GESTURE-BASED INTERACTIVE BEAM BENDING EXERCISES: AN INTERACTIVE AND INTUITIVE TOOL FOR STUDENTS

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Abstract

Immersion and interactive experience are introduced into a Solid Mechanics beam bending lab exercise by utilizing gesture-based analysis that is inexpensive, utilizes off-the-shelf cameras, and is highly portable for ease of use in the classroom. A cantilever I-beam is rendered in virtual reality (VR) and a user's gestures are captured and interpreted in real-time to allow for natural interaction with the beam. Users can bend the I-beam with up to three degrees-of-freedom, via mechanics governed by well-known elastic beam theory. This approach evokes a more immersive feeling in students, the intended users of the application, keeping them more engaged in the exercise. A simple web camera captures hand motion and algorithms interpret various gestures in real-time. For instance, simply by moving their hand up/down or left/right, seeming to "grab" and push or pull the end of the beam, students can intuitively vary input parameter such as load or displacements to the free end of a cantilever beam. Feedback, such as axial stress distributions, is displayed in real time. This approach provides a supplementary tool that is much more current with the state of the art for learning tools and provides for the need to keep students engaged and interested in various exercises, while still delivering many of the pertinent concepts found in lecture-based engineering courses. Results are discussed from student engagement in supplementary exercises to a traditional sophomore-level undergraduate Solid Mechanics course. Future improvements to the current application are discussed.

Motivation

The Aerospace Engineering degree program at Embry-Riddle Aeronautical University is a comparatively standard four-year engineering program, much like engineering programs offered at numerous other universities throughout the United States. Much of the freshman year consists of courses in calculus, physics, and composition, the sophomore year includes courses in mechanics, the junior year provides depth in the particular engineering discipline, and much of the senior year revolves around the senior design project. While the Aerospace Engineering department has been active in increasing design and laboratory content throughout the curriculum, certain courses have changed little over the many years they have been taught. Solid Mechanics is one of these courses.

Solid Mechanics, typically taken during the second semester of the sophomore year by engineering students, has been taught to aspiring mechanical, civil, and aerospace engineers for numerous decades, and the course content has changed little over that period of time. Solid Mechanics may be considered the first course in engineering structures (perhaps this could be argued, depending on how one views the prerequisite course Statics), and involves computing the stresses and strains in rods, shafts, beams, columns, and other simple structures. One of the authors took such a class as an engineering student at a different university and used the wellknown text Mechanics of Materials by Gere and Timoshenko[1]. Now the author teaches the same class with the sixth edition of the same text[2].

A typical method for teaching Solid Mechanics and similar courses in mechanics is to spend some portion of the class time lecturing on theoretical principles, and the remaining time working problems on the board. Most student homework involves completing similar problems with pencil and paper, time and again sketching free-body diagrams and working with equations. Some instructors will take students into the laboratory once or twice during the semester and provide a quick demonstration of a tensile test or a beam bending experiment. The addition of a new undergraduate laboratory for the Aerospace Engineering program at Embry-Riddle has led to the addition of increased laboratory content in the solid mechanics course, including assignments based on strain gage data gathered by students, allowing for the comparison of experimental data with theoretical predictions in numerous instances. However, the implementation of such laboratories is difficult to accomplish on a weekly basis with multiple sections of 20-30 students each semester. Further, students often have difficulty visualizing stresses and strains in rigid structures, such as large beams loaded in the laboratory. An aluminum or steel beam under moderate loads will often deflect imperceptibly, perhaps leading to a lackluster demonstration.

