualize the non-linear and unpredictable motion of compliant mechanisms and soft robots in MATLAB using additional tools such as Simulink and Simscape. Many institutions provide students with free access to MATLAB, and it is often taught as an introductory programming course to first-year engineering students. Users can create models of rigid and compliant mechanisms or machines using Simulink blocks or by importing CAD models. They can visualize the motion in the Mechanics Explorer while recording output data in the Simscape toolbox. To validate the results obtained from Simscape models, we first developed a compliant and soft five-bar mechanism. Then, we created their corresponding models in Simscape and compared the tip positions of each mechanism by attaching a six degrees of freedom sensor. As shown in Figure 2, the tip positions from the physical prototypes and Simscape model show a good alignment. While the Simscape model keeps following the same trajectory for continuous loading, the slight differences are due to the resistance applied to the mechanisms by the sensor cable.

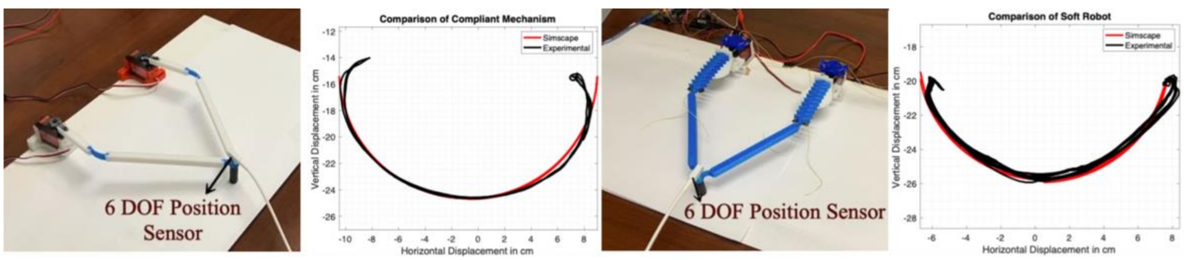

Figure 2. Validation of MATLAB Simscape Models by using a compliant and soft five-bar

The virtual lab simulations presented in this paper, along with additional simulations focused on compliant mechanisms and soft robots, are developed by junior and senior mechanical engineering students through a structured training model. In this model, a trained student proficient in MATLAB Simscape conducts weekly three-hour workshops for mechanical engineering students for the entire semester. An example of such a workshop on training new undergraduate students on developing rigid mechanisms, compliant mechanisms, and soft robots, led by a master's student, is shown in Figure 3. Students who consistently attend these workshops and complete the assigned homework are invited to join the corresponding author's research group. These students subsequently mentored new participants in subsequent semesters. This approach has demonstrated success in increasing undergraduate interest in research, with five students from the research group continuing their studies at the graduate level. By providing students with clearly defined learning objectives and hands-on opportunities, the training model helps students with skill development, enhances research participation, and promotes coding among undergraduate students.

Figure 3. Simscape training session led by a GRA.

Virtual Lab Simulations for Soft Robotics and Compliant Mechanisms Courses.

A mechanism can be created in MATLAB by building the model in Simulink using Simscape library blocks. However, this approach is limited to simple linkages and actuation methods. Alternatively, the CAD model of a complex machine or mechanism can be imported into Simulink. Once the model is imported as an assembly, no additional identification of joints is needed to create motion. Unlike MSC Adams, a commercially available software used to perform motion analysis of mechanisms and machines, MATLAB-Simulink automatically recognizes joints and incorporates mobility limitations. Compliant mechanisms and soft robots can be modeled in Simscape using two approaches: (1) the reduced-order model or (2) discretizing the beam elements. After importing the CAD model of a compliant mechanism or soft robot into Simulink, the soft and compliant members can be converted into deformable components using the reduced-order model block. This is achieved by adding mesh, material properties, and frames to enable connections between members and their neighboring parts. In the discretization method, multiple flexible body element-joint-body element blocks can be connected in series to form a flexible member. Analysis using the discrete beam element method is restricted to bending motions only. While the reduced-order model is easier to construct than the discrete beam element method and provides reliable results for small deformations, it tends to exhibit exaggerated deformation and unrealistic stretching under large deformations. Building flexible members using discretization is more challenging, particularly when assigning precise stiffness values for joints. However, the motion analysis yields reliable results. It is important to note that increasing the number of discretized segments in a beam improves solution accuracy but significantly increases simulation time.

The presented virtual lab consists of four main modules, including compliant hinges, large deflecting beams (buckling and compression), compliant mechanisms, and soft robots, as the overall image of the virtual lab is shown in Figure 4. Additionally, each module has several submodules. Compliant hinges include submodules of elliptical, fillet, rectangle, semi-circular, parabolic, and hyperbolic flexure hinges. Large deflecting beams have a total of ten submodules for the analysis of various types of buckling and compression flexible beams. The compliant mechanisms (CM) module has submodules with integrated modules within each. CM-Submodule 1 focuses on the models of flexible links using the pseudo-rigid body modeling (PRBM) method and compares it with the discrete beam element method. CM-Submodule 2 includes basic planar-compliant mechanisms, such as various combinations of four-bar, five-bar, slider-crank, and double-slider mechanisms. CM-Submodule 3 demonstrates the motion analysis of two actuators: a forced slider with rotational output and X-Bob. CM-Submodule 4 features two dwell mechanisms consisting of variable flexible beams. CM-Submodule 5 shows the design and motion of four rotational compliant mechanisms. CM-Submodule 6 has different bistable mechanisms, one as a four-bar and the other as an initially deformed fixed-fixed compliant beam. CM-Submodule 7 showcases the motion of two straight-line mechanisms. Finally, the soft robots

