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Virtual Laboratories for Vibrations and Mechanisms and Machines Courses

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Virtual Laboratory for Mechanisms and Machine Design Courses

Abstract

Teaching and learning abstract topics taught in mechanisms and machines, machine dynamics, and mechanical vibrations courses are difficult since the content is highly mathematical and there are not adequate resources available for the faculty and engineering students to visualize the topic in the classroom. Additionally, such courses are delivered in traditional formats and students are passive learners. Although students engage more in laboratories, mechanisms, and machines courses don't have lab components unlike vibrations and control labs or electrical/mechatronics and robotics courses. To address this problem, we developed an open-source virtual lab for the mechanisms and machines and machine design courses in MATLAB Simscape to visualize the 3D motions of illustrated systems and content. The user-friendly virtual lab consists of several submodules including mobility, examples of linkages and machines, motion analysis of machines, SDOF and MDOF vibrations, large deformation, and buckling of beams to demonstrate fundamentals presented in the targeted courses.

Keywords

Virtual lab, mechanisms, and machines, vibrations

1. Introduction

Since engineering involves the use of scientific principles to solve real-world problems, theoretical concepts imparted to the students in traditional classroom settings must be supported by practical experience through hands-on experiments and/or virtual labs [1-3]. One salient, but also challenging, ABET outcome is that an engineering graduates should be able to solve a well-defined engineering problem by combining theory and practice [4]. Improving student problem-solving skills is a requisite to educate new engineers who can meet today's challenges and become experts in their field of interest [5,6]. As prior research shows, hands-on experiences and lab components of engineering courses provide critical learning experiences for students to better understand fundamental concepts [7-12]. However, many institutions have limited resources for laboratory equipment, and these limitations inhibit student learning due to constraints on the use of available turnkey equipment. As a result, the lab components are often limited as equipment is expensive, few in number, bulky, and inaccessible to those with physical disabilities [13-15]. Moreover, labs associated with engineering courses are often offered in the following semester. Since students take the labs in future semesters, many fail to remember essential topics and lose interest in the subject. Virtual labs have the potential to provide enhanced learning experiences, and while several virtual labs are available for college-level science courses, there is still a substantial need to develop and evaluate virtual labs specifically designed for engineering courses [16,17]. Existing virtual labs have certain constraints, including limited topics and restricted data collection, and they typically provide a poor user experience with no scaffolding, leading to low student engagement. Some commercially available engineering virtual labs also exist, but they are expensive. Also, existing open-source virtual labs have certain constraints, including limited topics and restricted data collection options. Furthermore, student engagement is minimal because students simply click on available buttons. Additionally, while some commercially available engineering virtual labs exist, they are expensive, especially for public institutions.

The availability of ubiquitous computing resources has made it possible for engineering students to perform lab experiments without the need to go to a physical lab. This has opened a door for teaching advanced concepts with the help of computer programs – some of these experiments are either prohibitively expensive to perform in an academic setting or technically infeasible without the full industrial infrastructure. For example, Du Val and He used state-of-the-art aircraft modeling and simulation tools for rotorcraft design, analysis, test, and full-flight simulation applications [18]. They also developed Graphical User Interfaces that provide user-friendly operation. Likewise, Jasti et al.'s study showed that student performance in the application, analysis, synthesis, and evaluation learning levels improved compared to those not provided in the virtual lab [19]. Auer et al. argued that virtual engineering labs are valuable for distance education students and learners in the workplace [20]. These labs can be accessed without traveling, and this flexibility is particularly important for life-long learning. Also, using computer-based labs removes or reduces the obstacles of cost, time-inefficient use of facilities, inadequate technical support, and limited access to labs. It has been suggested that virtual labs will continue to play a major role in the teaching of engineering and physical sciences in the future due to their convenience and low cost [21]. Virtual labs for mechanical vibrations, control theory, and helicopter theory courses were developed in [22-24].

In this study, an open-source, and user-friendly virtual lab in MATLAB Simscape to visualize and demonstrate the fundamental concepts taught in the undergraduate level mechanisms and machines, machine dynamics, and mechanical vibrations courses was developed. The submodules are designed as a mask to allow the user the geometry and parameters of the illustrated systems so students or instructors can observe the effect of the parameter on the output while exporting data to the workspace and 3D visualizing the motion in the mechanics explorer. The virtual lab is open-access and can be downloaded from [25]. The remainder of the paper is as follows. Section 2 describes the developed modules and Section 3 presents example simulations and discusses how the virtual lab can be implemented in the targeted courses. Concluding remarks are provided in the conclusion.

