Engineering Haptic Virtual Manipulatives to Enhance K-12 Math and Science Education

Abstract

The United States economic and scientific leadership is endangered by low student performance in K-12 mathematics. Experts recommend that new tools are urgently needed to teach topics such as number sense, fractions, algebra, and geometry and measure. One of the most efficient methods currently available for math and science instruction is the use of **manipulatives,** using real world objects to teach abstract concepts. Computer software has been used to construct **virtual manipulatives**; however, these lack the crucial sense of touch of real manipulatives. The recent advent of haptic devices that allow touch-based interaction with the computer suggests a possible solution. A haptic device, essentially a computer controlled robot that uses electric motors to push or pull against the user, is a unique computer output device that allows the user to actually feel forces or vibrations. A haptic device is proposed to add a touch component to extend virtual manipulatives; that is, creating **haptic virtual manipulatives** holds the potential to revolutionize the educational field of math and science instruction.

The students in the first semester of the electrical engineering senior design class were tasked to ***"Design and build a haptic interface that can be used to add a sense of touch to virtual manipulatives for math and science education"*** while being introduced to the larger global implications of the task. Specifically, the engineering students were to design a haptic device (robotic computer interaction device) that could be used in teaching third-grade students rotational symmetry or relative weights of objects. (Note: A commercial designer of manipulatives helped set the requirements for the design using physical manipulatives from the company's curriculum.). The students followed a design process in which each team: researched and developed a design, documented their design, built a prototype of their design, demonstrated the prototype to the customer to gain feedback and improve design, and presented the technical aspects of their work to an industry panel consisting of IEEE members and led by a PE. The IEEE members evaluated and ranked the designs.

Feedback from the meeting with the industry panel gives the students confidence in their abilities while informing them of their weaknesses. An interactive presentation to the students by members of the industry panel emphasizes the importance of life-long learning and the role of the IEEE in this endeavor. This discussion also serves as an opportunity for the instructor to gain insight that will allow adaptation of the course to evolving contemporary topics raised by the panel.

This design project links a challenging engineering design problem to a relevant social question: i.e., how to excite kids about math and science in a manner that will facilitate long-term retention of new knowledge. As the engineering students address the technical challenges of building a haptic device they also address this important educational challenge. The engineering students practice programming, closed-loop control, design principles, MATLAB/Simulink simulation tools, teamwork, oral and written communication, and circuit design in their projects. However, it is only through the interaction with working engineers that these students actually appreciate the necessity of these skills in the next phase of their career. This connection with engineering practice is crucial to overcoming student skepticism about the importance of topics such as safety and environmental concerns and, at the same time, help the instructor keep the course relevant to the field.

This project produced promising results; it demonstrated the feasibility of combining haptics with virtual manipulatives. The ideas generated in this project will be refined in future semesters of the class and in spin-off research.

Section I: Project description

The Need

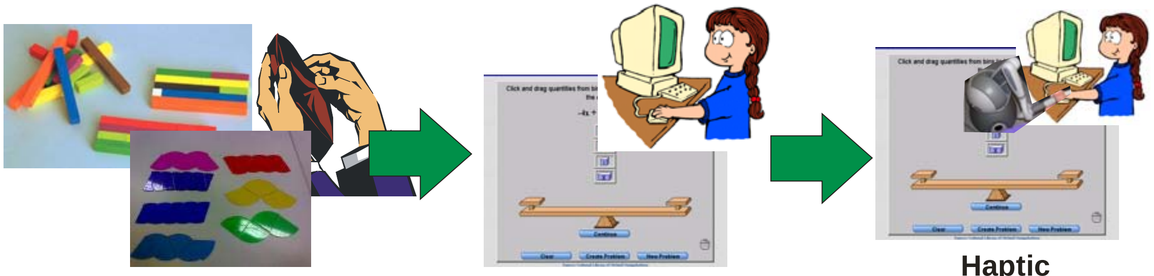
In a recent report the National Mathematics Advisory Panel (NMAP) states that "comparisons show that American students have not been succeeding in the mathematical part of their education at anything like a level expected of a national leader". Anecdotal statistics included in the report, such as 71% of adults cannot calculate miles per gallon on a trip, accentuate the failures in our educational system. The report then suggests the risks these results portend for our economic and physical security. The report recommends that new tools are urgently needed to teach topics such as number sense, fractions, algebra, and geometry and measure. The Panel makes specific recommendations including use of Computer Aided Instruction to improve student learning.

