Haptics-Augmented Undergraduate Engineering Education

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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. Two sample software interaction screens are given in the figures below. 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. This paper describes our project, along with our educational philosophy, followed by a description of our haptics-augmented undergraduate engineering educational products and software design evaluations with students enrolled in target courses at Ohio University.*

Index Terms *— engineering mechanics education, haptics, haptic interface, haptics-augmented education*

1. 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 paper 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.

An educational group [5] is involved with virtual learning environments including a Power Glove with tactile feedback, investigating virtual learning environments, constructivism, and experiential learning. A research group at the Ohio Supercomputing Center has applied haptics in virtual environments to improve tractor safety by training young rural drivers [6]. 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" [7], although the authors do not elaborate on the type of education intended. Haptics has been applied to make virtual environments accessible to blind persons [8,9]. The effectiveness of virtual reality in the learning process has been demonstrated by many authors (e.g. [10]).

Jones et al. [11] 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 paper has been developing haptics-augmented software activities and tutorials for improving the teaching and learning of various K-12 science topics [12-14]. This work has included alpha and beta software testing with students and teachers.

Immersion Corporation [15] has investigated the potential benefits of incorporating their commercial haptic mouse into software intended for college and high school physics curricula. Bussell [16] 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 paper in attempt to answer it. The thesis of Dede et al. [17] 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 paper [18]: “I've often wondered if you could teach physics more effectively if your students could feel molecular attraction or planetary motion.” Other than the authors’ work [19], our literature search only revealed one other group involved in an undergraduate engineering educational haptics project. Okamura et al. [20] 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 paper. 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 paper describes our project, along with our educational philosophy, followed by a description of our haptics-augmented undergraduate engineering educational products and software design evaluations with students enrolled in target courses at Ohio University.

2. PROJECT MOTIVATION

The Problem: *Current example and homework problems in basic undergraduate engineering courses are flat, static, boring, and non-engaging. In the worst case this leads to attrition since some students fail ‘weed-out’ courses three times. Even for the best students, current practices do not engage them fully, and deep learning, understanding, and retention of fundamental principles may not be achieved.*

Engineering students who drop out have a disproportionate percentage of women and minority students (two-thirds of underrepresented students drop out vs. only one-third for others [21]). Therefore, success in our project may help to increase the diversity of our engineering workforce.

A recent journal paper [22] presents an evaluation of mechanics of materials educational software (without haptics augmentation). They start by presenting in detail the drawbacks of traditional learning in engineering mechanics. Their reference list includes no fewer than ten projects with software to assist in learning engineering mechanics, none of which use haptics for the feel of the forces involved. Another recent journal paper [23] presents interactive instructional learning tools for mechanics of materials, again with no haptics augmentation. There is a large interest currently in alternative, multi-media educational augmentation. The time is ripe for haptics augmentation, the focus of this paper.

Our Vision:*To produce a new generation of animated, interactive ‘Schaum’s Outline Series’ on CD, with force feedback (“feeling is believing”), for augmenting the learning and teaching of basic and advanced undergraduate engineering courses nationwide. To focus on applying educational pedagogical research to improve the quality of education for all students in undergraduate engineering programs, rather than focusing on the requisite technology.*

Our Hypothesis: *Use of interactive, haptics-augmented activities in conjunction with standard engineering courses will promote deeper learning and retention and reduce student attrition nationwide.*

The current paper does not deal with this overall hypothesis; instead, the goal of this paper is to present our haptics-augmented software activities for engineering mechanics and to evaluate the design of the software relative to its suitability for the instructors, students, and topics of the intended courses. The software design and implementation has been conducted in a manner known to be effective in educational settings, according to the previous experience of the third author in unrelated science education projects [24]. In the future we will attempt to test the big hypothesis stated above using pre- and post-tests with treatment (with haptics-augmented software) and non-treatment (no haptics-augmented software) groups over time, both at Ohio University and at external test sites.

3. EDUCATIONAL PHILOSPOHY

From National Science Education Standards, books.nap.edu/html/nses/html/index.html, in future science teaching there should be less emphasis on "Maintaining current resource allocations for books" and more emphasis on "Allocating resources necessary for hands-on inquiry teaching"; there should be less emphasis on "Textbook- and lecture-driven curriculum" and more emphasis on "Curriculum that includes a variety of components, such as laboratories emphasizing inquiry"; there should be less emphasis on "Investigations confined to one class period" and more emphasis on "Investigations over extended periods of time"; there should also be less emphasis on "Knowing scientific facts and information" and more emphasis on "Understanding scientific concepts and developing abilities of inquiry".

Now, these are for K-12 science education and hence undergraduate engineering education is not subject to these standards. However, it’s not a bad idea to take a look at what the K-12 education experts are saying for improving technical teaching and learning. In fact, our educational philosophy closely follows the statements in the above paragraph. Our products support all of these aspects: we are not trying to replace instructors or textbooks, rather we are adding the sense of touch and forces to hands-on, long-term, inquiry-based, virtual-laboratory educational experiences. We are striving for improved teaching and learning of mechanics that is more compelling, fun, and engaging, with deeper learning, and reduced student attrition.