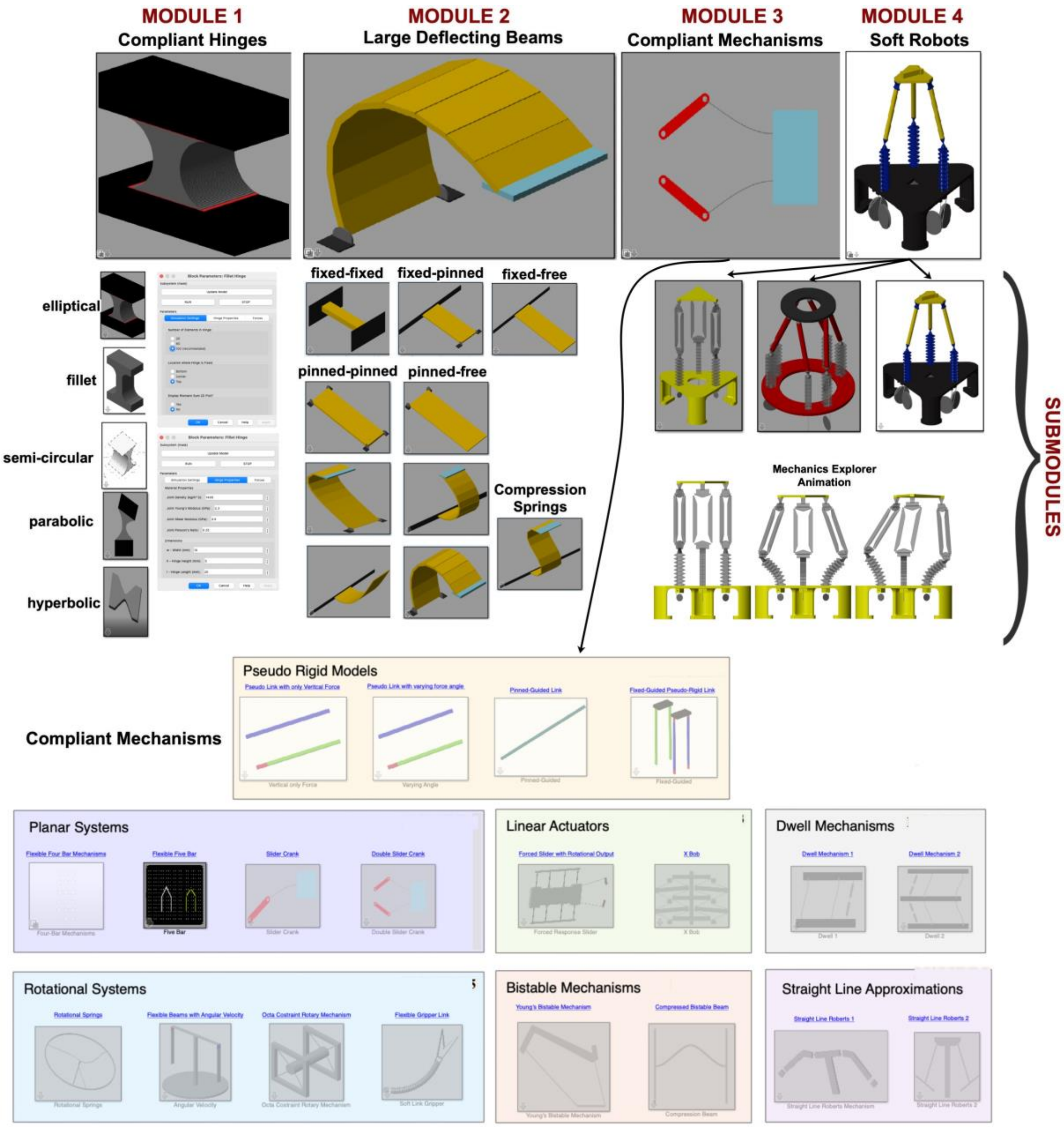

Figure 4. Developed virtual lab for soft robots and compliant mechanisms

module showcases the motion analysis of three well-known robots: Delta, 6 DOF, and a 3-USR robot. Each module, including the submodules, has masks to enable the user to adjust the parameters. The virtual lab can be downloaded from the corresponding authors' institutional website or directly from this link.

Various compliant mechanisms can be designed using flexible beams. For instance, an initially deformed fixed-fixed flexible beam can be utilized in bistable mechanism designs, while pinned-pinned flexible beams function as buckling beams and serve as translational springs, making them useful in dwell mechanism designs. Module 2 enables users to analyze different motion types of flexible beams that can be integrated into slider-crank, four-bar, and dwell mechanisms. CM-Module 1 enhances the understanding of deformation analysis in compliant mechanisms by providing examples such as a simple link under a vertical tip load, an inclined load, and a pinned-guided link subjected to a translational force. It also explores the application of flexible beams in a parallel arm mechanism. CM-Modules 2 through 7 visualize the deformation analysis of well-known compliant mechanisms under selected loading conditions, offering a comprehensive approach to studying their behavior.

Fundamentals of Flexible Beam Simulations. Submodule 1 in compliant (flexible) mechanisms is designed to enhance the understanding of deformation analysis through a commonly applied approach in compliant mechanisms, including a flexible beam subjected to only vertical tip load, inclined load, pinned-guided link with a translational force, and application of flexible beams in an example of a parallel arm mechanism. In order to model a flexible beam in MATLAB Simscape, 20 rigid rectangular blocks consisting of brick solid-revolute joint-brick solid are combined. Since flexible links deform large, Euler-Bernoulli equations can no longer be applied. In PRBM, a flexible link is modeled as a rigid link with a torsional stiffness, attached to the characteristic pivot, having the same load-deflection behavior as the compliant link. The torsional stiffness is a function of the material and geometric property and can be determined by solving the first and second kinds of elliptical integrals that are limited to simple geometries.

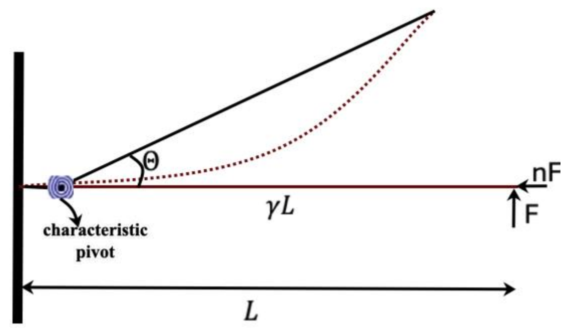

Figure 5. PRBM of a flexible beam with tip load

For example, consider a flexible beam with a length of L subjected to tip loading, as illustrated in Figure 5. The characteristic pivot is located at a distance of $(1-\gamma L)$ from the beam's fixed end, where γ is the characteristic radius constant. The reader can refer to [16,23] for more details on the stiffness calculation. Assuming only a vertical tip load is applied, then *n=0* and $\gamma = 0.85$. The torsional spring constant (K) is given by $K = \pi\gamma^2\frac{EI}{L}$, where E is the Young's modulus of the material and I is the moment of inertia.

The horizontal and vertical coordinates of the tip of the beam are described by the equations

$x = L - \gamma L(1 - cos\Theta)$ (1)

$y = L\gamma sin\Theta$ (2)

Here Θ is the PRBM angle. While the theory gives an accurate solution for angles up to 55°, discrepancies between theoretical predictions and actual beam deformation increase for larger angles.