Recent statistics published in the *Journal of Learning Disabilities* indicate that one-half of all students with learning disabilities require supplemental work in math. Almost 3 million children (ages 6 through 21) have some form of a learning disability and receive special education in U.S. schools. The number of children diagnosed with learning disabilities has increased by 22% over the past 25 years.

One of the most efficient methods used for math instruction is the use of **manipulatives**. Manipulatives are real world objects - like Cuisenaire rods shown in Figure 1 - used to teach abstract math concepts. A proven, effective strategy is the Concrete-to-Representational-to-Abstract (CRA) paradigm. The recently released NMAP final report specifically recommends the increased use of the CRA instructional sequence:

Stage 1 (Concrete): hands-on learning through the use of manipulatives
Stage 2 (Representational): learning through static representations of manipulatives
Stage 3 (Abstract): learning through abstract notation (symbols, equations)

Computer software has been used to construct **virtual manipulatives**; the Algebra Balance virtual manipulative is shown in the center of Figure 1. Advantages of virtual manipulatives include *universal access, standardized instructional plans for teachers,* and *focused involvement from students*. While teachers often report of students becoming distracted with concrete manipulatives, virtual manipulatives enable greater focus.


Manipulatives

Virtual Manipulatives

Haptic Virtual Manipulatives

Figure 1: Evolution of physical manipulatives to virtual manipulatives to haptic virtual manipulatives.

The missing piece, however, in virtual manipulatives is the crucial sense of touch. That is, the student manipulates a mouse or keyboard that has no physical correlation to the manipulative. It is hypothesized that the sense of touch is a crucial component in the success of physical manipulatives. The recent advent of haptic devices for touch-based interaction with the computer suggests a possible solution. A haptic device, essentially a computer controlled robot that uses electric motors to push or pull against the user, is a unique computer output device that allows the user to actually feel forces or vibrations. Many recent games (driving simulators, etc.) have already begun incorporating haptic feedback. A haptic device is proposed to add a touch component to extend virtual manipulatives to teach fundamental science and math concepts; that is, creating **haptic virtual manipulatives** holds the potential to revolutionize the educational field of math and science instruction.

Engineering Context

The National Academy of Engineering has proposed "Grand Challenges for Engineering", which if solved will have huge impact on human life. One of these challenges is to "enhance virtual reality" where virtual reality is defined as a computer generated illusionary environment. In describing this challenge the proposers note that "touch poses an especially formidable challenge." Thus, designing a haptic device is a significant engineering design problem.

The Design Challenge

The students in the electrical engineering senior design class were tasked to ***"Design and build a haptic interface that can be used to add a sense of touch to virtual manipulatives for math and science education."*** Math Out of the Box® is a K-5 manipulatives-based mathematics curriculum. The co-developer served as the "customer" for the design project. The Customer chose two physical manipulatives from the curriculum that could potentially be translated to haptic virtual manipulatives.

In the "Symmetry and Shapes" lesson the "students recognize and create shapes that have symmetry." Sample exercises are shown in the first two panes of Figure 2. The exercise requires the students to trace the shape of interest on a piece of paper and then rotate the shape to identify rotational symmetry. The tracing paper can slide and move out of place, causing frustration and leading to an incorrect accounting of the degrees of symmetry. In the "Large and Small" lesson "students investigate weight (mass)." The weight comparison exercise uses the balance shown in the right pane of Figure 2 to compare the weights of common objects, such as pencils. An obvious limitation of this physical manipulative is that it does not allow comparison between very large objects, e.g. comparing a car to a whale.