Since we are not proposing changes in course content, but are augmenting learning via *feeling* the forces, our haptics-augmented educational products also support ABET criterion. Assuming each target course supports ABET criteria (this is the case at Ohio University), our products should enhance ABET accreditation at any engineering school across the nation. In addition to the general statements above, our products address ABET criteria a, e, and k.

Our haptics-augmented activities will provide a presentation of basic principle concepts through an interactive multimedia simulation in which a joystick is used to allow students to *feel* the forces in action. The use of the multimedia-based software and joystick allows the student to develop a pictorial representation of the concept as well as tactile understanding of force. The abstractness of physics and engineering for many students can be become concrete through the use of interactive multimedia software such as our haptics-augmented products. The “minds-on, hands-on” use of the interactive multimedia found in our products combines the use of pictorial simulations of various engineering principles with the tactile sense which acts to reinforce the concepts presented and to allow the mind to create a cognitive link to the pictorial concept and force by providing a nonlinear representation of the basic concepts so often found in the equations. Our proof-of-concept study presented in this paper recognized that students of today live in a digital environment in which the use of pictorial and other sensory cues can motivate and enhance learning, and enable deeper understanding.

4. 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 in Table I; some were used in more than one course.

Table I. Haptics-Augmented Activities by Course

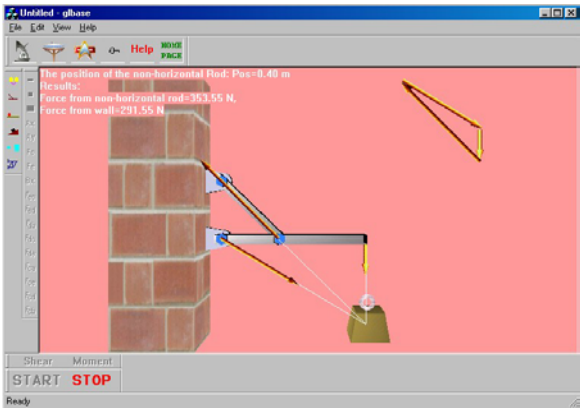
Physics	Statics	Dynamics
1. Vector Addition: Boats Towing Barge 2. Concurrent Forces: Three-Force Member 3. Projectile Motion 4. Newton’s Three Laws 5. Interactive Dynamics Free-Body-Diagram 6. Conservation of Linear Momentum 7. Non-concurrent Forces: Truss Structure Reactions	1. Vector Addition: Boats Towing Barge 2. Concurrent Forces: Three-Force Member 3. Interactive Statics Free-Body-Diagram 4. Beam: Shear and Moment Diagrams 5. Pulleys 6. Statically-Determinate Truss Structure	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 7. Rigid Body Dynamics: Box Motion

For example, consider the three-force member shown in Figure 1 (Activity 2 in physics and statics from Table I). 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 (see Figure 2 for more examples; also, the Appendix describes each activity in detail. In Figure 2, the student can *feel* any of the FBD 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 (website given below), including a Comprehension Assignment to motivate the student to continue using our simulations in order to solidify the basic principles being conveyed. This novel educational method has promise in undergraduate engineering education, according to our proof-of-concept evaluations (see Section 5). For more information, including the tutorials accompanying each of our haptics-augmented activities, please see our project website:

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

We use economical, commercially-available haptic interfaces (about $70) for students to interact with all of our software activities. Figure 4a shows the haptic interface in this study[1]; Figure 4b shows a haptic interface that will soon be enabled[1]. 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.



The position of the non-horizontal Rod: Pos=0.40 m
Results:
Force from non-horizontal rod=353.55 N,
Force from wall=291.55 N

Figure 1. Haptics-Augmented Statics Example: Three-Force Member (Concurrent Forces)

Figure 2. Newton's 2nd Law

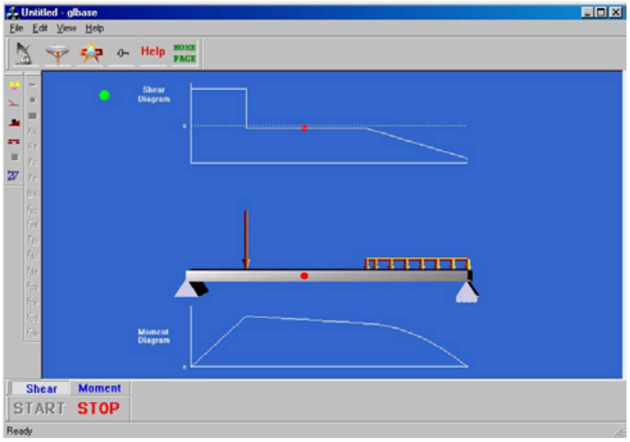


Figure 3. Shear/Moment Diagrams

Figure 4a. Microsoft Sidewinder®

Figure 4.b. Logitech Wingman®

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[1] **Note**: Ohio University is not endorsing the use of any particular commercial product.