The use of finite element (FE) theory, when supplemented with assignments that must be completed using a commercial FE computer program, such as NASTRAN or ANSYS, can begin to fill this gap. Students can create structures, load and constrain them, and then view the solutions. Color-coded stress distributions and plots of structural displacements greatly advance students' understanding of the effect of loading on structures and the subsequent possibilities for structural failure. However, sophomore students enrolled in solid mechanics are generally considered to be not far enough along in their education to be introduced to FE concepts and associated software. Due to a lack of widely-used visualization software, Solid Mechanics instructors typically resort to their frequently

poor artistic skills to communicate such concepts to their students. Drawn on the board, the simple structures of beams, rods, shafts, and columns all look like rectangles, which is certainly uninspiring.

It is critical that the Solid Mechanics student fully understand the complete deformation behavior and stress distribution in the study of loaded structures. It is too easy for students to learn to simply view a set of equations as a 'black box' and to accept without question the answers that this produces. Students often experience a lack of context while solving such problems, and therefore can have little sense of whether or not an answer is correct. Appropriate visualization of both inputs and final results is critical to resolving this difficulty. Increased awareness on the part of the student of the problem at hand will lead to much-needed enthusiasm toward engineering during the sophomore year, which is key to larger issues such as student retention.

Laboratory Simulation for Education

There exists a vast array of computer simulation directed towards education, and the broad field of engineering is no exception. In an effort to reduce the need for costly laboratories desired for hands-on student engineering instruction, many educators are focusing attention on developing supplementary computer exercises, referred to by some as "virtual instruments."[3] These efforts are seen as particularly important as an increasing number of distance-learning degree programs are established.[4-6] There has also occurred some of the necessary comparison in student learning outcomes between real and simulated laboratory environments,7 although it appears that a thorough evaluation remains incomplete.

Educational simulations that incorporate virtual reality (VR) strive to increase realism and to immerse the user in an interactive environment. One of the many educational goals is to increase participation in active learning, and thus increase retention of key learning

concepts. Many educators are creating such simulations and exploring the impacts on student learning outcomes.[8-12] The use of display devices worn on the head and instrumented gloves to provide tactile feedback can greatly enhance the immersion and interaction of the user within the simulated environment. Some of the workers in the cited references are uncovering benefits to learning outcomes, but such costly equipment can limit the usefulness when serving large numbers of students. The computer vision application described in this work offers many of the same benefits from VR, but without much of the costly equipment that has so far been associated with the term.

Computer Vision and Gesture Recognition

Computer vision is a technology that enables computers to perceive the world around them[13]. This is accomplished by analysis of images or other multidimensional data to come to conclusion regarding distribution patterns in such images. Computer vision applications span a plethora of fields, from medical imaging, to surveillance, to human-computer interfaces through gesture recognition. Gesture recognition is a discipline of computer vision in which users' gestures are interpreted via spatial pattern distributions using various mathematical algorithms. Gestures, as spatial data information, are usually grabbed via cameras or other remote sensing devices. This information is then relayed to a computer in which various algorithms are utilized to interpret the data within a given context, to identify one of a number of intended gestures. Gesture recognition involves machine training on a predefined data set, and is usually accomplished in real-time, enabling a new generation of human-computer interactivity that precludes a mouse, keyboard, or any other peripheral mechanical device, which results in a more natural medium of interactivity[14]. Such a more natural, ergonomic approach makes applications much more immersive, and thus easier to accept for users. This is advantageous for educational implementations, since student

engagement and retention is very important. Immersion of students into fundamental physical concepts by allowing manipulation of various parameters via the technologies of computer vision and gesture recognition gives educators a clear advantage in concept delivering.

Implementation

El Doker and Lanning, faculty in the departments of Electrical Engineering and Aerospace Engineering, respectively, came together to pursue projects in undergraduate education. El Doker, with a specialty in computer vision, proposed the creation of a series of computer laboratory exercises to enable student to visualize and manipulate an object or series of objects that otherwise may not be easily done in a typical lecture or laboratory setting. It was decided that Solid Mechanics would be an appropriate course for which a set of exercises could be created. Students enrolled in this course often do not fully grasp concepts of stress distribution and deformation patterns. The manipulation of computer-generated images of engineering structures, with displacements and stress distributions displayed in real-time, with certain displacements appropriately exaggerated, could lead to quicker mastery of essential concepts. Justin Gigliotti is an electrical engineering student previously working on other computer vision projects, and was chosen to implement the programming. It is noteworthy that he has no background in solid mechanics, but nevertheless completed the initial simulation admirably.