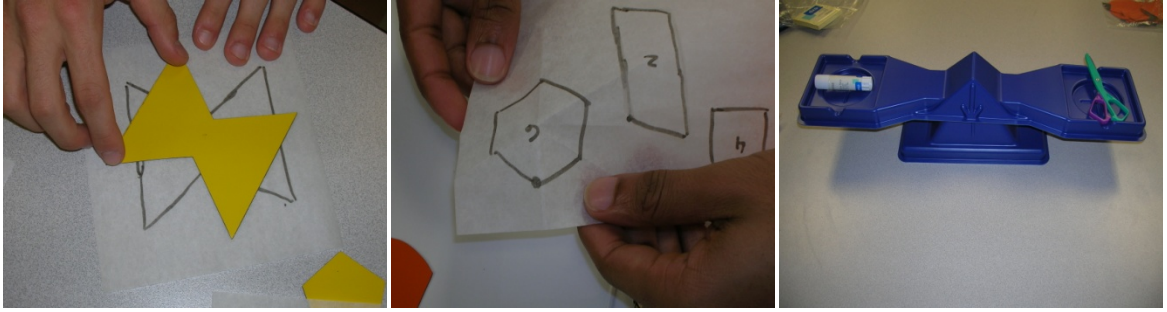


Figure 2: Physical manipulatives from Math Out Of The Box®. Left and center panes show rotational symmetry exercises and right-hand pane shows a balance used to teach comparative weights.

Laboratory Constraints and Supplies

Students must design the haptic device to interface with the Real-Time Workstation supplied to each group. The workstation consists of a PC with a Quanser Q4 data acquisition card. The WINCON software allows a control and measurement program designed and built using MATLAB/Simulink to execute at a fixed 1kHz sample rate under MS Windows operating system. This hardware and software represents the state-of-the-art in PC-based controllers. An important benefit of this system, over a microcontroller system, is that the control program can communicate with other MS Windows programs using shared memory. In this project, the groups were given a shell program with pre-defined communications hooks to the control software. The groups used the shell to build the graphical display. Each group was supplied with two electric motors with a 400 count position measurement encoder.

The Design Process

During the Spring 2009 semester sixteen students were equally divided into three competing teams, each team was tasked to complete an independent design. Students followed the steps in the general design process shown in Figure 3. As the first step, "Identify Need" the students met with their customer from Math Out of The Box®. Figure 4 shows the students using the manipulative lessons to explore the concepts of Symmetry and Weight. The students then performed additional research on topics to support their design, including: haptics and closed-loop motor position and torque control. The class developed "Customer Requirements", Table 1, and then each group chose a manipulative and created "Engineering Specifications".