In Summer/Fall 2002 the physics software was developed; it was field tested during Fall 2002. Faculty from Education, Engineering, and Physics met and examined the software to determine if the content was valid and if it supported the physics course material. The software was also evaluated by the faculty for instructional design elements and usability issues. The faculty determined that the software was ready to pilot with Physics 251 undergraduates towards the end of Fall 2002. A similar schedule was followed in ensuing quarters for statics and dynamics software and evaluations.

5. SOFTWARE DESIGN EVALUATION RESULTS AND DUSCUSSION

During the project, our software development occurred in the order: physics, statics, then dynamics. Therefore, our evaluation schedule for our proof-of-concept study was according to Table II (in which X indicates pilot evaluation and O indicates evaluation with data presented in this section). The pilot evaluations in both physics and statics were used to improve our products and our evaluation approach (the dynamics software was not ready in time for a pilot evaluation, but our evaluation methods were mature by Spring 2003).

Table II. Proof-of-Concept Evaluation Schedule

Quarter	Physics	Statics	Dynamics
Fall 2002	X		
Winter 2003	X	X	
Spring 2003	O	O	O

We now present the highlights of our software design evaluations for the haptics-augmented physics, statics, and dynamics activities, listed in Table I and explained in the Appendix. All undergraduate participants were enrolled in Physics 251, Statics (CE 220), or Dynamics (ME 224) at Ohio University. Physics student volunteers participated via their regular laboratory; statics and dynamics students volunteered to participate outside of class. Self-selected volunteers are not ideal for educational effectiveness studies, but self-selection is typical in software design evaluation studies such as this one. In compliance with university policy, Human Subjects Research Compliance was sought and received. Almost 300 undergraduate students participated in our pilot evaluations and evaluations with data presented here during the 2002-03 academic year. Due to space limitations, only the Spring 2003 evaluation data is presented in this paper; we did not see major differences between the pilot and Spring 2003 evaluations in physics or statics.

A three part evaluation survey was designed and field tested to support our evaluations. Part 1, *Evaluation of Content* examined the educational content of the activities. Part 2, *Evaluation of Software Design* examined design and usability concerns. 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. The survey used a four-point Likert scale for Part 1: 4=very effective (VE), 3=effective (Eff), 2=somewhat effective (SE), and 1=not effective (NE). The other two (Part 2 and Part 3) used the same four-point Likert scale except the wording was: 4=strongly agree (SA), 3=agree (A), 2=disagree (D), and 1=strongly disagree (SD). No neutral values were used; this forced the selection of an agreeable or disagreeable choice. Observations were also collected of the students using our haptics-augmented physics activities. The comments gathered while the students were engaged with the software provided information about usability as well.

After the Fall 2002 physics pilot evaluation, it was determined that some of the survey questions were ambiguous. These were refined using the comments from students and teaching assistants, observations, and from student interviews. It was also found that the students were not responding to the third choice, “somewhat effective” on Part 1 of the survey. In Part 2 and Part 3, the students responded to all categories. It was decided to change the Part 1 evaluation to a three-point Likert scale: 4=very effective (VE), 3=effective (Eff), and 2=not effective (NE). Parts 2 and 3 remained unchanged. The number of questions was also decreased. If the student did not answer an item, the tables below list no response (NR). Item and factorial analyses of the survey found that the items in each section did address the conceptual framework. From Fall 2002, the reliability was Cronbach’s alpha = 0.69. In Winter 2003, the haptics-augmented physics activities and survey were again field tested. With the changes in the survey a Cronbach’s alpha = 0.79 was obtained, which was a stronger indication of the reliability of the survey to identify the desired concepts. Our experience in physics evaluation was transferred to statics and dynamics evaluations. We again stress that our evaluations reported in this paper were for software design and topic effectiveness. In Part 3 of the survey we asked the students to self-evaluate their learning with our products; however, there were no pre- and post-tests, no treatment vs. non-treatment groups, and no retention tests over time. The general educational effectiveness of our haptics-augmented products including these issues will be evaluated in future work.

The software was also presented at the SITE (Society for Information Technology in Education) Conference in Albuquerque NM on March 22, 2003. 25 educators participated in an evaluation of the software during the poster session of the conference. Of the 25 participants, 8 were past or present physics instructors. Comments included:

- *Wow, this is great! I didn't realize that the force would be that strong even though I have taught this for years. You really can feel the reaction as it happens.*
- *Can I try this again? [Comment of former physics teacher]. This is wonderful. Put this on the web and you have a great product.*
- *When will you finish this? I think it could really help students. I have never thought of this reaction in this way.*

Participants from the SITE conference were very positive in their feedback and indicated that having the software accessible from the Internet or CD so that students could access it in their dorm rooms and in labs would be an added plus.

5.1 Physics Evaluations

Our physics evaluations findings from Spring 2003 are as follows; there were *n*=64 students. Part 1 of the survey asked students to rate the effectiveness of our haptics-augmented activities to support their learning of the physics content. Table III provides the results for the ratings of physics content. Part 2 of the survey asked the undergraduates to rate the software design. Table IV provides the results from Part 2 of the survey instrument. Part 3 examines the learning environment and was a more holistic view of the use of the software. Table V provides the results from Part 3 from the student evaluation survey. Table VI contains a summary of the means and standard deviations for each part of the physics survey.