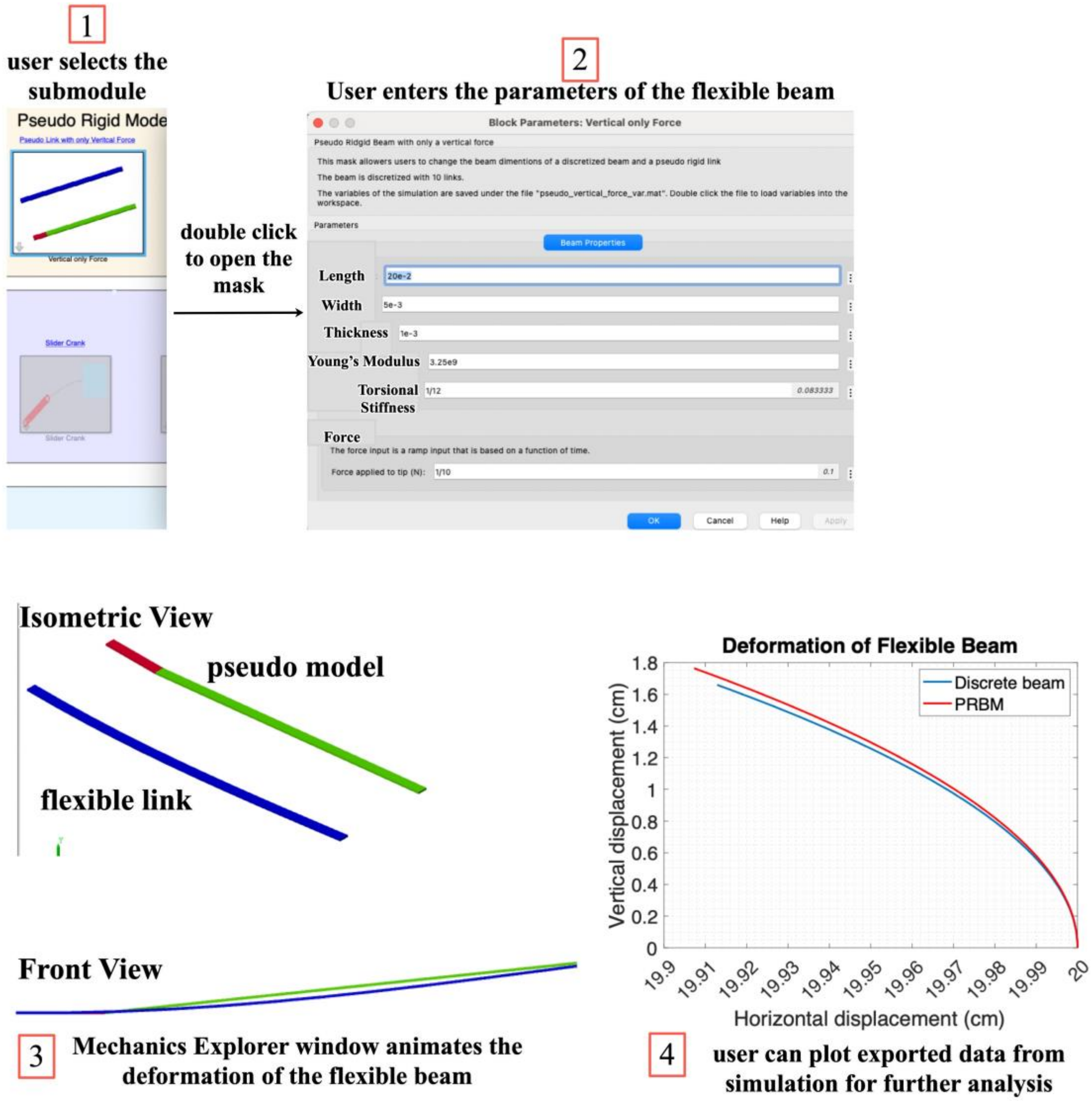

Figure 6. Simulation of a fixed-free beam: (1) the user selects the submodule by clicking on the subtitle, (2) double-clicks to open the mask and enter flexible beam parameters and geometry as well as the force magnitude, (3) once the simulation is started, mechanics explorer animates the deformation of the flexible beam, and (4) user can plot the results for

Users can apply the theory by using the geometry and material properties to calculate the characteristic radius constant and torsional stiffness, which can then be used to determine the tip coordinates of the discretized flexible beam. Users can design the same beam by selecting the subtitle “Pseudo link with only vertical force” to access the submodule, then double-clicking the submodule image to modify beam parameters and simulation time. After running the model, the deformations of both the flexible link (using the discrete beam element method) and its pseudo-rigid body model are animated in the Mechanics Explorer. The outputs, including tip coordinates, input force, and the pseudo angle, can be exported for further analysis, as shown in Figure 6. Users can increase the applied force to observe changes in link deformation and deviations between the two models.

Once the user gets familiar with deformation relationships in simple links, they can move on to analyzing a compliant parallel arm mechanism composed of two flexible fixed-free beams connected to a mass. It is important to note that the deformation of each arm in the mechanism is treated as a combination of two fixed-free beams, as illustrated in Figure 7. Additionally,