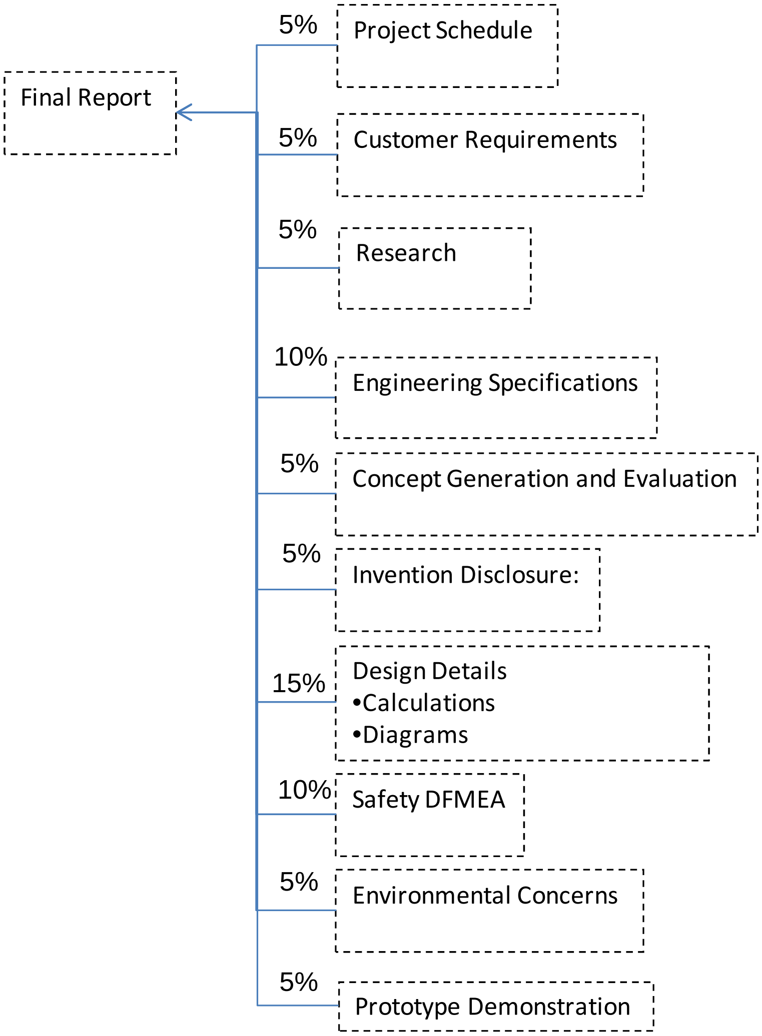


Figure 3: General design process (left) and milestone documents for the design process (right).

Figure 4: Students investigate physical manipulatives in the research phase of the design process.

<table>
<tr><td colspan="2">General Requirements:
• Allow the user to interact and receive force feedback from the virtual environment
• Portable
• Cost Target: Build for $100 in quantities of 1000 units
• Power Source: AC power preferred over a battery, USB power would be acceptable
• Durable
• Appealing to kids (colors)
• Safe for K-5, ages 5-12 years
• Easy to use, user friendly</td></tr>
<tr><td>Rotational Symmetry
• Use the aforementioned method of tracing paper and manipulative in a virtual environment.
• Design elements: real world shapes young students can relate to, such as hubcaps
• Simple shapes
• The concept of “Infinite” is introduced as a possible answer in rotational symmetry</td><td>Weight Comparison
• Feature real world objects in the virtual environment
• Use haptics to illustrate the differing force of objects. Example, light vs. heavy
• Be able to illustrate the weight of larger items such as trucks or elephants
• Sense of balance: use multiple smaller objects to balance one large object</td></tr>
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Table 1: Customer Requirements

The students created ideas and “Concepts” that could be used to implement a haptic virtual manipulative. One team chose the weight comparison task and concluded that the user should feel the weight on each side of the balance; that is, they chose a literal interpretation of the physical balance as shown in Figure 5. In their proposed system the user holds two handles to represent either side of the balance. The force felt on the handles is proportional to the difference in the weights of the objects on the scale. The group designed and built a prototype of the haptic balance as shown in Figure 6.