2. Development of Submodules of The Virtual Lab in MATLAB Simscape

Matrix Laboratory (MATLAB) is a commercially available numerical simulation and programming software favorably utilized in almost all engineering programs. Students have free access to MATLAB in many institutions, and an introductory-level MATLAB class is frequently offered to First-Year Engineering students. MATLAB Simscape is the modeling environment analyzing both rigid and flexible systems using either the blocks provided in the library or the CAD models imported from modeling software and creates a 3D visualization of the developed model in mechanics explorer while sharing specified output data in the command window.

The virtual labs developed for the selected courses consist of multiple submodules to simulate systems with a different set of parameters, analyze results, and visualize system behavior with Simscape Mechanics Explorer. To test how accurately Simscape models simulate and visualize the deformation and shape configuration, we developed a 3D printed compliant fixed-free beam, attached 3 magnets along the beam, and deformed the beam using electromagnets. We compared the Simscape model and the experimental data using image processing. As seen in Fig. 1, the overall results showed that Simscape perfectly simulated the physical prototype, and the discrepancy is due to the interaction of the magnets.

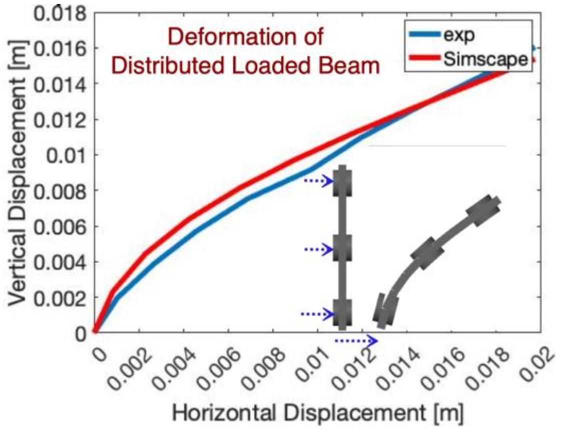


Fig. 1 Comparison of Simscape model and experimental data

The Simscape model of the mechanism can be created in two ways: using the library blocks or importing the CAD models from SolidWorks. A multibody Simscape model starts with a world frame, mechanism configuration, and solver configuration. The multibody model is composed of blocks; physical parts of the system can be constructed with body element blocks (brick solids for simple rectangular links, extruded solid for complex shapes, flexible bodies in the form of beams, etc.), joints (revolute, prismatic, 6 DOF) for assembling parts, actuation can be implemented as forces/torques or input motion through the joints or directly applied to the frames and the output data can be sensed from the point of interest using transform sensor or from the joints. The library also provides gear and coupling relationships. MATLAB has a default variable step size solver for Simscape models. Once the model is built, the mechanics explorer will open to 3D visualize the motion behavior as an animation under specified actuation. The output will be stored in the workspace so the user can do further analysis. Flexible bodies available in the library only allow for zero initial displacements and are valid for small deformations. On the other hand, the discretized parts integrate a certain number of rigid links connected by revolute joints with a defined stiffness having the same load-deflection behavior as the physical setup. As an alternative to constructing the model using library blocks, the user can import a SolidWorks assembly with the Simscape multibody link plugin which can be installed from MathWorks. For systems incorporating soft links and flexible mechanisms, the user can bring flexible bodies from the library or discretize the imported SolidWorks parts which were initially assumed rigid.

The virtual lab consists of 9 submodules including mobility, machine dynamics, buckling and compression beams, four-bar linkages, pulley systems, five-bar linkages, straight line generators, quick return mechanisms, rotating unbalance, and beam engine as depicted in Fig. 2. To work on