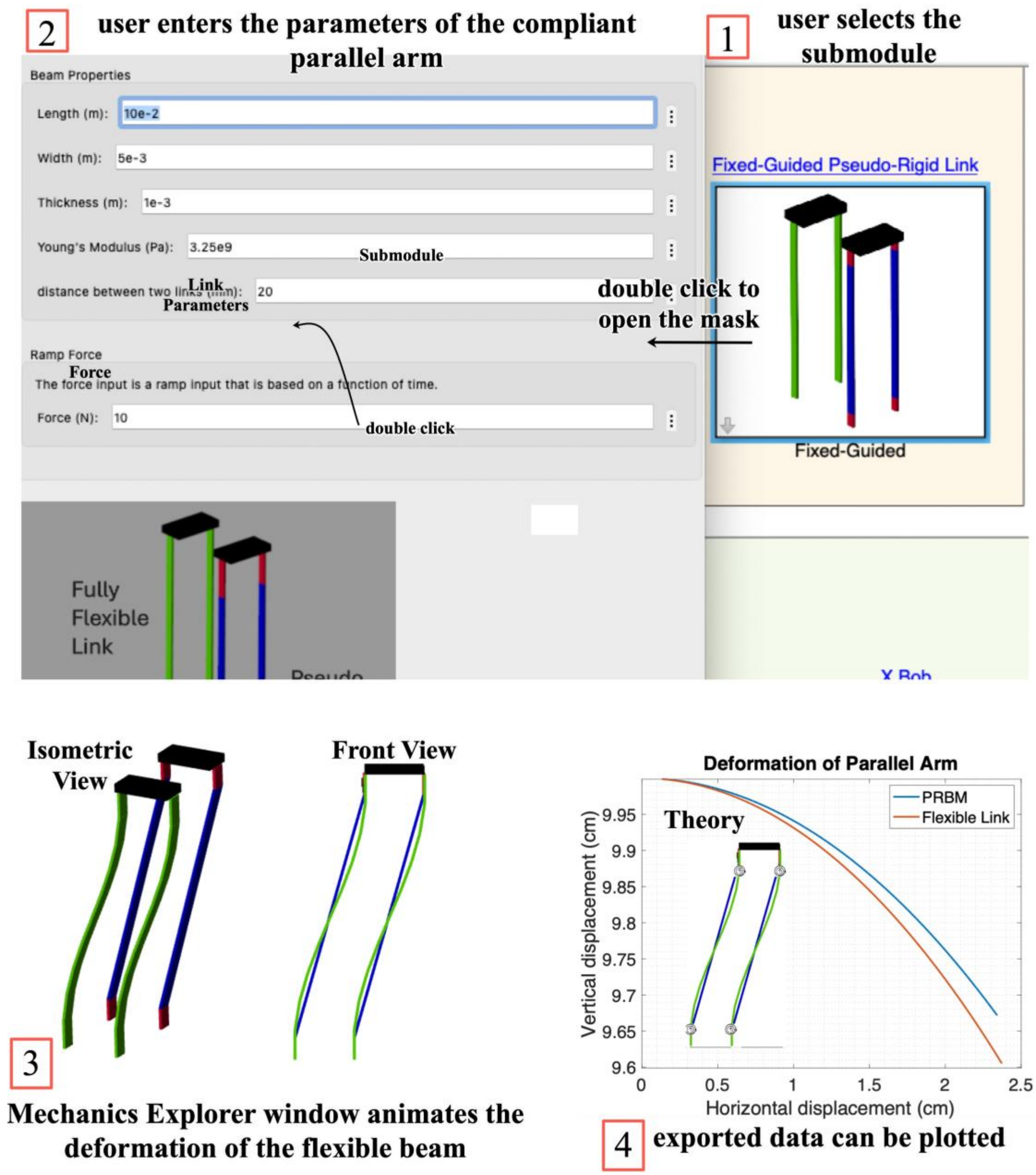

Figure 7. Simulation of a compliant parallel arm mechanism

instructors can assign Elliptica Problem solutions for graduate students to compare the results obtained from Elliptica Theory, PRBM, and flexible links developed by discrete beam elements.

After confirming the accuracy of the model, the user can apply an impulse force, though it increases simulation time and represents an initial displacement or free response for system identification. The free-response motion can be plotted to calculate parameters such as the logarithmic decrement, damping ratio, damping constant, damped and natural frequencies, and the equivalent stiffness of the system. This process is governed by the second-order differential equation representing the motion of the parallel arm:

$$m\ddot{x}(t) + b\dot{x}(t) + k_{eq}x(t) = F(t) \quad (3)$$

where *m* is the mass, *b* is the damping constant, k_{eq} is the equivalent stiffness, $x, \dot{x}, \ddot{x}$ are the position, velocity, and acceleration of the parallel arm, and *t* is the time. Also, the dynamical model can be represented as a transfer function.

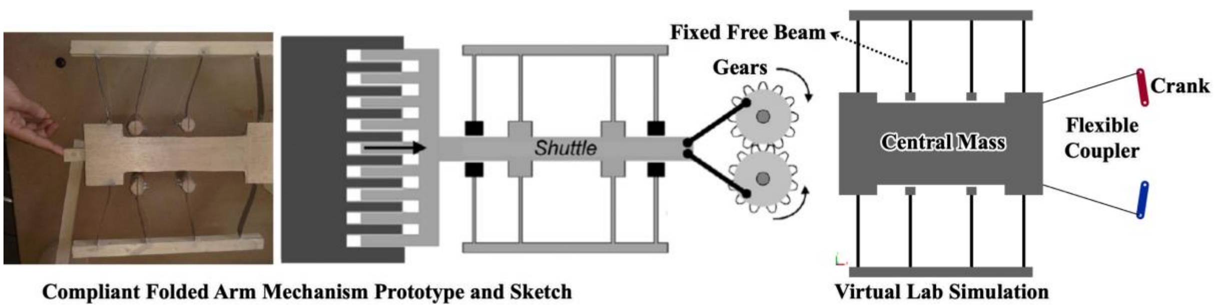

Figure 8. Simulation of a compliant folded arm mechanism from Module 3

Mechanisms with Flexible Beams. We modeled several mechanisms found in the compliant mechanisms books [23] and literature [16-18,20-24]. One such example is the compliant folded beam mechanism [25], also known as a forced slider with rotational output, as shown in Figure 8. This mechanism converts translational input motion into rotational output motion through a compliant parallel arm mechanism, which is coupled with fixed-free and free-free beams. It has various applications, functioning as an indexing or dwell mechanism and being scalable for both micro- and macro-level designs. The equation of motion for this mechanism is expressed as

$$M\ddot{x}(t) + b\dot{x}(t) + k_{NL}(x) = F(t) \qquad (4)$$

where *M* is the central mass, *b* is the damping constant, and mass connections, and k_{NL} is the equivalent non-linear stiffness, $F(t)$ is the applied force, and $x, \dot{x}, \ddot{x}$ are the position, velocity, and acceleration of the central mass. The relation between the position of the mass and angular rotation is given by

$$x = rcos\theta + Lcos\beta = rcos\theta + \sqrt{L^2 - r^2 \sin^2\theta - x_0} \qquad (5)$$

Here, θ, β are the crank and coupler angles, L and r are the coupler and crank lengths, and x_0 is the initial position of the central mass. Equivalent stiffness of the beams can be found either using Elastica theory for graduate-level courses and PRBM in undergraduate courses. For PRBM, the user can refer to the simulations provided in Module 1. These methods allow users to evaluate the deformation and compliance of the beams based on their respective analytical frameworks.

Five-Bar Simulations. To give an example of another study, the user can design both a rigid and compliant five-bar mechanism by selecting the submodule of Module 2 and adjusting the link lengths and angular displacement of the base links. Users practice designing flexure hinges that serve as revolute joints, similar to ball bearings. We designed the compliant five-bar mechanism by discretizing the curved beams into five segments. The analysis not only provides a comparison between the trajectories followed by a rigid and compliant five-bar mechanism but also demonstrates that while the rigid mechanism locks due to kinematic constraints, the compliant version traces a larger workspace due to the significant deformation capabilities of flexure hinges. As seen in Figure 9, the compliant mechanism exhibits a larger workspace along the horizontal axis compared to its rigid counterpart.