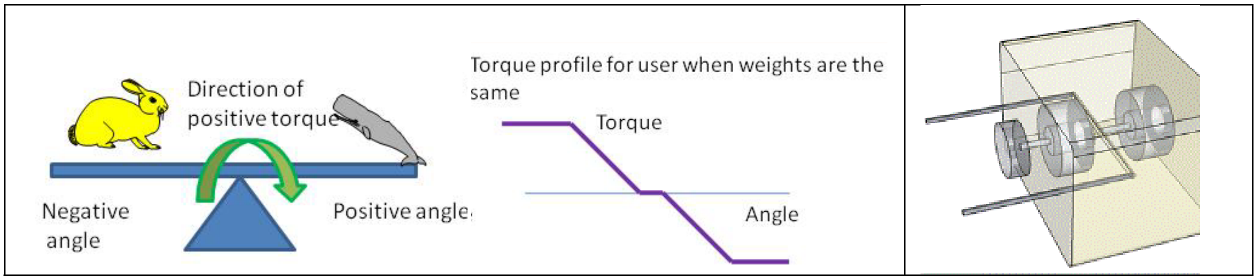
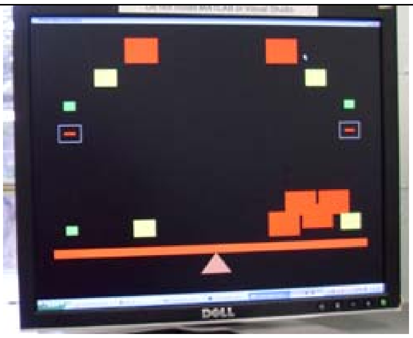
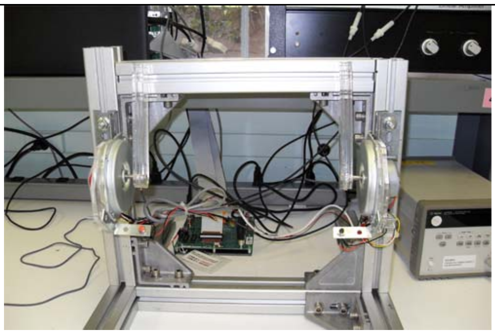


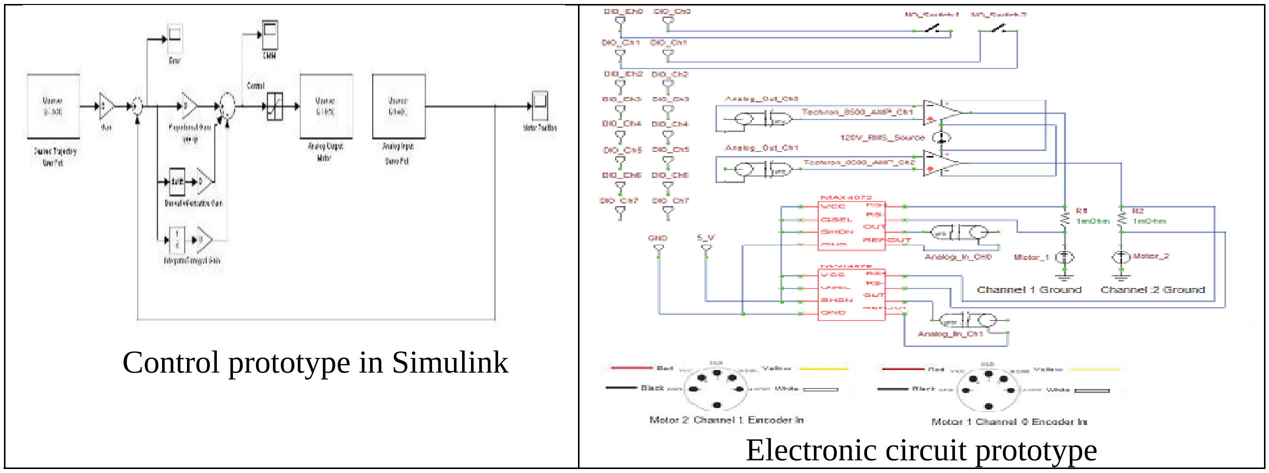
Figure 5: Design ideas for the haptic balance manipulative



Software prototype



Hardware prototype


Control prototype in Simulink

Electronic circuit prototype

Figure 6: Prototype software interface and hardware for the haptic balance.

The remaining two groups chose to implement the haptic rotational symmetry manipulative. The approach taken was that the user would rotate a handle and feel a torque that directed the user towards the nearest angle of symmetry. At the angle of symmetry the user feels a détente, i.e., a lack of force in either direction; Figure 7 illustrates the key features of this approach. The two groups designed and built devices that implemented this manipulative.

