Haptics-Augmented Engineering Mechanics Educational Tools

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ABSTRACT

We have developed a unique set of software activities and tutorials to augment teaching and learning in standard required undergraduate engineering courses. With our products students are able to change parameters, predict answers and compare, interact with animations, and *feel* the results. This is possible via economical haptic interfaces, giving forces to the user's hand from our virtual PC activities. Teaching and learning can be more compelling, fun, and engaging, with deeper learning: "*feeling is believing*"; reduced student attrition may result, including those underrepresented in engineering.

In a proof-of-concept project funded by NSF, we developed haptics-augmented educational software products for physics, statics, and dynamics. Our software design evaluations at Ohio University have shown potential for our products to enhance undergraduate engineering courses by adding force feedback and the human sense of touch to learning.

INTRODUCTION

Haptics is related to the sense of touch and forces in humans. Haptic interfaces provide force and touch feedback from virtual models on the computer to human users. This article describes project using economical, commercially-available haptic interfaces to assist learning and teaching of undergraduate engineering students in an innovative manner. Any course involving forces and torques can benefit.

Most existing papers relating haptics and education are in the medical training field. The Interventional Cardiology Training Simulator [1] links technical simulation with specific medical education content. A virtual reality based simulator prototype for the diagnosis of prostate cancer has been developed using the PHANToM haptic interface [2]. The Immersion corporation (www.immersion.com) has developed haptic interfaces for injection training and sinus surgery simulation; these interfaces are relatively expensive and are special-purpose. The GROPE Project [3] has developed over 30 years a 6D haptic/VR simulation of molecular docking. A virtual haptic back model is described in [4], under development and evaluation at Ohio University for improving the teaching and learning of palpatory diagnosis by Osteopathic medical students and related fields.

A research group at the Ohio Supercomputing Center has applied haptics in virtual environments to improve tractor safety by training young rural drivers [5]. Their results show haptics increases training effectiveness, but access to their unique training system is limited. The SPIDAR haptic interface has been adapted to serve as "the next generation education system" [6], although the authors do not elaborate on the type of education intended. Haptics has been applied to make virtual environments accessible to blind persons [7]. The effectiveness of virtual reality in the learning process has been demonstrated by many authors (e.g. [8]). Jones et al. [9] are exploring viruses with middle and high school students using

haptic feedback from the very expensive (but very nice) PHANToM haptic interface. The first author in the current article has been developing haptics-augmented software activities and tutorials for improving the teaching and learning of K-12 science topics [10]. This work has included alpha and beta software testing with students and teachers.

Immersion Corporation [11] has investigated the potential benefits of incorporating their commercial haptic mouse into software intended for college and high school physics curricula. Bussell [12] poses the question "Can haptic technology be applied to educational software and Web sites to enhance learning and software usability?" and then presents a review article in attempt to answer it. The thesis of Dede et al. [13] is that "learning difficult, abstract material can be strongly enhanced by multi-sensory immersion" (including haptic feedback).

M.I.T. haptics expert J. Kenneth Salisbury is quoted in a Discover magazine article [14]: "I've often wondered if you could teach physics more effectively if your students could feel molecular attraction or planetary motion." Okamura et al. [15] have developed their own single axis force-feedback 'haptic paddle' which they have applied for representing friction, inertia, and the effect of controller gains for linear systems education; their focus is on construction, analysis, and control of the haptic interface itself. Their title includes 'Feeling is Believing', a phrase we have used in print before their article. By contrast, our project uses economical commercial haptic joysticks with two axes, for planar vector forces; we also focus on various engineering mechanics educational applications. This article describes our project, with a description of our haptics-augmented undergraduate engineering educational products and a summary of evaluations with students enrolled in target courses at Ohio University.

HAPTICS-AUGMENTED SOFTWARE AND TUTORIALS

In close consultation with experienced professors who teach physics, statics, and dynamics to undergraduate engineering freshman and sophomore students at Ohio University, we developed, implemented, and evaluated the haptics-augmented software activities (plus web-based tutorials) listed as follows; some were used in more than one course.

Physics: 1. Vector Addition: Boats Towing a Barge, 2. Concurrent Forces: Three-Force Member, 3. Projectile Motion, 4. Newton's Three Laws, 5. Interactive Dynamics Free-Body-Diagram, 6. Conservation of Linear Momentum, and 7. Non-concurrent Forces: Truss Structure Reactions.

Statics: 1. Vector Addition: Boats Towing a Barge, 2. Concurrent Forces: Three-Force Member, 3. Interactive Statics Free-Body-Diagram, 4. Beam: Shear and Moment Diagrams, 5. Pulleys, and 6. Statically-Determinate Truss Structure.