Additionally, though still in its preliminary phase, we designed and built the same setup by 3D printing the rigid links separately using PLA filament and assembling them via ball bearings. The compliant version is designed with flexures and 3D printed as a single piece using TPU filament. The base links are connected to servo motors and controlled by an Arduino. The setup is mounted on a pegboard, and the total cost of a setup is approximately $71. By combining a hands-on kit with its virtual lab, an activity design can be implemented in any of the aforementioned listed courses.

Soft Robot Simulation. Users can simulate any of the three tendon-driven soft robots provided in the Soft Robotics Module. To begin, the desired model is selected by choosing the corresponding title to activate the Simscape model. Next, by double-clicking on the image of the selected figure, the mask interface is opened, allowing users to specify the desired tip trajectory for the robot. Additionally, users can adjust the stiffness of the discretized soft link elements and the damping constant. After configuring the simulation parameters, such as simulation time, and running the simulation, the Mechanics Explorer animates the robot's resulting displacement. This process offers significant benefits, particularly for students and beginners in soft robotics, by enabling them to observe and gain a deeper understanding of the motion characteristics of soft robots. Figure 10 depicts the steps to be followed for running the simulation of a 3-USR soft robot so its tip follows a helical motion with a user-inputted radius and height.

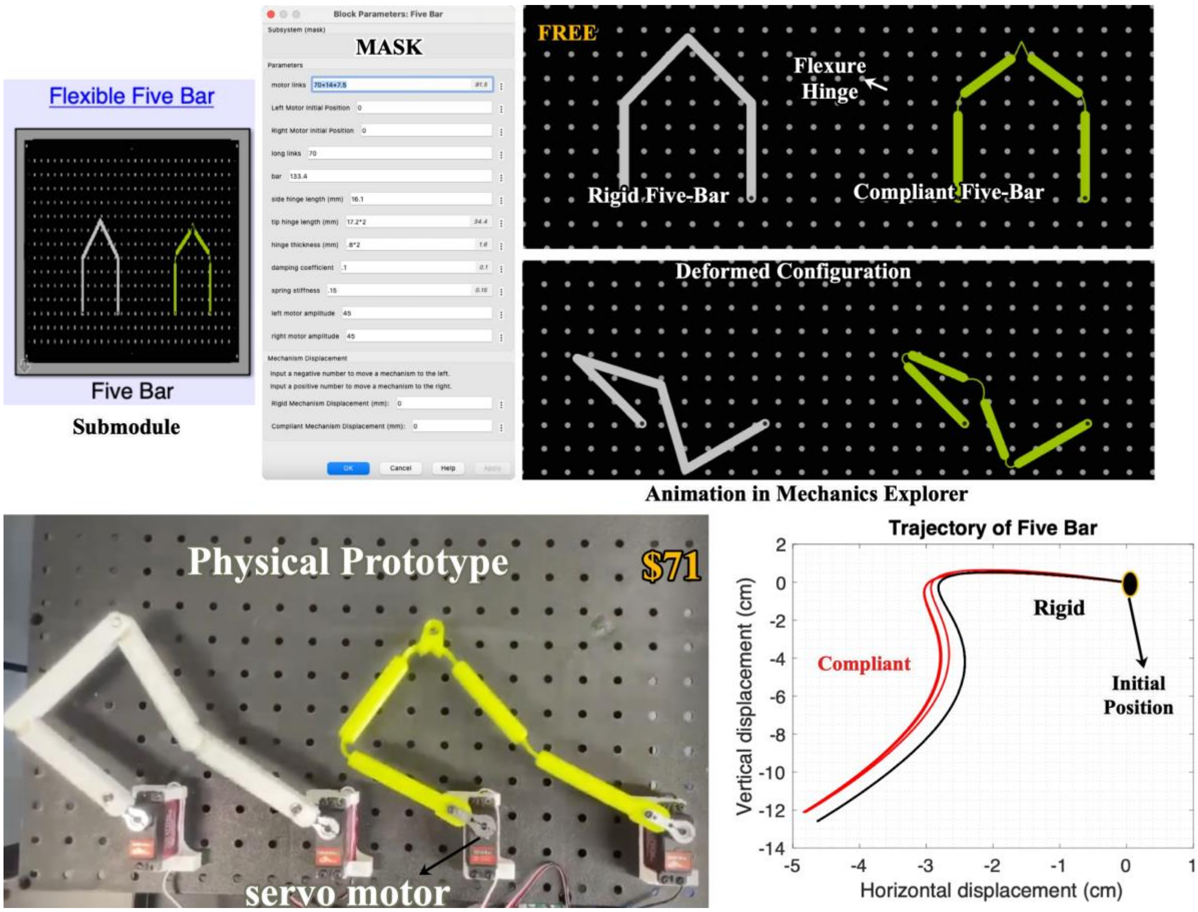

Figure 9. Simulation of compliant and rigid five-bar mechanisms

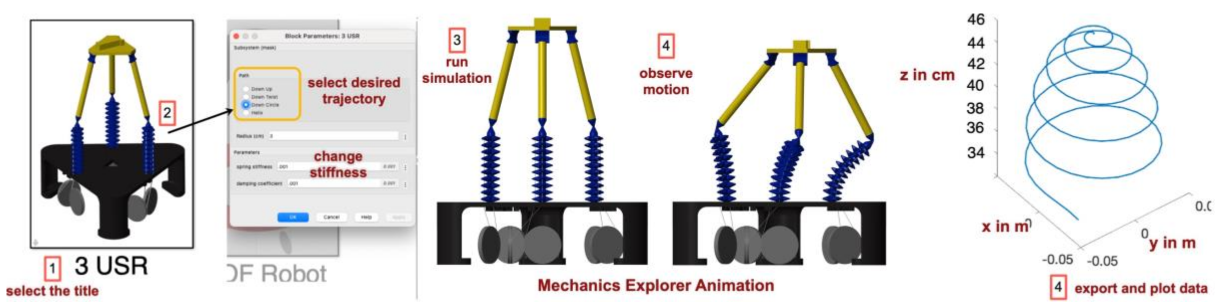

Figure 10. Simulation of 3-USR soft robot

Implementation and Learning Objectives for Virtual Lab Simulations

The integration of virtual lab simulations into face-to-face and online engineering courses provides an innovative framework to connect theoretical concepts with their practical applications to address a critical need in engineering education. The virtual lab modules developed in this study are designed to systematically enhance students' understanding of soft robotics and compliant mechanisms while equipping them with the technical skills required to navigate a rapidly evolving field. The simulations also serve as a window into emerging fields such as soft robotics. Students can experiment with advanced designs, such as folded beam mechanisms, and explore their potential applications in robotics or biomedical devices.