We now discuss our physics findings. Table VI shows that Parts 1 and 2 have a mean greater than 3, and the mean of Part 3 is approximately 3. A mean of 3.40 in Part 1, which examined the content of the haptics-augmented physics activities, shows that the students felt the content was effective (4 was very effective and 3 was effective). A mean of 3.15 for Part 2, which examined the software design, agreed that the design was effective in delivering content (4 was strongly agree and 3 was agree). A mean of 2.99 in Part 3 is approximately saying that the undergraduates are agreeing that the learning environment is effective (3 was agree and 2 was disagree). In the questions on motivation, needs and goals, and problem-solving, 14.1%, 15.6%, and 17.2% were scored at the 2 (disagree) value, respectively; these three questions had an impact to push the mean just below 3.00.

It was interesting to see that the values for content delivery were very high as shown in Table III. The *not effective* value was less than 10% in all cases. In Part 2, Table IV responses indicate that the undergraduates generally support the use of the software and its design with all questions save one providing 83% or higher as *strongly agree* and *agree* for the design of the software (three questions were well over 90%). In Part 3, Table V responses indicate that the undergraduates generally felt our software supported the learning environment; all questions save two provided 81% or higher as *strongly agree* and *agree*.

Table III. Part 1 – Evaluation of Physics Content (*n* = 64)

Question	VE (%)	Eff (%)	NE (%)	NR (%)
How effective is the software in helping you to learn physics topics?	23.4	65.6	9.4	1.6
How effective are the following modules?	3 Force Member 26.6 Boats Towing Barge 25.0	3 Force Member 65.6 Boats Towing Barge 46.9	3 Force Member 4.7 Boats Towing Barge 9.4	3 Force Member 3.1 Boats Towing Barge 18.7
How effective was the use of this technology to your learning physics?	82.0	17.2	0	0.8
Please rate the effectiveness of the joystick in helping you understand physics.	50.0	17.2	4.7	28.1

Table IV. Part 2 – Evaluation of Physics Software Design (*n* = 64)

Question	SA (%)	Agree(%)	D (%)	SD (%)	NR (%)
The purpose of the software is clear.	25.0	60.9	12.5	1.6	0
The structure of the software is clear.	18.8	70.3	7.8	3.1	0
The content is accurate, complete and well-written.	18.8	67.2	9.4	1.6	3.0
The content is appropriate for the course.	37.5	48.5	10.9	3.1	0
The text is neat, legible and formatted for easy reading.	42.2	51.5	3.1	1.6	1.6
I can move around the software easily.	29.6	64.1	4.7	0	1.6
There is a place to get help in the software.	15.6	67.2	4.7	3.1	9.4
The software encourages me to learn more about the topic.	25.0	53.1	17.2	4.7	0
The software has a professional, academic yet friendly image.	32.8	64.1	3.1	0	0

The graphics are used effectively to enhance and supplement the text.	43.8	42.2	9.4	4.6	0
The graphics make a significant contribution to the learning the topic.	32.8	54.7	9.4	3.1	0
There is significant information to make the site worth using.	20.3	64.1	10.9	3.1	1.6

Comments that were recorded during interviews and observations indicated that physics students would like to have the software available all quarter and available online. Comments from the SITE participants were very positive with the most common question being, "*When will it be available for all of us to use online?*" The educators were especially interested in use of the haptic joystick for tactile interaction that is generally missing in physics experiences and understanding. Students are often surprised at the force of the joystick as it simulates Newton's Three Laws and other principles. This discovery of the "feelings of force in physics" has produced discussions among students as they work with the software. It is suspected that these discussions are helping to reinforce the software's presentation of basic physics principles.

Table V. Part 3 – Evaluation of the Physics Learning Environment (*n* = 64)

Questions	SA (%)	Agree (%)	D (%)	SD (%)	NR (%)
The software encourages you to learn more about the topic.	15.6	70.3	9.4	3.1	1.6
The software motivates your learning.	14.1	67.2	14.1	1.6	3.0
The software helps you understand the material easily.	25.0	60.9	7.8	3.1	3.2
I feel quite comfortable in this learning environment.	17.2	70.3	7.8	3.1	1.6
This environment helps me to gain an understanding of physics.	15.6	71.9	7.8	3.1	1.6
This software fit my needs and goals.	10.9	64.1	15.6	3.1	6.3
This software helps me in developing my problem-solving skills in physics.	14.1	62.5	17.2	3.1	3.1

Table VI. Means and Standard Deviations for the Physics Survey (*n* = 64)

Section	Mean	Standard Deviation
Part 1	3.40	0.31
Part 2	3.15	0.12
Part 3	2.99	0.08

5.2 Statics Evaluations

For our Spring 2003 statics evaluations we used the same approach developed and improved for physics (and the Winter 2003 pilot statics evaluation). There were *n*=15 students participating. Table VII reports the Part I results (statics content), Table VIII reports the Part 2 results (statics software design), and Table IX reports the Part 3 results (statics learning environment). Table X contains a summary of the means and standard deviations for each part of the statics survey. The table headings are identical in meaning to those of the physics evaluation (note that in statics, and also dynamics (see Section 5.3) there were full responses on all questions, thus the NR column has been eliminated).