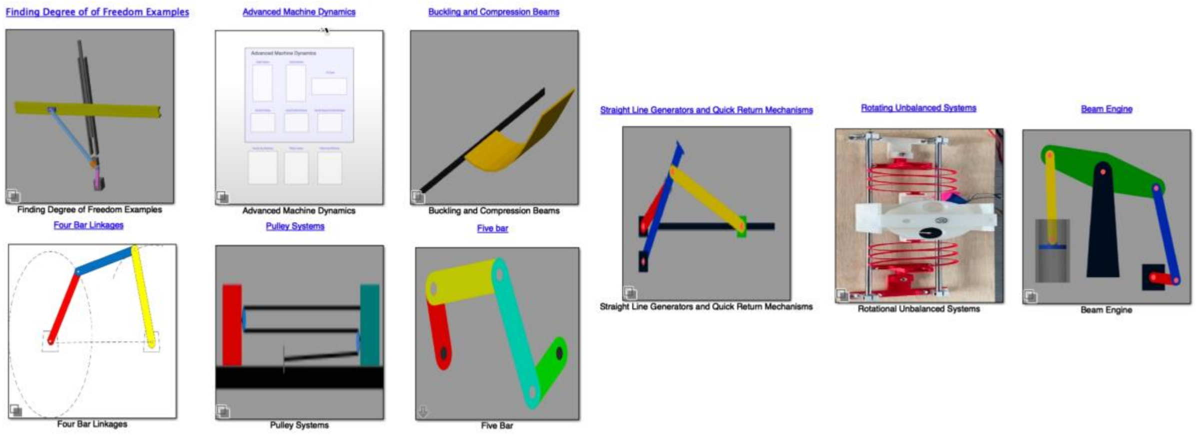


Fig. 2 Submodules of the developed virtual lab

the submodules user needs to select the corresponding title and then double click on the image to open the mask.

2.1 Submodule 1: Mobility Analysis

The mobility of a mechanism can be calculated using Gruebler's equation

$$DOF = 3(n-1) - 2J_1 - J_2 \qquad (1)$$

where n is the number of links, J_1 and J_2 are the numbers of lower and higher pair kinematic joints. To visualize the degrees of freedom of mechanisms, we selected example systems from [27]. This module allows the user to animate the motion of the designed rigid and compliant mechanisms as shown in Fig. 3.

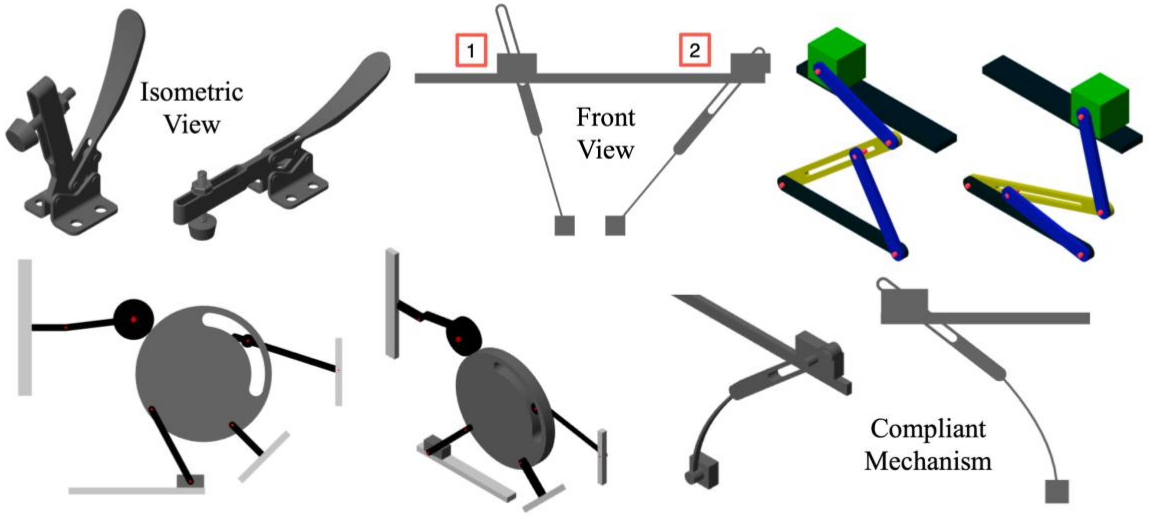
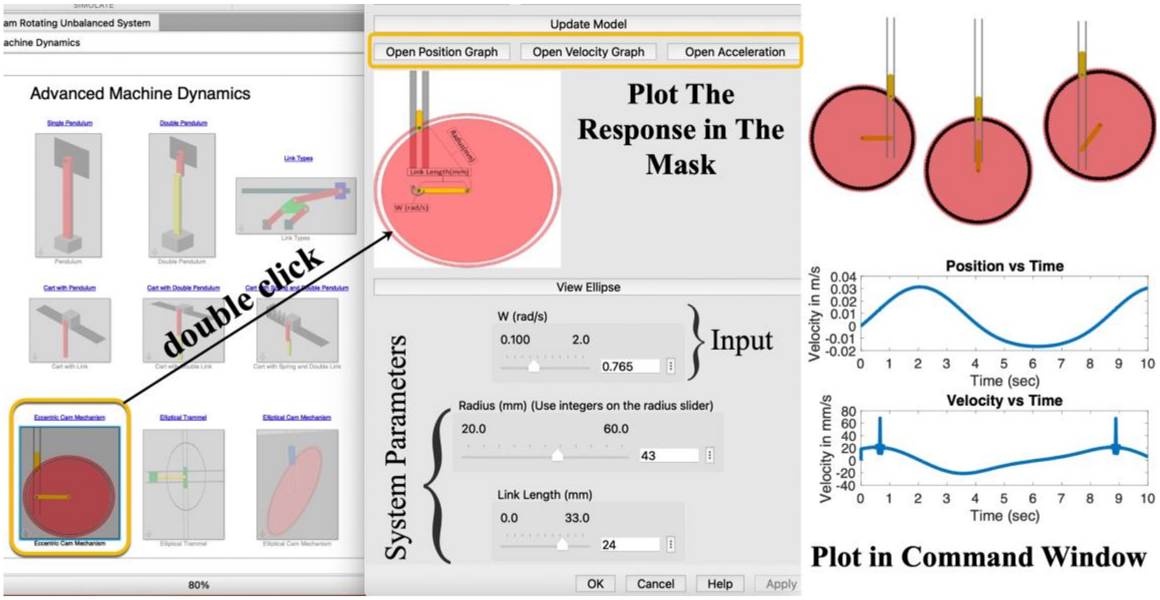