Dynamics: 1. Projectile Motion, 2. Newton's Three Laws, 3. Interactive Dynamics Free-Body-Diagram, 4. Conservation of Linear Momentum, 5. Conservation of Energy: Pendulum, 6.

Particle Dynamics: Box Motion, and 7. Rigid Body Dynamics: Box Motion

For example, consider the three-force member shown in Figure 1 (Activity 2 in physics and statics). From statics, we know that all three forces must pass through a common point; therefore, given an external load to be supported, we know the directions of the two reaction forces and then can find their magnitudes; this is typical of the snapshot, lifeless homework that may be assigned in statics. Using our software, the user can change the connection point and length of the support strut; for each case, the computer calculates the magnitude and direction of the reaction forces, given the tip location of the external load. The computer then displays the system diagram, numerical results, and vector force diagram. The user may *feel* the three planar vector forces (one at a time) via a flight-stick haptic interface.

The ability to change parameters, see the system configuration (and animation, if applicable), numerical answers, and vector diagrams, plus *feel* the results of the selected parameters is common to all of our haptics-augmented activities. In Figure 2, the student can *feel* any of the dynamic forces or the inertial forces of the cart or block; in Figure 3, the student can *feel* the shear force or moment magnitude at any point on the beam, indicated by the red dot). If there are multiple vector forces to be felt, the user can choose them singly via joystick buttons; the active force is felt and also highlighted on the animation and force diagram on the screen (for example, in Figure 1, the vertical (down) weight force is currently being felt by the student). Each activity has an Internet-based tutorial, including a Comprehension Assignment to motivate the student to continue using our simulations in order to solidify the basic principles being conveyed. For more information, including the tutorials accompanying each of our haptics-augmented activities, please see our project website:

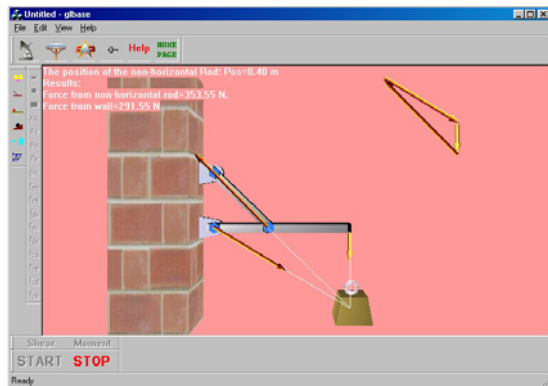www.ent.ohiou.edu/~bobw/html/HapEd/NSF/UGHome.htm

Figure 1. Three-Force Member (Concurrent Forces)

We use economical, commercially-available haptic interfaces (about $70) for students to interact with all of our software activities: the Microsoft Sidewinder® and Logitech Wingman® 2-dof haptic flight sticks. The student can enter position commands via the flight-stick interface and make choices via various buttons. The haptic interaction is provided via force feedback on both axes of the flight stick, allowing the user to feel planar vector forces, depending on the simulation, parameters, and interaction choices. We describe some of our additional haptics-augmented simulations below.
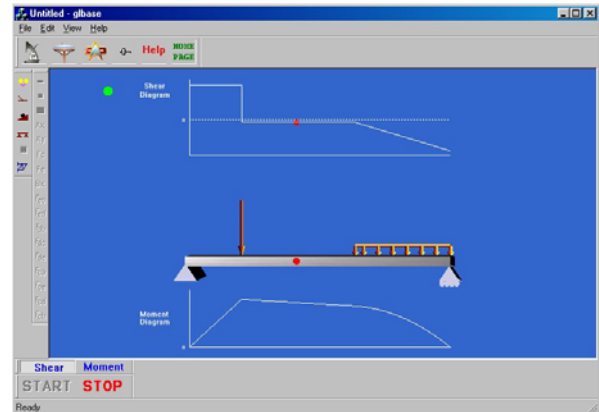

Figure 2. Newton's 2nd Law

Figure 3. Shear/Moment Diagrams

Vector Addition of Concurrent Forces: Boats Towing a Barge. As shown in Figure 4, two boats apply forces via cables to move a barge upriver; the computer sets a constant resultant force upriver. The student sets the force magnitude and direction of the second boat; the computer then calculates (and displays) the required vector force of the first boat. The student visualizes the barge being towed and the vector force diagram. The student can feel any of the vector forces (singly): resultant, boat 1, or boat 2.
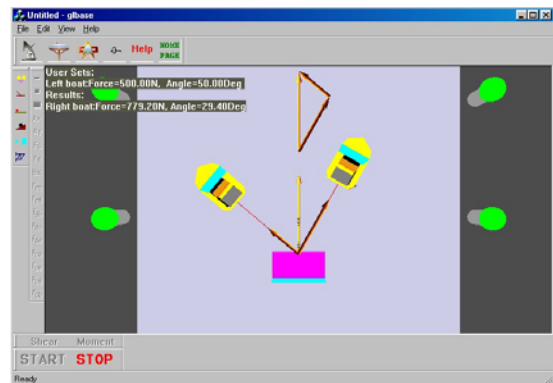