Beam bending

The first simulation was a cantilever beam bending exercise with transverse point loads at the free end. This is a basic configuration used in countless solid mechanics problems, and while students have a reasonably clear understanding of the displacements, the overall stress distribution is often underappreciated. The cantilever beam is loaded at the free end, with

point loads possible in both primary directions perpendicular to the beam axis (side to side and vertical). These point loads in the y and z-directions, resulting in unsymmetric bending, gives a stress distribution that the solid mechanics student may not encounter until a later class in structures. Students should catch on to the additional concepts quickly after completing the demonstration, however.

Bending stresses in linear elastic unsymmetric beams, as taught in most undergraduate structures courses, follow the general equation:

$$\sigma_x = \frac{I_z M_y + I_{yz} M_z}{I_y I_z - I_{yz}^2} z - \frac{I_y M_z + I_{yz} M_y}{I_y I_z - I_{yz}^2} y$$

Eq. 1

where the x-direction is along the axis of the beam, σ_x is the bending stress, I_y and I_z are second area moments of inertia, I_{yz} is the product of inertia, M_y and M_z are the bending moments, and y and z are coordinates with respect to the cross-section centroid. The coordinates are shown in Figure 1.

In the present version of the exercise, the problem was simplified by the use of a symmetric cross-section, and since I_{yz} therefore goes to zero, the bending stress equation simplifies to:

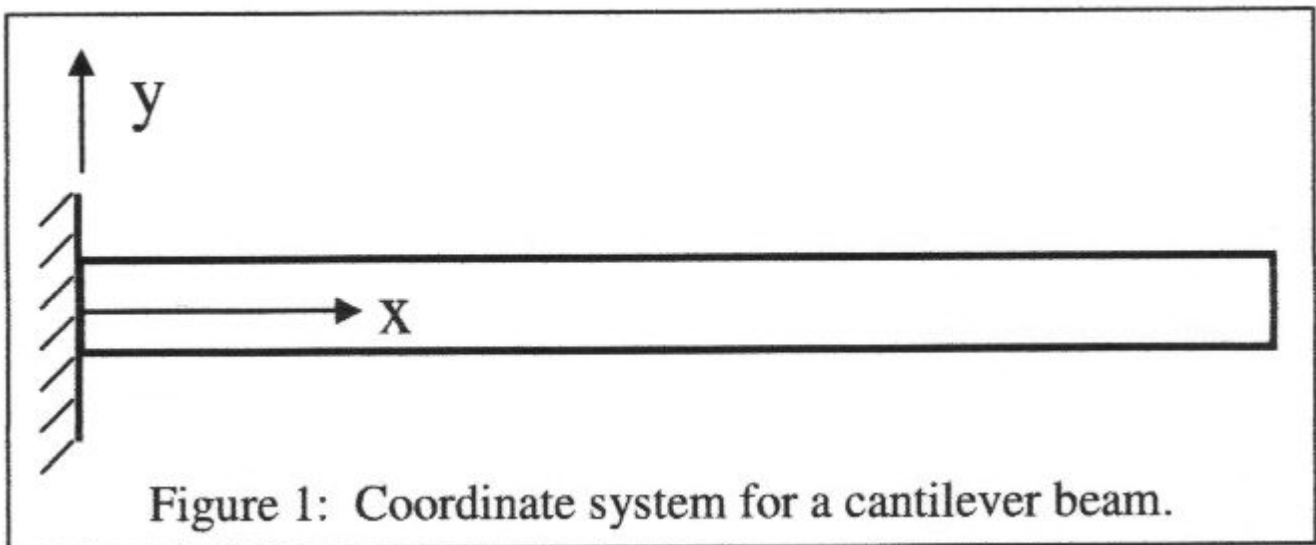$$\sigma_x = \frac{M_y}{I_y} z - \frac{M_z}{I_z} y$$