Table VII. Part 1 Evaluation of Statics Content (*n* = 15)

Question	VE (%)	Eff (%)	NE (%)
How effective is the software in helping you to learn statics topics?	73.3	26.7	0
How effective are the following modules?	Truss 46.7 Shear and Moment 40.0	Truss 53.3 Shear and Moment 53.3	Truss 0 Shear and Moment 6.7
How effective was the use of this technology to your learning statics?	66.7	33.3	0
Please rate the effectiveness of the joystick in helping you understand statics.	53.3	40.0	6.7

Table VIII Part 2 Evaluation of Statics Software Design (n = 15)

Question	SA (%)	Agree (%)	D (%)	SD (%)
The purpose of the software is clear.	53.3	46.7	0	0
The structure of the software is clear.	33.3	60.0	6.7	0
The content is accurate, complete and well-written.	46.7	53.3	0	0
The content is appropriate for the course.	60.0	40.0	0	0
The text is neat, legible and formatted for easy reading.	53.3	46.7	0	0
I can move around the software easily.	40.0	60.0	0	0
There is a place to get help in the software.	13.4	73.3	13.3	0
The software encourages me to learn more about the topic.	26.6	66.7	6.7	0
The software has a professional, academic yet friendly image.	40.0	60.0	0	0
The graphics are used effectively to enhance and supplement the text.	53.3	46.7	0	0
The graphics make a significant contribution to the learning the topic.	46.7	53.3	0	0
There is significant information to make the site worth using.	20.0	66.7	13.3	0

Table IX. Part 3 – Evaluation of the Statics Learning Environment (n = 15)

Questions	SA (%)	Agree (%)	D (%)	SD(%)
The software encourages you to learn more about the topic.	26.7	60.0	13.3	0
The software motivates your learning.	20.0	66.7	13.3	0
The software helps you understand the material easily.	40.0	46.7	13.3	0
I feel quite comfortable in this learning environment.	33.3	60.0	6.7	0
This environment helps me to gain an understanding of statics.	20.0	73.3	6.7	0
This software fit my needs and goals.	93.3	6.7	0	0
This software helps me in developing my problem-solving skills in statics.	6.7	66.7	26.6	0

Table X. Means and Standard Deviations for the Statics Survey (n = 15)

Section	Mean	Standard Deviation
Part 1	3.53	0.16
Part 2	3.37	0.20
Part 3	3.23	0.35

We now discuss our statics findings from Spring 2003. Table X shows that all Parts 1 through 3 have means between 3 and 4, indicating that the students clearly felt (more strongly than in physics) the content, design, and learning environment was effective.

The values for statics content delivery (Table VII) were very high; the *not effective* value was 6.7% (only one student) for two cases and zero for the other three. In Part 2, Table VIII responses indicate that the undergraduates generally support the use of the software and its design; zero students chose strongly disagree on any question and only one or two students out of 15 chose disagree (twice each). In Part 3, Table V responses indicate that the undergraduates generally felt our software supported the learning environment, though there is more disagreement than in the last two tables. Four out of the 15 students did not agree that our haptics-augmented statics software helped with their problem-solving skills, an important area for us to improve on in the future.

Comments from interviews and observations indicated that statics students had many positive things to say about our activities. Among the suggestions for improvement were to increase the interaction speed, add the ability to build your own virtual trusses, include zero-force members, and allow a varying distributed load. These comments (useful for our improvements) indicate that the students are relating our activities to their course experience.

5.3 Dynamics Evaluations

For our Spring 2003 dynamics evaluations we used the same approach developed and improved for physics and statics. There were n=21 students involved. Table XI presents the Part I results (dynamics content), Table XII presents the Part 2 results (dynamics software design), and Table XIII presents the Part 3 results (dynamics learning environment). Table XIV contains a summary of the means and standard deviations for each part of the dynamics survey. All table headings are identical in meaning to those of the physics and statics evaluations (again, since there were full responses to all questions, the NR column was eliminated).

Table XI. Part 1 Evaluation of Dynamics Content (*n* = 21)

Question	VE(%)	Eff (%)	NE (%)
How effective is the software in helping you to learn dynamics topics?	14.3	81.0	4.7
How effective are the following modules?	Pendulum 42.9 Rigid Body Box 23.8	Pendulum 47.6 Rigid Body Box 71.5	Pendulum 9.5 Rigid Body Box 4.7
How effective was the use of this technology to your learning dynamics?	85.7	14.3	0
Please rate the effectiveness of the joystick in helping you understand dynamics.	38.1	61.9	0

Table XII. Part 2 Evaluation of Dynamics Software Design (*n* = 21)