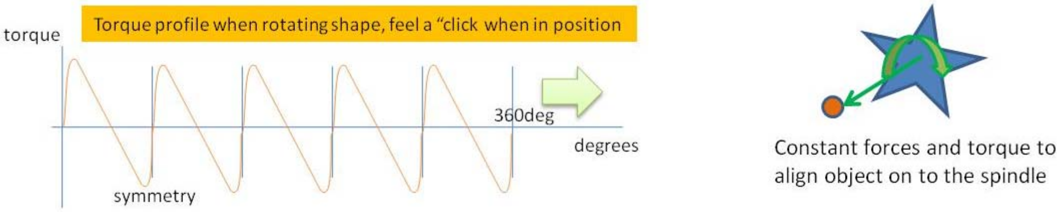
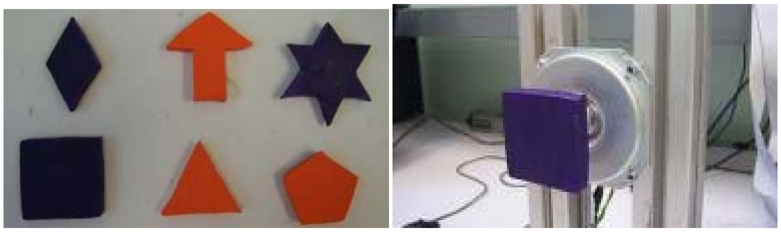


Figure 7: Design ideas for haptic rotational symmetry manipulative



An innovative feature is that the virtual shape is matched to a physical shape on the input handle. The shapes can be easily changed.

Figure 8: Haptic rotational symmetry manipulative. Demonstration of Prototype

The groups each presented their design ideas and prototypes to the customer and the course instructor. Figure 9 shows presentations in the laboratory. The customer response and the instructor's impression were used to determine a grade for quality of the system and how well the customer felt that the demonstrations matched the corresponding physical manipulatives.

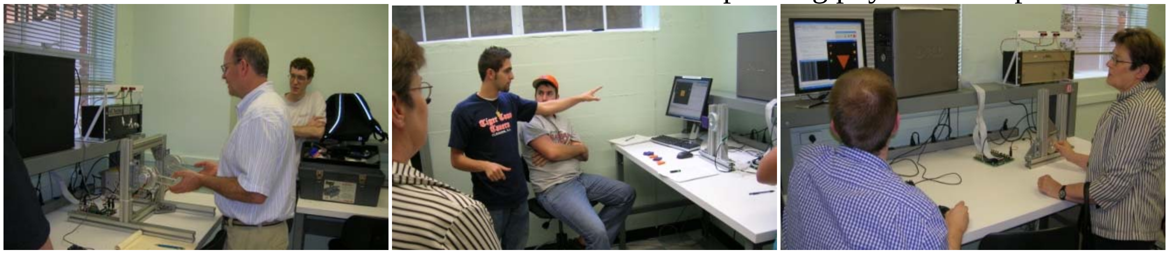


Figure 9: Student demonstrating their systems to the customer and course instructor.

Technical Review

The students presented their designs to a panel of engineers from IEEE (Institute of Electrical and Electronics Engineers). The engineers work in local industries and the panel was led by a PE. They provided feedback on the technical merit of the designs and determine part of the student grades. The IEEE members also made a presentation about lifelong learning.

Section IV: Impact on raising social consciousness

This project linked a challenging engineering design problem to a relevant social question: how to excite kids about math and science. Electrical engineering is taught as a rigorous application of math and science to solve specific problems; for example, students have been taught to "solve for the current in a resistor" and told that this will be important in their careers. This design project, however, made the connection that solving for the current in a resistor will allow one to build a device that can help children learn. The project further facilitated realization of the social implication of enhanced learning, that is, the project allowed the students to understand the strong connection between the work of an electrical engineer and the need and opportunity to increase science and math education for K-12 students. During the semester, the students read excerpts from "Rising Above the Gathering Storm", published by the National Academy of Engineering, which expounds on the need to educate more engineers and scientists in order for the country to remain competitive. The students realized that they themselves are the product of a training system that must be perpetuated, continually improved, and made widely available in order to secure the very best future for our society. The discussions during the design process on application of the technology led to ideas of how the learning devices could be used in rural parts of the state to offset low budgets and reduced infrastructure. The students completed the class with a greater understanding of their role as leaders in an educated society, including a greater appreciation for what they have learned, and a greater recognition of their potential to use their electrical engineering skills and training to help others. That is, the students completed the class with enhanced technical and communication skills as well as a clear understanding of their role in a global community.