Eq. 2

This is often referred to as unsymmetric loading of a beam with a symmetric cross-section. As the beam is loaded, the deformed beam is displayed following the well-known transverse displacement equations for an end-loaded cantilever beam:

$$v = -\frac{P_y x^2}{3EI}(3L - x)$$
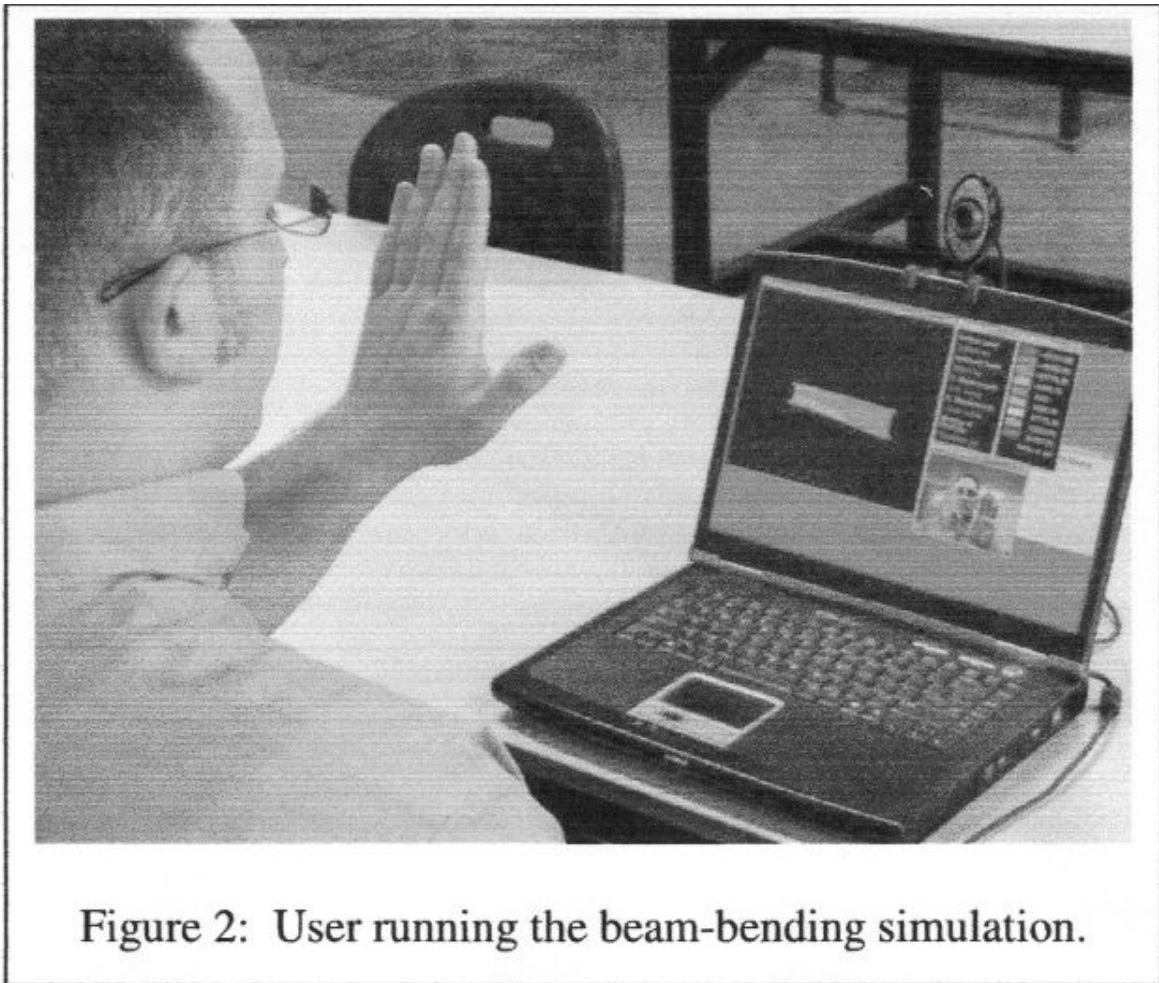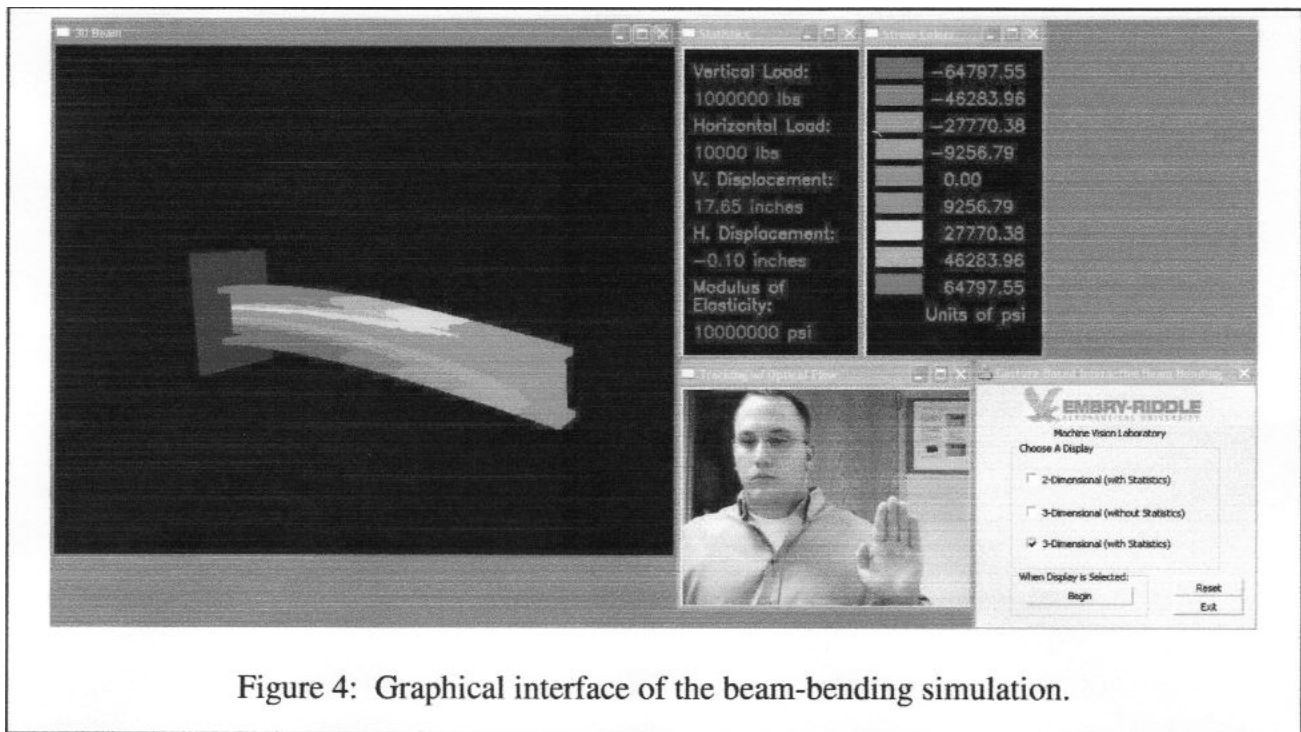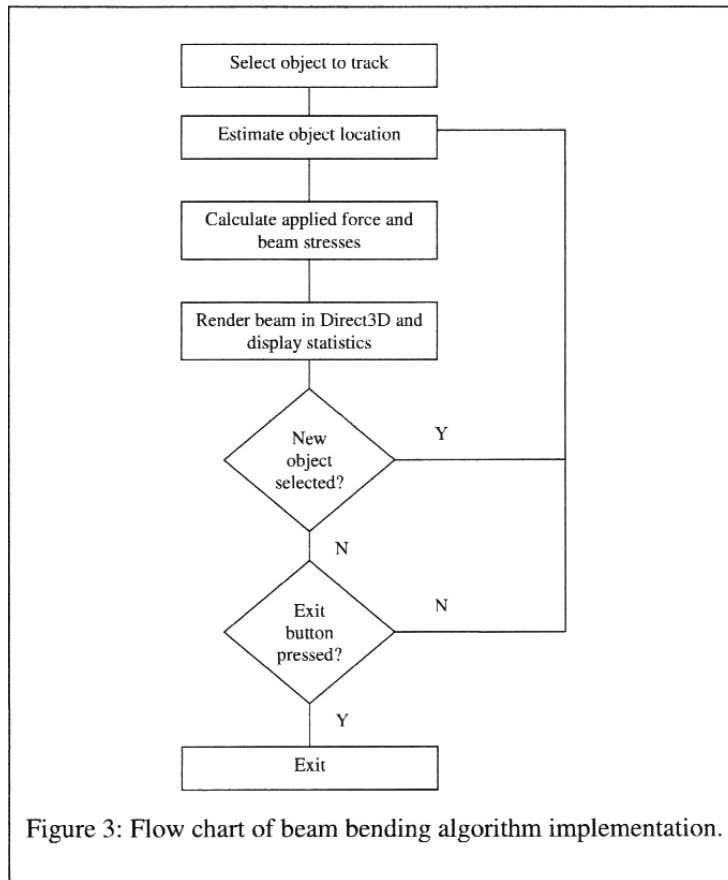
Eq. 3