Question	SA (%)	Agree (%)	D (%)	SD(%)
The purpose of the software is clear.	28.6	71.4	0	0
The structure of the software is clear.	19.0	81.0	0	0
The content is accurate, complete and well-written.	38.1	57.1	4.8	0
The content is appropriate for the course.	47.6	38.1	9.5	4.8
The text is neat, legible and formatted for easy reading.	52.4	42.9	4.7	0
I can move around the software easily.	52.4	47.6	0	0
There is a place to get help in the software.	19.0	66.7	4.8	9.5
The software encourages me to learn more about the topic.	9.5	76.2	14.3	0
The software has a professional, academic yet friendly image.	42.9	52.4	4.7	0
The graphics are used effectively to enhance and supplement the text.	23.8	76.2	0	0
The graphics make a significant contribution to the learning the topic.	47.6	47.6	4.8	0
There is significant information to make the site worth using.	19.0	71.5	9.5	0

Table XIII. Part 3 – Evaluation of the Dynamics Learning Environment (*n* = 21)

Questions	SA (%)	Agree (%)	D (%)	SD (%)
The software encourages you to learn more about the topic.	9.5	61.9	28.6	0
The software motivates your learning.	9.5	61.9	28.6	0
The software helps you understand the material easily.	14.3	76.2	9.5	0
I feel quite comfortable in this learning environment.	42.9	57.1	0	0
This environment helps me to gain an understanding of dynamics.	19.0	66.7	14.3	0
This software fit my needs and goals.	14.3	57.1	28.6	0
This software helps me in developing my problem-solving skills in dynamics.	4.8	38.1	47.6	9.5

Table XIV. Means and Standard Deviations for the Dynamics Survey (*n* = 21)

Section	Mean	Standard Deviation
Part 1	3.37	0.29
Part 2	3.26	0.19
Part 3	2.91	0.32

We now discuss our Spring 2003 dynamics findings. Table XIV shows that Parts 1 and 2 have a mean greater than 3, which indicates that the students felt the dynamics content and software design was effective. A mean of 2.91 in Part 3 is saying that the undergraduates are between agreeing and disagreeing that the learning environment is effective; the result is closer to agreeing (3) than disagreeing (2). Generally the results of Tables XI and XII (Parts 1 and 2, respectively) are very encouraging. However, the results of Table XIII give us a lot to work on for dynamics since a large minority (in the last row, a majority) do not agree that our software encourages the student to learn more, motivates their learning, fits their needs, or helps in dynamics problem solving skills. Regarding learning environment, the physics and statics students rated our products much higher than the dynamics students did.

The values for dynamics content delivery (Table XI) were very high; the *not effective* value was 4.7% (only one student) for two cases, 9.5% (two students) for another case, and zero for the other two. In Part 2, Table XII responses indicate that the undergraduates generally support the use of the software and its design with all questions save three providing 95% or higher as *strongly agree* and *agree* for the design of the software. The overall Part 3 responses for dynamics (learning environment) were the lowest responses in all our evaluations; except for feeling comfortable in our learning environment, the first six questions had a large minority disagreeing. Fully ten of the 21 students did not agree that our haptics-augmented dynamics software helped with their problem-solving skills, which we must improve on in the future.

Again, comments from interviews and observations indicated that dynamics students had many positive things to say about our activities. Unfortunately, considering they rate the learning environment much lower than the physics and statics students did, they did not offer nearly as many constructive criticism comments. One requested an activity to help with understanding 3D vector forces (an excellent idea, but not possible at one time with the 2-dof commercial haptic interfaces of Figures 4). Another stated that our haptics-augmented dynamics software does not help develop problem solving skills because the applicable equations are not displayed; that student requested we add capability to see the equations.

In summary for our physics, statics, and dynamics software design evaluations at Ohio University, we are encouraged by the positive software design evaluation results to pursue our goal of augmenting the learning and teaching of basic undergraduate engineering mechanics courses nationwide via interactive software activities with force feedback. Our evaluations had the following limitations: relatively small sample size and self-selected student volunteers. Despite these limitations we received much valuable feedback for future improvements. Prior to our planned educational effectiveness testing, we will improve our existing physics, statics, and dynamics products according to student and instructor feedback, we will add more activities in physics, statics, and dynamics, plus we will start adding additional basic engineering courses where forces are important. Our future testing will then use larger, more random student populations, both at Ohio University and, more importantly, at independent external university test sites. The future testing will focus on educational effectiveness (including pre- and post-tests, treatment vs. non-treatment groups, and retention tests over time), rather than on the software design as this paper has.

6. CONCLUSION

This paper 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 nationwide.

Our software design evaluations indicate that the Haptics-Augmented Mechanics Activities can help students gain a better understanding of the basic course concepts (in the future we will test whether our products assist students to better retain these concepts over time, plus we will test the educational effectiveness of our haptics-augmented software). 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). We are in the process of developing integrated curriculum wherein our products will be central to the teaching of these courses. We are also soliciting universities to serve as external test sites in our nation-wide beta evaluations; please contact the first author if you are interested.