Fig. 3 Motion of selected systems from Submodule 1

2.2 Submodule 2: Advanced Machine Dynamics

The second submodule allows the user to change the parameters, dimensions, and input of single pendulum, double pendulum, cart with pendulum, cart with double pendulum, cart with a spring and a pendulum, eccentric cam, elliptical trammel, and elliptical cam mechanisms. To give an example of how to change parameters and run a simulation; if the user selects the title Eccentric Cam Mechanism and then double-clicks on the box, enters dimensions for the links, changes the input, updates the model, and runs the simulation, then the animation pane will be available in the mechanics explorer and plot the response either in the mask or in MATLAB command window as sown in Fig. 4. Although prior knowledge is not required to run any simulation in the presented virtual lab, if the user has Simscape experience, then they can click on the tiny arrow located in the below corner to open the Simscape model. Each example system in submodule 2 has a different mask to allow the user to modify the parameters.

2.3 Submodule 3: Buckling and Compression Beams. The large deformation of various types of buckling and compression beams as clamped-clamped, clamped-free, clamped-pinned, pinned-pinned, and pinned-free are created. Since flexible rectangular beams are utilized in the design of



W (rad/s) 0.100 2.0 0.765

Radius (mm) (Use integers on the radius slider) 20.0 60.0 43

Link Length (mm) 0.0 33.0 24

Fig. 4 Motion of selected systems from Submodule 2

buckling beams, user can only see the deformation shape and export force data. However, since we created the buckling beams by using discrete elements connected to each other through revolute joints, the user can extract the deformation of several points from the compression beams as well as the load-deflection curves.

2.4 Submodule 4: Four Bar Linkages. Based on the ratio of the length dimensions and which link is fixed, a four-bar mechanism follows different types of motion: double-crank, double-rocker, and crank-rocker. According to Grashoff's theorem, the shortest link can follow a full rotation if the sum of the shortest and longest link lengths is smaller than the sum of the other two lengths. The user selects an example system to simulate and double clicks to enter link dimensions along with desired angular displacement and angular speed, runs the simulation, and analyzes while observing the motion in the animation pane. If the selected dimensions are correct, then the program runs without any warning, however, if the link dimensions are selected properly for a desired motion type, then the mask prints the following comment after the user clicks on Apply: "the total length of the shortest link, fixed link, and the longest link is greater than the total lengths of the other two" for the drag mask.

2.5 Submodule 5: Pulley Systems. The submodule includes 6 example problems from Engineering Dynamics book [27]. The user selects one of the example systems, double clicks on the box, solves the shown problem using theory, and compares the theoretical solution with the simulated response While system outputs can be plotted, the user can find the final values by writing a script either in the command window or editor.