Figure 4. Boats Towing a Barge

Newton's Three Laws. In our Newton's 1st Law simulation (not shown) a block of constant mass initially at rest is free to slide on a frictionless, flat plane. The student inputs vector forces to the block via the joystick, feels the vector inertial force (zero during constant velocity motions), and observes the resulting motion. The student can input reverse forces to try and keep the block in the visible workspace. Kinematic motion plots are generated in real-time. As shown in

Figure 2, in our Newton's 2nd Law simulation two masses are connected by a cable. The student sets the two masses and the dynamic coefficient of friction between the cart and motion surface. The system is released from rest (via a joystick button) and the student visualizes the gravity-driven motion (plus motion plots). The computer calculates (and displays) the acceleration (same for the two masses), the cable tension, and the friction force. The student feels the vector inertial forces for either mass, the weight, the cable tension, or the friction force. In our Newton's 3rd Law simulation (not shown) we have two choices: a. A linear spring the student can compress (or extend) via the joystick and feel the equal-and-opposite force exerted by the virtual spring. b. Two projectiles, one fired from a fixed pier and the second fired from a boat. The student fires each projectile and feels the gun recoil using the joystick; the fixed pier-mounted gun projectile reaches its target, while the boat-mounted gun projectile falls short due to the boat moving back according to Newton's 3rd Law.

Statically-Determinate Truss Structure. In the truss shown in Figure 5 the student sets the strut angle and two loads to resist at points *C* and *E*. This truss is used in two activities. In Non-concurrent Forces: Truss Structure Reactions (physics), given the student inputs, the computer calculates (and displays) the reaction forces at points *A* and *B*. In Statically-Determinate Truss Structure (statics), the reaction forces are involved, but we also calculate and display the individual strut axial forces. In both cases, the student visualizes the motionless truss, with forces as seen in Figure 5. The student feels any of the vector forces (chosen via buttons and highlighted on the screen).
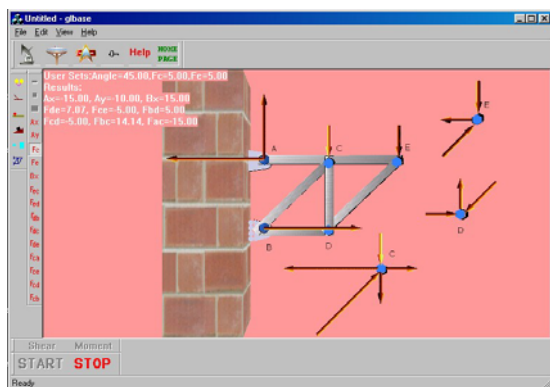

Figure 5. Truss Structure

Interactive Statics and Dynamics Free-Body-Diagrams. The block-on-ramp system of Figure 6 is also used in two activities. Both are an interactive free-body diagram (FBD); for statics the parameters are related so that static equilibrium is maintained so there is no motion, while for dynamics motion is allowed. The student sets the point mass, coefficient of friction between the mass and ramp, the ramp angle, and the applied force angle relative to the ramp. For statics, given the student inputs, the computer calculates (and displays) the force required for static equilibrium, the weight, friction force, and normal force (the student can feel any of these vector forces singly; they are highlighted in the interactive FBD while being felt). For dynamics, given the same student inputs, the computer calculates the minimum applied force (for static equilibrium; higher forces will cause motion up the ramp). The student then enters the applied force magnitude (its angle was already given) and watches the resulting motion up the ramp, in addition to viewing the FDB. Again, the student feels any of the vector forces (chosen via joystick buttons and

highlighted on the screen while being felt), either relative to a horizontal or ramp reference frame.
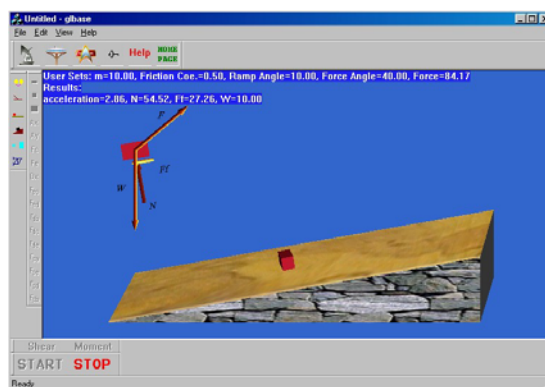