At the freshman level, these virtual labs can serve as an introduction to foundational principles. For example, in an Introduction to Engineering course, students can explore the deformation behavior of compliant mechanisms by modifying material properties, link dimensions, or applied force magnitudes within the simulation. These modifications allow students to observe the direct effects of input parameters on system behavior and foster an intuitive understanding of the underlying theory for flexible links. By engaging with these concepts early, students gain a strong foundation that supports their progression through the curriculum.

In junior-level courses, such as Mechanical Vibrations, the focus shifts to applying theoretical knowledge to practical problems. Students can use virtual lab simulations to design compliant mechanisms, such as a parallel arm mechanism, analyze their motion, and validate theoretical models. By calculating equivalent stiffness values, damping ratios, and system frequencies, students link abstract mathematical equations to real-world behavior and deepen their understanding of advanced concepts. These exercises also prepare students to tackle nonlinear deformation and dynamic modeling challenges that are essential topics in soft robotics.

At the senior level, in courses such as "Introduction to Robotics," the virtual labs emphasize innovation and advanced problem-solving. Students can design both rigid and compliant mechanisms, such as five-bar systems, and compare their workspaces, trajectories, and performance under varying conditions. Additionally, physical prototypes of these mechanisms can be fabricated using 3D printing, allowing students to validate their simulation results experimentally. This combined approach of utilizing hands-on kits and their virtual lab simulations enhances students' technical expertise and promotes interdisciplinary thinking and innovation.

To ensure alignment with course objectives, the virtual lab modules are tailored to different academic levels. In introductory courses, they focus on developing an intuitive understanding and exploring fundamental concepts. For core courses, it reinforces theoretical knowledge through practical application and model validation. In advanced electives, they challenge students to innovate and apply their knowledge to emerging fields such as soft robotics. This structured progression provides an opportunity to provide meaningful learning experiences at every stage of the curriculum.

Example Learning Activity Design. Students learn about modeling SDOF and 2 DOF systems in engineering dynamics, mechanical vibrations, and control theory courses. They also perform position, velocity, and acceleration analysis in machine design courses. The proposed learning

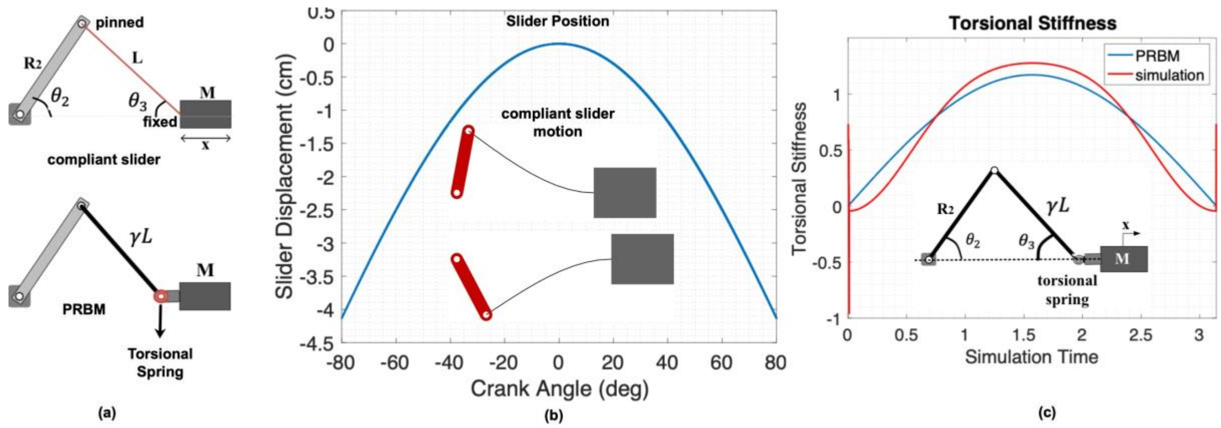

Figure 11. Motion analysis of a compliant slider mechanism: (a) compliant slider and its PRBM, (b) images of the simulation results and slider position obtained from the virtual lab, and (c) comparison of the torsional stiffness calculated from theory and virtual lab

activity can focus on the motion analysis of a compliant slider-crank mechanism that can be implemented in mechanical vibrations, control theory, and machine design courses. The learning objectives for the activity can be listed as: (1) draw the PRBM model referring to the theory, (2) calculate the torsional stiffness of a fixed-pinned beam, (3) derive the equation of motion for the compliant slider-crank mechanism using PRBM, Newton's laws of motion or Lagrangian methods, (4) simulate the dynamic behavior of the mechanism in Simulink under varying input conditions, (5) compare results from the simulated model with outputs obtained from the virtual lab environment, and (6) analyze discrepancies between theoretical predictions, simulation results, and virtual lab data to refine understanding and improve modeling accuracy.

To complete the activity, students would first need to be introduced to the theoretical principles, such as using PRBM to calculate the torsional stiffness of a fixed-pinned beam by referring to Section 5.2 in the compliant mechanisms book [22] or the online resources such as [23].

Students can work in groups depending on the number of students in the class and the duration of the learning activity could be one week. As shown in Figure (11a), the crank has a length of R_2, the flexible beam serving as the coupler has a length of L, the slider mass is M, and the crank and beam angles are θ_2 and θ_3. The fixed-pinned flexible link is represented as two rigid links connected through a torsional stiffness, K_s, and the coupler link length is γL. The equation of motion of the PRBM model of the compliant slider can be obtained using Newton's laws of motion by drawing the free body diagram of each link or using the Lagrangian method. The total kinetic and potential energies of the assuming the crank and coupler links have a negligible mass compared to the slider, for simplicity, are

$$T = \frac{1}{2} m_s \dot{x}_s^{\,2} \quad (6)$$

$$V = \frac{1}{2} K \left[sin^{-1} \left(\frac{R_2}{\gamma L} sin\theta_2 \right) \right]^2 \quad (7)$$

The slider position (x_s) with respect to the fixed frame is

$$x_s = R_2 cos\theta_2 + \sqrt{(\gamma L)^2 - R_2^2 \sin^2\theta_2} \quad (8)$$

Using the Lagrangian equation, $\mathcal{L} = T - V$, the equation of motion can be defined as