$$w = -\frac{P_z x^2}{3EI}(3L - x)$$

Eq. 4

Figure 1: Coordinate system for a cantilever beam.

where Py and Pz are point loads that are considered positive if they are in the negative y- and negative z-directions, respectively, L is the length of the beam, x is the coordinate along the axis of the beam, and E is the elastic modulus. The displacements v and w are in the y and $z$directions, respectively.

Computer vision implementation

There are three main subsystems to this pplication: i) The vision control system, ii) the rendering system, and iii) the user interface:

i) The vision control system: The real-time computer vision system is made up a twodegree of freedom controller. Image frames are captured in real-time from a camera, with a user in the camera's field of view. The user then clicks in the region of motion (the user's hand), and an optical tracking algorithm13 is then utilized to track the hand motion. The beam is then controlled and manipulated as the hand moves left/right and up/down. Figure 2 shows a user interacting with the simulation while sitting in front of a laptop with a simple web camera. Figure 3 illustrates the overall block diagram of the system.

Figure 2: User running the beam-bending simulation.

Figure 3: Flow chart of beam bending algorithm implementation.

Figure 4: Graphical interface of the beam-bending simulation.

ii) The rendering system: openGL is utilized to render the I-beam using point sprites, and a transformation function given by the beam equations present in Eqs. 1-4. Multithreading is utilized to enhance the system's performance, such that the vision and rendering are each processed on separate threads.

iii) The graphical user interface, shown in Figure 4, is comprised of a series of input fields in which various parameters are manipulated. The user inputs vertical and horizontal load by moving the hand in those respective directions. The magnitude is controlled by the extent of the motion in the corresponding direction. The stresses are color-coded in a fashion typical of FE software, blue for compressive stresses grading to red for high tensile stresses. Currently, the colors are coded to absolute values of stresses, so that as the magnitude of the load is increased, the stress distributions are seen to develop from low magnitudes to high magnitudes.