Figure 6. Interactive FBD

Conservation of Energy. As shown in Figure 7, a simple gravity-driven point mass pendulum with massless rod is used to demonstrate Conservation of Energy (assuming no friction or wind resistance). The student enters the pendulum length and maximum angle. The computer displays the kinematic motion and energy plots in real-time and the student views the pendulum animation. The student feels the pendulum kinetic energy (+/-) on the joystick *X* axis and the pendulum potential energy on the joystick *Y* axis. Note in this case the student does not feel actual forces.
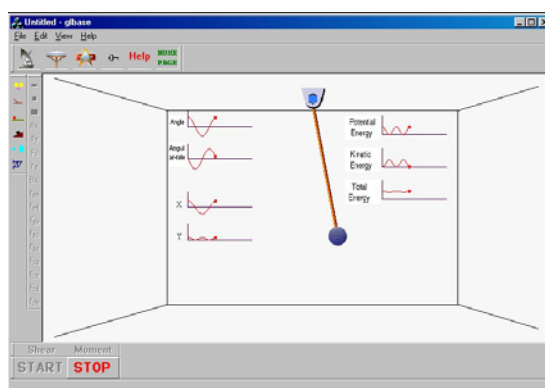

Figure 7. Pendulum

Rigid Body Dynamics: Box Motion. In dynamics, particle and rigid-body motion are important subtopics. We have already considered particle motion wherein a box is assumed to be a point mass and moves up a ramp (Figure 6). In Figure 8 a rigid-body box is simulated, in motion along a straight line, with potential tipping. The student inputs the coefficient of friction between the box and the floor, plus the height above the box CG that the external force is applied. Based on these inputs the computer calculates the range of forces (minimum associated with zero acceleration and maximum associated with the onset of tipping). The student then selects a force within this range and then visualizes the resulting motion, including real-time kinematic plots. The student feels, by choice, the applied external force, the weight or normal force, the friction force, or the inertial force of motion.
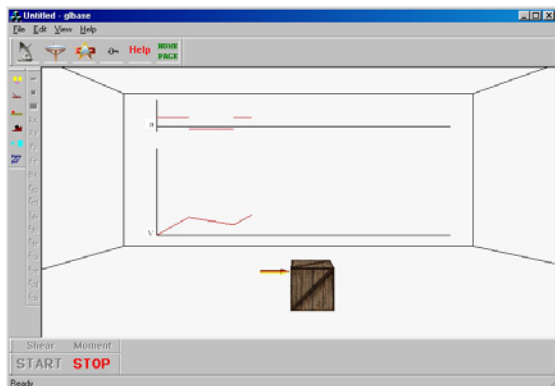
Figure 8. Rigid Body Dynamics

HAPTICS-AUGMENTED SOFTWARE EVALUATIONS
During one academic year we performed evaluations of our products with physics (N=64), statics (N=15), and dynamics (N=21) classes at Ohio University. A three part evaluation survey was used: Part 1, *Evaluation of Content* examined the educational content of the activities; Part 2, *Evaluation of Software Design* examined design and usability concerns; and Part 3, *Evaluation of the Learning Environment* examined the possible factors in motivation to use the software and supported a holistic view of the software and content. For detailed evaluation results, please see [16, 17]. Overall, these pilot evaluations were very positive, indicating the potential of haptics-augmented activities in engineering education.

CONCLUSION
This article has presented a novel educational approach to augment the teaching and learning of basic engineering mechanics courses. We use economical haptic interfaces to provide vector forces to the student from virtual computer simulations. Our idea originated with the prevalence of CD supplements to augment the homework in standard engineering and physics textbooks; we thought, "Wouldn't it be great to be able to not only change parameters and see the resulting motion animations, but also to *feel* the various associated forces?" Our products have the potential for more engaging, more fun learning with deeper understanding and retention, plus reduced student attrition: *feeling is believing*. Our vision is to fundamentally change the manner in which basic engineering mechanics is taught and learned.

Our software design evaluations indicate that the Haptics-Augmented Mechanics Activities can help students gain a better understanding of the basic course concepts Our short-term future goals include improvement of our products based on pilot study feedback; expanding the number of activities in physics, statics, and dynamics; and expanding the number of courses covered, including additional required courses where forces are important (strength of materials, fluid mechanics, dynamics of mechanisms, robotics, machine design, vibrations, analysis and control of linear systems, among others).

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