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\theta}_2}\right) - \frac{\partial \mathcal{L}}{\partial \theta_2} = \vartheta_{\theta_2} \quad (9)$$

where ϑ_{θ_2} includes the information on damping forces and the moment acting on the slider due to the torsional spring. Substituting Equations (6–8) into Equation (9) gives

$$m_s\left[\frac{R_2^6 \sin^3\theta_2 \cos^3\theta_2}{a^2} + \frac{R_2^5 \sin^3\theta_2 \cos^2\theta_2}{a^{1.5}} - \frac{R_2^4 \sin^3\theta_2 cos\theta_2}{a} + \frac{R_2^4 sin\theta_2 \cos^3\theta_2}{a} + 2\frac{R_2^3 sin\theta_2 \cos^2\theta_2}{\sqrt{a}} - \frac{R_2^3 \sin^3\theta_2}{\sqrt{a}} + R_2^2 sin\theta_2 cos\theta_2\right]\dot{\theta}_2^2 + ms\left[\frac{R_2^4 \sin^2\theta_2 \cos^2\theta_2}{a} + 2\frac{R_2^3 \sin^2\theta_2 cos\theta_2}{\sqrt{a}} + R_2^2 \sin^2\theta_2\right]\ddot{\theta}_2 + \frac{k sin^{-1}\left(\frac{R_2}{\gamma L} sin\theta_2\right) R_2 cos\theta_2}{\sqrt{a}} = \vartheta_{\theta_2} \quad (10)$$

Here, $a = (\gamma L)^2 - R_2^2 \sin^2\theta_2$.

Students can design a compliant slider mechanism provided in Module 2, let $R_2 = 5\ cm, L = 10\ cm$, and the flexible link width and thickness are 1 cm and 6 mm respectively. The Young's modulus can be 206.8 MPa with zero eccentricity between the fixed joint and slider. The crank angle can be a harmonic function, such as $\theta_2(t) = 80\sin(4t)$. It's important to note that the flexible beam designed for the compliant slider is created by using a flexible beam element, not a discretized beam.

The average values for the characteristic radius (γ) and the torsional stiffness coefficient (K_θ) are 0.85 and 2.65. The stiffness of the beam is

$$K = \frac{\gamma K_\theta EI}{L} \quad (11)$$

The equation can be solved by writing a code in MATLAB or MATLAB Live Editor to find the total moment and force applied to the system. Similarly, the slider position (see Figure 11b) and coupler angle are exported as vector data in MATLAB command for further analysis. The mass is calculated from the virtual lab simulation knowing the geometry and the material properties, and for simplicity, the damping constant can be assumed as 0.1. Since the force is mass times acceleration, the reaction force from the slider can be calculated by taking the second derivative of the slider position and multiplying by mass. This can be used to find the remaining moments acting on the slider, particularly from the torsional stiffness, by taking the difference between Equation 10 and reaction force. The torsional spring moment, per the PRBM approach, is:

$$\tau_\theta = K sin^{-1}\left(\frac{R_2}{\gamma L} sin\theta_2\right) \quad (12)$$

As seen in Figure 11c, the theoretical and simulated torsional stiffness results align well. Students can further explore how changes in the flexible beam's thickness and length affect the slider position and torsional stiffness. By creating the same model in MATLAB Simulink, they can compare theoretical and virtual lab results, identify discrepancies, and refine their models.

To promote critical thinking, students may engage with questions such as: (1) How does compliance in mechanisms impact their performance compared to their rigid counterparts? This question is particularly relevant in Module 3: Compliant Mechanisms and Module 4: Soft Robots, where students analyze compliant sliders, five-bar mechanisms, four-bar mechanisms, and 3 DOF and 6 DOF soft robots. Through simulations, they can observe how compliance influences motion and overall functionality by comparing these mechanisms to rigid Delta and Stewart robots. (2) In what real-world applications would compliance be advantageous? After running simulations in Modules 2-4, students can observe significant deformations in flexible members and reflect on how compliance provides benefits in various applications. This question is suitable for students at all levels, from freshman to senior years. (3) What assumptions were made during the derivation of the equation of motion, and how do they affect accuracy? This discussion is particularly relevant in Module 4: Soft Robots, where even the Simscape model relies on the constant curvature assumption. Additionally, for simple compliant mechanisms modeled using the Pseudo-Rigid-Body Model (PRBM), accuracy is limited to specific angular deformations. Encouraging students to critically evaluate these modeling assumptions can initiate deeper discussions, especially in courses like machine design, vibrations, and control theory. (4) How do material and geometry considerations influence the design of compliant mechanisms? This question applies across all modules, as students can modify dimensions and material properties within each submodule. By adjusting these parameters, they gain insights into how material selection and geometric configurations affect flexibility and system performance.

Finally, students can submit a comprehensive technical report detailing their theoretical derivations, simulation processes, results, and reflections. This activity encourages students to gain technical expertise while developing analysis, critical thinking, and communication skills.

Conclusion and Future Consideration

Engineering students often struggle to connect theoretical concepts to their practical applications, and this issue becomes more significant in emerging fields such as soft robotics and compliant mechanisms. Traditional teaching methods face limitations, including time constraints, financial barriers, and the lack of accessible tools to visualize and analyze the complex, nonlinear behavior of systems with bendable components. To address these challenges, this study presents a virtual lab developed in MATLAB Simulink and Simscape to provide an interactive platform both for faculty teaching and student learning of compliant mechanisms and soft robots. These simulations allow students to explore deformation analysis, nonlinear dynamics, and system behavior in a hands-on manner to enrich their understanding of challenging topics.

While this study has successfully developed and validated virtual lab modules, they have yet to be implemented in an actual classroom setting. Future efforts will focus on integrating these simulations into undergraduate engineering courses, such as Mechanical Vibrations, Control Theory, and Introduction to Robotics. Pilot studies will be conducted to evaluate the impact of these modules on student learning outcomes, using qualitative and quantitative data collected through surveys, assignments, and project-based assessments. Insights gained from this implementation will guide iterative improvements to the modules. Since most engineering institutions provide MATLAB licenses and the presented soft robots virtual lab simulations are open-source, it increases their accessibility. Additionally, future work will explore expanding the scope of the virtual lab to include more advanced topics, such as the design of soft actuators, bio-inspired mechanisms, and deployable compliant mechanisms.

We will implement multiple evaluation strategies to gather feedback from both students and instructors on the use of the soft virtual lab. Pre- and post-assessments will measure students' conceptual understanding before and after engaging with the simulations, while task-based exercises will evaluate their ability to apply theoretical knowledge in a simulated environment. Additionally, student feedback will help identify areas where they faced challenges and highlight opportunities for improvement.