2.6 Submodule 6: Five Bar Linkage Systems. A closed-chain five-bar mechanism is designed. In addition to the Simscape model which includes two actuators attached to the base links, four excluded solids, and revolute joints. We also embedded a code to assist the user to enter the correct dimensions and initial configuration in the mask as well as the initial and final angular positions of the base links.

Since the designed five bar is a closed chain mechanism, the geometric constraint from the vector closure loop equations along the horizontal and vertical axes are

$$r_2c\theta_2 + r_3c\theta_3 - r_4c\theta_4 - r_5c\theta_5 = r_1 \qquad (2)$$

$$r_2cs + r_3s\theta_3 - r_4s\theta_4 - r_5cs = 0 \qquad (3)$$

where r_2, r_5 are the left and right base links, r_3, r_4 are the upper links connected to r_2, r_5 correspondingly, r_1 is the fixed distance between base links, and $\theta_2, \theta_5, \theta_3, \theta_4$ are the angles of the links read from the positive *x*-axis in counterclockwise direction. Since the user selects the dimensions of the links and base link angles, then the unknowns of Eqns. (3,4) are the upper angles only (θ_3, θ_4). To solve for the unknown angles, the following equations

$$r_3c\theta_3 - r_4c\theta_4 = a \qquad (4)$$

$$r_3s\theta_3 - r_4s\theta_4 = b \qquad (5)$$

in which $a = r_1 + r_5c\theta_5 - r_2c\theta_2$, $b = r_5s\theta_5 - r_2s\theta_2$ should be solved. If an intermediate variable is defined as

$$\sigma = b\sqrt{\begin{array}{l}(-a^2 - b^2 + r_3^2 + 2r_3r_4 + r_4^2) * \\ (a + 2 + b^2 - r_3^2 + 2r_3r_4 - r_4{}^\wedge 2)\end{array}} \qquad (6)$$

Also,

$$y_1 = -\frac{ab^2 + \sigma_1 - ar_3^2 + ar_4^2 + a^3}{2r_4(a^2 + b^2)} \qquad (7)$$

$$y_2 = -\frac{ab^2 - \sigma_1 - ar_3^2 + ar_4^2 + a^3}{2r_4(a^2 + b^2)} \qquad (8)$$

Finally, the unknown angles can be calculated using

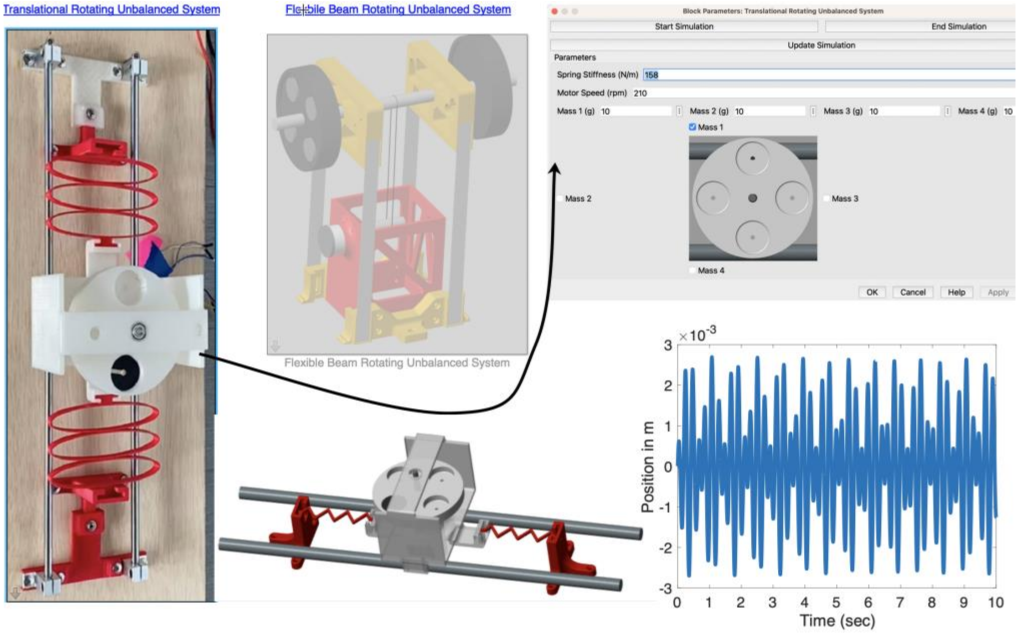
$$\theta_3 = \frac{a + r_4y_1}{r_3} \qquad (9)$$