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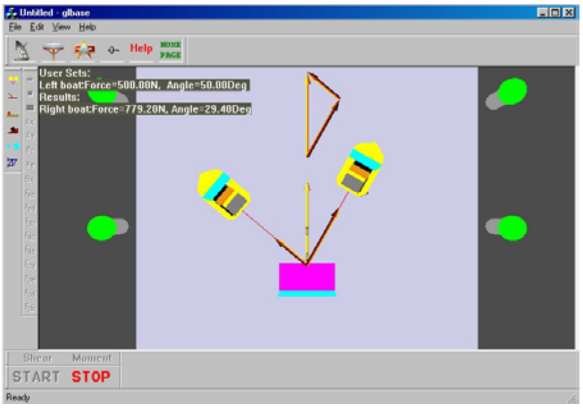
APPENDIX. HAPTICS-AUGMENTED ENGINEERING MECHANICS ACTIVITIES

This appendix presents a brief summary of our haptics-augmented physics, statics, and dynamics educational software activities, summarized in Table I. For each we present sample graphics, plus what the computer assumes, what the user may change (each activity starts with a reasonable default for user inputs), what the user sees on the screen, and what the user can *feel*. For complete tutorials accompanying each of these haptics-augmented software activities, please see the project website (listed in Section 4).

1. Vector Addition of Concurrent Forces: Boats Towing Barge.   As shown in Figure A.1, 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.



User Sets:
Left boat:Force=500.00N, Angle=50.00Deg
Results:
Right boat:Force=779.20N, Angle=29.40Deg

Figure A.1 Boats Towing Barge

User Sets:
Muzzle velocity=1000.00 m/s, cannon angle=45.00 Deg
Results:
time(final)=144.16 sec, x(final)=101936.80 m, yMax=25484.29 m

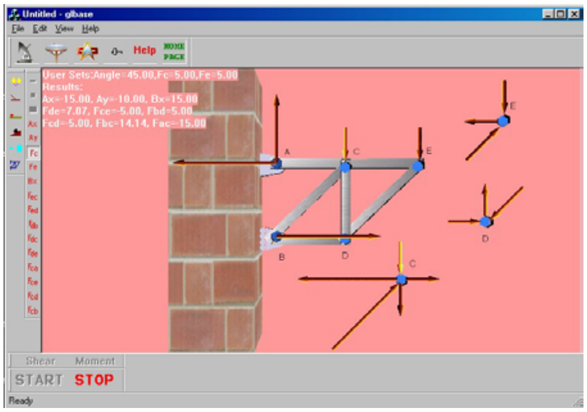
Figure A.2 Projectile Motion

2. Concurrent Forces: Three-Force Member. As shown in Figure 1 (in the body of the paper), a constant weight is to be supported at the end of the strut of constant length. The student sets the support strut length and angle; the computer then calculates (and displays) the geometrical parameters and the vector strut and wall reaction forces. The student visualizes the structure (no animation) and the vector force diagram. The student can feel any of the vector forces (singly): weight, support strut, wall reaction; the chosen force is highlighted on the screen.

3. Projectile Motion. As shown in Figure A.2, a cannon shoots a projectile given an initial muzzle velocity and cannon angle, set by the student. The computer sets gravity in the negative vertical direction and then calculates (and displays) the maximum and final horizontal and vertical positions, plus times. The student visualizes the projectile motion including a tracking curve. The student feels the projectile momentum, *X* and *Y* components simultaneously via the joystick forces. Note in this case the student does not feel actual forces (these would be boring due to constant gravity in the *Y* direction and zero acceleration in the *X* direction).

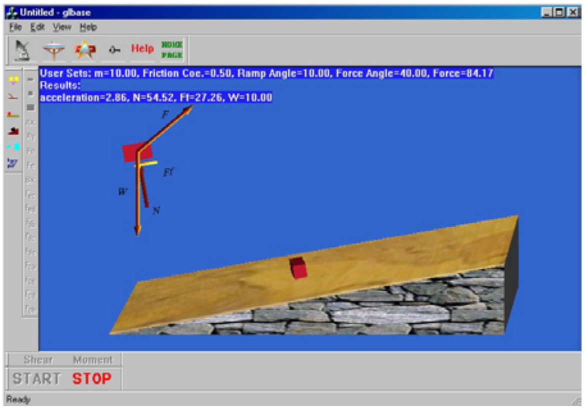
4. Newton's Three Laws. In our Newton's 1st Law simulation (not shown) a block of constant mass initially at rest is free to slide on a frictionless, flat plane. The student inputs vector forces to the block via the joystick, feels the vector inertial force (zero during constant velocity motions), and 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 the body of the paper), 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.

5. Statically-Determinate Truss Structure. In the truss shown in Figure A.3 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 to scale as seen in Figure A.3. The student feels any of the vector forces (chosen via joystick buttons and highlighted on the screen while being felt).



User Sets:Angle=45.00,Fc=5.00,Fe=5.00
Results:
Ax=-15.00, Ay=-10.00, Bx=15.00
Fde=7.07, Fce=-5.00, Fbd=5.00
Fcd=-5.00, Fbc=14.14, Fac=-15.00

Figure A.3 Truss Structure



User Sets: m=10.00, Friction Coe.=0.50, Ramp Angle=10.00, Force Angle=40.00, Force=84.17
Results:
acceleration=2.86, N=54.52, Ff=27.26, W=10.00

Figure A.4 Interactive FBD

6. Interactive Statics and Dynamics Free-Body-Diagrams. The block-on-ramp system of Figure A.4 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.