References

1. Yasa, Oncay, Yasunori Toshimitsu, Mike Y. Michelis, Lewis S. Jones, Miriam Filippi, Thomas Buchner, and Robert K. Katzschmann. "An overview of soft robotics." Annual Review of Control, Robotics, and Autonomous Systems 6, no. 1 (2023): 1-29.
2. Walker, James, Thomas Zidek, Cory Harbel, Sanghyun Yoon, F. Sterling Strickland, Srinivas Kumar, and Minchul Shin. "Soft robotics: A review of recent developments of pneumatic soft actuators." In Actuators, vol. 9, no. 1, p. 3. MDPI, 2020.
3. Rus, Daniela, and Michael T. Tolley. "Design, fabrication and control of soft robots." Nature 521, no. 7553 (2015): 467-475.
4. El-Atab, Nazek, Rishabh B. Mishra, Fhad Al-Modaf, Lana Joharji, Aljohara A. Alsharif, Haneen Alamoudi, Marlon Diaz, Nadeem Qaiser, and Muhammad Mustafa Hussain. "Soft actuators for soft robotic applications: A review." Advanced Intelligent Systems 2, no. 10 (2020): 2000128.
5. Chen, Ang, Ruixue Yin, Lin Cao, Chenwang Yuan, H. K. Ding, and W. J. Zhang. "Soft robotics: Definition and research issues." In 2017 24th international conference on mechatronics and machine vision in practice (M2VIP), pp. 366-370. IEEE, 2017.
6. Tekes, Ayse, Hongkuan Lin, and Kevin McFall. "Design, modelling and experimentation of a novel compliant translational dwell mechanism." Journal of Mechanical Science and Technology 33 (2019): 3137-3145.
7. Lozano, Raul, Lucas Schwenck, Casey Tran, Vincent Nguyen, and Ayse Tekes. "Preliminary Results From Vibration-Induced Locomotion of A Compliant Robot." In SoutheastCon 2024, pp. 1615-1620. IEEE, 2024.
8. Ling, Mingxiang, Larry L. Howell, Junyi Cao, and Guimin Chen. "Kinetostatic and dynamic modeling of flexure-based compliant mechanisms: a survey." Applied Mechanics Reviews 72, no. 3 (2020): 030802.
9. Limited, C. B. I. P. (2023a, September 18). Soft robotics market to hit US$ 8,748.87 million by 2030: Research analysis. GlobeNewswire News Room. https://www.globenewswire.com/news-release/2023/09/18/2744636/0/en/Soft-Robotics-Market-to-Hit-US-8-748-87-Million-By-2030-Research-Analysis.html
10. Xiong, Jiaqing, Jian Chen, and Pooi See Lee. "Functional fibers and fabrics for soft robotics, wearables, and human–robot interface." Advanced Materials 33, no. 19 (2021): 2002640.
11. Zhu, Mengjia, Shantonu Biswas, Stejara Iulia Dinulescu, Nikolas Kastor, Elliot Wright Hawkes, and Yon Visell. "Soft, wearable robotics and haptics: Technologies, trends, and emerging applications." Proceedings of the IEEE 110, no. 2 (2022): 246-272.
12. Ghobadi, Narges, Nariman Sepehri, Witold Kinsner, and Tony Szturm. "Beyond Human Touch: Integrating Soft Robotics with Environmental Interaction for Advanced Applications." In Actuators, vol. 13, no. 12, p. 507. MDPI, 2024.
13. Brophy, Sean, Stacy Klein, Merredith Portsmore, and Chris Rogers. "Advancing engineering education in P-12 classrooms." Journal of Engineering Education 97, no. 3 (2008): 369-387.

14. Reeves, Shalaunda M., and Kent J. Crippen. "Virtual laboratories in undergraduate science and engineering courses: A systematic review, 2009–2019." Journal of Science Education and Technology 30 (2021): 16-30.
15. Potkonjak, Veljko, Michael Gardner, Victor Callaghan, Pasi Mattila, Christian Guetl, Vladimir M. Petrović, and Kosta Jovanović. "Virtual laboratories for education in science, technology, and engineering: A review." Computers & Education 95 (2016): 309-327.
16. Howell, Larry L., Spencer P. Magleby, Brian Mark Olsen, and John Wiley, eds. Handbook of compliant mechanisms. New York, NY, USA:: John Wiley & Sons, Incorporated, 2013.
17. Perai, Seberang. "Methodology of compliant mechanisms and its current developments in applications: a review." American Journal of Applied Sciences 4, no. 3 (2007): 160-167.
18. Talley, Connor, Anthony Tetrault, Parker Woods, Majazz Allah, Nathan Jones, Catherine Wilson, Coskun Tekes, and Ayse Tekes. "Design, Development, Analysis, and Preliminary Testing of a Compliant Knee for Bipedal Robots." In ASME International Mechanical Engineering Congress and Exposition, vol. 87639, p. V006T07A062. American Society of Mechanical Engineers, 2023.
19. Wang, Yuzhe, Zhen Xie, Huishi Huang, and Xinquan Liang. "Pioneering healthcare with soft robotic devices: A review." Smart Medicine 3, no. 1 (2024): e20230045.
20. Garcia, Martin, Andrea-Contreras Esquen, Mark Sabbagh, Devin Grace, Ethan Schneider, Turaj Ashuri, Razvan Cristian Voicu, Ayse Tekes, and Amir Ali Amiri Moghadam. "Soft Robots: Computational Design, Fabrication, and Position Control of a Novel 3-DOF Soft Robot." Machines 12, no. 8 (2024): 539.
21. Garcia, Martin, Paul Pena, Ayse Tekes, and Amir Ali Amiri Moghadam. "Development of novel three-dimensional soft parallel robot." In SoutheastCon 2021, pp. 1-6. IEEE, 2021.
22. Rus, Daniela, and Michael T. Tolley. "Design, fabrication and control of soft robots." Nature 521, no. 7553 (2015): 467-475.
23. Howell, Larry L. "Compliant mechanisms." In 21st Century Kinematics: The 2012 NSF Workshop, pp. 189-216. London: Springer London, 2013.
24. Boyle, Cameron, Larry L. Howell, Spencer P. Magleby, and Mark S. Evans. "Dynamic modeling of compliant constant-force compression mechanisms." Mechanism and machine theory 38, no. 12 (2003): 1469-1487.
25. Tekeş, Ayşe, Ümit Sönmez, and Bilin Aksun Güvenç. "Compliant folded beam suspension mechanism control for rotational dwell function generation using the state feedback linearization scheme." Mechanism and Machine Theory 45, no. 12 (2010): 1924-1941.