Laboratory in the Classroom

A small section (8 students) of Solid Mechanics was chosen for the introduction of the beambending simulation in the autumn semester of 2006. The programming was completed towards the end of the semester, and unfortunately the classroom exercise was conducted with only two weeks before the end of the semester. This was quite some time after beam stresses were introduced in the course, which typically occurs during week six or seven. A single laptop with camera was brought into the classroom for the demonstration.

The instructor introduced the exercise, including the concept of color-coded stress distributions over the surface of a simple structure, and asked the students to describe what they would expect to see for basic loading conditions. The idea of unsymmetric bending (bending components mutually perpendicular to the loading axis and each other) was discussed, and again students were asked to speculate on the resulting stress distributions for various loading combinations. The students then sat down individually at the laptop/camera workstation and manipulated the beam through hand movements to see if their assumptions were correct. The laptop display was also projected by the overhead projector onto a screen for the rest of the class to observe. Afterwards, the instructor led a discussion to determine the reactions of the students to the exercise.

First, the students were interested in and intrigued by the new technology itself. While the use of technology solely for entertainment is certainly of limited value in the classroom, it can focus immediate interest in the exercise. The use of gestures to interact with the simulation appeared to keep students involved for the duration of the exercise. Perhaps more importantly, the use of gestures to control both the magnitude and direction of the force on the cantilever beam created a situation where the student could quickly and easily change input parameters.

Students appeared to respond favorably to a simulation environment in which abstract concepts were graphically realized on the computer screen, and manipulation of the object of interest was exceedingly easy. While all students understood that the highest stresses would be at the root of the cantilever beam, and it was acknowledged that this was a fairly simple loading case, they were interested in a tool that could be used for more complex loads and support conditions, where the user could easily modify the conditions of the problem and view the results in real time. Several students were interested in extending the exercises to problems in which they had particular difficulties understanding the relationship between loads and supports, such as solutions to indeterminate structures and the application of superposition for complex loadings.

The feedback was informal and qualitative, but critical to developing a plan for the subsequent semester (spring of 2007), in which additional features would be incorporated into the classroom tool. The instructor believed that students quickly developed an appreciation of concepts that were discussed minimally during lecture (unsymmetric bending) and an improved understanding of overall patterns of stress distributions. Students generally found that utilizing natural interaction via gestures to be intuitive and interesting. Currently, a plan for improved evaluation of student learning is being put together for the following semester. Several changes to the content of Solid Mechanics have been implemented in the past academic year, and the plan is to broadly identify whether or not ABET student learning outcomes are being positively or negatively impacted by these content changes, including the evolving beam simulation exercises.

Continued Development

Obviously, there are endless variations of problems that could be implemented using this gesture-based interactive tool for students, for Solid Mechanics as well as other courses. The challenge is to ensure that the development of this tool leads to improved student achievement. This preliminary classroom introduction served primarily to gauge students' reactions to the use of this technology for visualizing a particular problem, demonstrating the ease of use of such an interface and attempting to help students understand stress distributions of a cantilever beam.

In the next several months, the simulation will be expanded to include the effect of axial loads on the bending stress distributions, and perhaps torsional loads as well. The authors hope to expand options for user inputs on beam geometry and material properties. More importantly, a set of problems and questions will be constructed to accompany each computer exercise to be completed by the students. This will be used to create a more complete classroom exercise in which learning outcomes can be quantitatively evaluated. Student understanding of displacements and stress distributions must be evaluated before and after the use of the gesturebased simulation exercise. Finally, this must be designed so that it can be implemented easily with multiple sections of 20-30 students each semester.

Summary

A solid mechanics demonstration of beam bending has been paired with a computer vision tool allowing students to quickly develop a broader understanding of concepts of stress distributions and structural displacements. This new simulation environment has been developed to be easily implemented in a classroom environment, which allows for learning of concepts not easily grasped in a traditional lecture setting.

Acknowledgements

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