7. Beam: Shear and Moment Diagrams. As shown in Figure 3 (in the body of the paper), a beam resists a concentrated vertical load and a distributed vertical load. The student sets the magnitudes and locations for these loads; the computer then calculates (and displays) the shear and moment diagrams. The student visualizes the beam plus diagrams (no animation other than the student moving along the chosen diagram) and can feel any point on the shear or moment diagrams (as indicated by the red dot on Figure 3).

8. Pulleys. Students can select a 1:1, 2:1, or 4:1 pulley (the 4:1 pulley is shown in Figure A.5). Using the joystick students apply force to the virtual rope to lift the weight. The principle to be learned by viewing the animation and feeling the force required is that the work is constant; for example, the 4:1 pulley only requires one-fourth of the force, but the weight only raises one-fourth of the vertical distance, compared with the 1:1 pulley case.

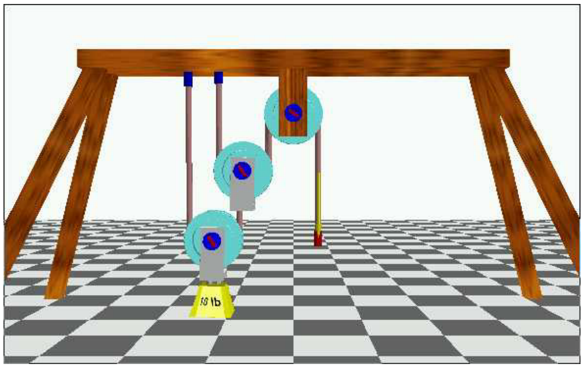


Figure A.5 4:1 Pulley System

```
User Sets:V_bullet=500.00,V_box=-22.00
Results:
mv_bullet=50.00, mv_box=-88.00, mv_final=-38.00, V_final=-9.27, t_before_meet=0.19
```

Figure A.6 Bullet Striking Box

9. <u>Conservation of Linear Momentum.</u> As shown in Figure A.6, bullet is fired with constant velocity into a point mass traveling at a constant initial velocity. With the assumptions of no friction or wind resistance, plus assuming the bullet perfectly lodges in the block upon impact, Conservation of Linear Momentum applies. The student enters the initial velocities of the bullet and the block (in either horizontal direction). The computer calculates (and displays) the time to impact, the final system velocity, plus the initial bullet and block momenta, and the final (total) system momentum. The student visualizes the bullet/block motion before and after impact. The student feels (singly) the initial bullet momentum, the initial block momentum, or the final system momentum (the sum of the two initial momenta) via the joystick forces. Note in this case the student does not feel actual forces (the inertial forces would be zero due to constant velocity motion).

10. <u>Conservation of Energy.</u> As shown in Figure A.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 (we could have enabled reaction force or inertial force).

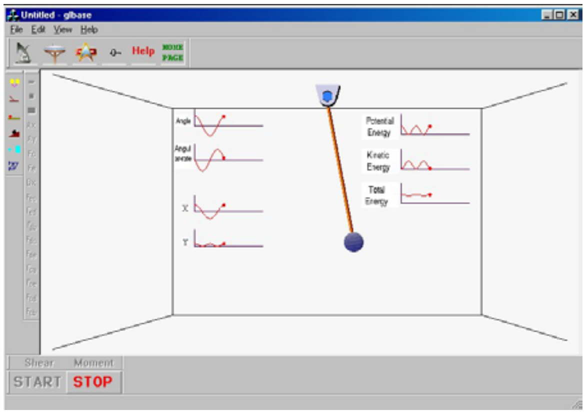


Figure A.7 Pendulum

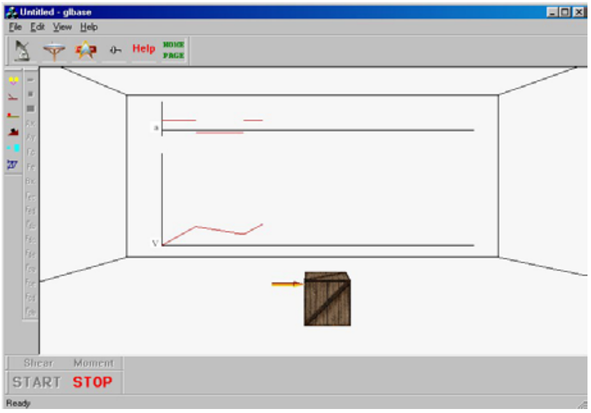


Figure A.8 Rigid Body Dynamics

11. <u>Rigid Body Dynamics: Box Motion.</u> 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 (see 6. Interactive Dynamics FBD and Figure A.4). In Figure A.8 a rigid-body box is simulated, in motion along a straight line, with potential tipping. The student inputs 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.