$$\theta_4 = \text{acos}\,(y_1) \qquad (10)$$

Then the geometric constraint to build a five-bar mechanism is that Eqns. 2 &3 should be satisfied for the initial configurations defined by the user. If the dimensions and initial angles are correct, then once the user updates the model, the mask prints '*Both constraints are satisfied. The system is correct.*', if the dimensions are correct but not the initial angles, then the mask prints, '*Adjust input angles*', otherwise user receives '*Both constraints are unsatisfied. Adjust fixed link length or input angles.*' Once the simulation is completed, the user can plot the angles and the tip coordinates of the mechanism.

2.7 Submodule 7: Special Task Mechanisms. We designed Tchebicheff's straight-line mechanism, Watt's straight-line mechanism, and two quick return mechanisms. While the user is only allowed to run simulations of straight-line mechanisms and export data using the predefined geometry for demonstration purposes, the dimensions can be modified for the quick return mechanisms.

2.8 Submodule 8: Rotating Unbalance Systems. Two vibratory mechanisms are designed to demonstrate undesired vibrations caused due to rotating unbalance. The first mechanism is a translational cart connected to two springs on each side and housing a DC motor and a disk. The second mechanism consists of four flexible beams, two disks, a DC motor, and a belt as seen in Fig. 5. The user can run the simulation without adding any load on the disk while the motor running and then compare the responses when the disk is unbalanced such that a load is added at a distance to the center of the disk. The user can add loads to the four specified locations.



Spring Stiffness (N/m) 158
Motor Speed (rpm) 210
Mass 1 (g) 10
Mass 2 (g) 10
Mass 3 (g) 10
Mass 4 (g) 10
☑ Mass 1
☐ Mass 2
☐ Mass 3
☐ Mass 4

Fig. 5 Vibrations caused by rotational unbalance simulation

2.9 Submodule 9: Beam Engine. The beam engine with and without the damping effect is designed to demonstrate the effect of damping on the beam engine speed. The user can run two simulations starting with the undamped engine, run the simulation, save the exported data, and then enter a value for the damping constant and compare the piston speed.

3. Implementation of The Virtual Lab

Students meaningfully engage in active learning and think about what they are doing in active learning. However, in most engineering courses, students are not engaged in the learning processes since they are not given the opportunity to apply what they have been taught. Also, considering the engineering faculties' heavy workload and research requirements, faculty might not find adequate time to create learning activities that could meaningfully engage students. With the inclusion of virtual labs, students can more readily apply that knowledge to real-world problems. The presented virtual lab can be implemented in the face-to-face or online mechanical vibrations, machine design, and machine dynamics courses to (1) visualize the motion of the mechanisms in the classroom before presenting the topic based on Kolb's four stages of the experiential learning cycle, (2) engage students by creating short in-class activities such as "Why" and "What would happen if I changed certain parameters?", (2) assign class homework/project or lab handouts so students can design the mechanism, obtain the equation of motion as a differential equation or sets of the equation, and compare the theoretical and simulated responses.

Although instructors are not limited to those, we designed two learning activities in MATLAB live editor to illustrate as example assignments that are available on the open-source GitHub website. Students are asked to design a four-bar linkage, identify the link dimensions and initial angular positions, derive the vector closure loop equations, identify the unknown parameters, and write a script to solve the unknown if the driver link is rotated either for a complete rotation or oscillate between two angles, plot the response of the outputs, design the same system in the virtual lab, run the simulation, and compare the results.

4. Conclusion

In this study, we designed a virtual lab that can be utilized in the mechanical vibrations, machine design, and machine dynamics courses to help students visualize abstract concepts, run simulations at their own pace, and also for faculty to adopt them in their courses to demonstrate fundamentals, engage students with in-class activities, and assign as a homework. The open-access virtual lab developed in MATLAB Simscape consists of 9 submodules with selected content from the targeted courses including the demonstration of mobility, linkage design, position, velocity analysis, buckling and compression beam deformations, undesired vibrations formed by imbalanced rotational forces, damping effects on the speed of engine piston. The future considerations will be focused on the compilation of the developed virtual lab to run as a stand-alone package and enhanced with AI tools to assist the user.

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