Section V: Impact of partnering teaching and professional practice

The industry panel, led by a PE and primarily constituted of electrical engineers, reviewed the design projects and provided essential validation of the students' work. Students are generally suspicious of the course structure in which they must solve an ill-defined, open-ended problem without knowing where the solution can be found (e.g. in the chapter preceding a traditional homework problem). Since the majority of their classroom learning has been well defined and specific, they initially feel that something is wrong with the design course. When they talk to the experienced engineers and the Customer over the course of the semester and during the design presentations, they discover that the design class is actually representative of the real world. In fact, during the courses leading to the design course, we give the students "dots" of information and, in the senior design class, we teach the students how to connect "dots" -- the credibility and strength of dot connecting skills relies heavily on the industry panel. The industry panel can provide high impact criticism, often the same criticism that is not heeded when offered by the instructor. It is always confounding, yet exciting, to see a student react when a panel member tells the student something that they have been repeatedly told during the semester and that they ignored. "Real world" input simply has enormous influence on students, especially regarding issues such as safety, budget, and environmental impact. The industry panel reinforces to the students the importance of lifelong learning. The panel members give a presentation on the IEEE society and the need to network, attend conferences, take courses, and read literature to stay current after graduation.

Feedback from the industry panel also helps improve the course. Improvements for the current semester include involvement of the practicing engineers earlier in the design process to address specific weaknesses in the Specifications and Safety Analysis components of the presentations. This semester, in response to previous panel input, Life Cycle Analysis will be addressed as a better approach to considering environmental impacts.

Section VI: Multidiscipline and/or allied profession participation

A number of participants were required to implement the project including:

- Electrical engineering faculty members
- Professional educators
- Graduate students from electrical engineering and bioengineering
- Electrical engineers from local industry
- Speaker from US Patent Office

Section VII: Knowledge or skills gained

- Engineering Tools: MATLAB/Simulink, C++ programming, data acquisition
- Technical Skills: closed-loop motor control, real-time control, electronic circuit design, haptics, a systematic design approach
- Other: teamwork, written and oral communication, project management

Section VIII: Viability of technology used

The project produced promising results that demonstrate the feasibility of combining haptics with virtual manipulatives and provided the springboard for translation to reality. Having reduced the idea to practice has allowed translation of the overall concept to other educators; there has been a high level of enthusiasm for these ideas. The discussions and prototyping have helped identify three concrete objectives towards fulfilling the potential of the technology: 1) create a haptic interface device that can implement multiple manipulatives, 2) demonstrate that haptic interaction enhances learning, and 3) use current technologies and commercial haptic devices to create a beta-level curriculum.

The first objective, create new haptic devices, is a longer-term activity will be addressed in future design courses. For example, the Spring 2010 design class is working to redesign the haptic balance and improve the force control. The course instructor is currently working with psychologists and education specialists to pursue National Science Foundation funding to pursue the second objective of demonstrating that the haptic component of the interaction can actually improve learning. The outcome of this work will better identify the salient relationships between physical and virtual manipulatives and will be used to improve the interface design.

The most tangible means to demonstrate this technology and develop haptics-based curriculum for math instruction will be to enhance existing virtual manipulatives with haptic effects. The course instructor is working with the customer to enhance virtual manipulatives available from the *National Library for Virtual Manipulatives*. Accordingly, graduate students in the Instructor’s haptics research laboratory will illustrate the process of constructing a haptic application. As an example, the existing “Seeing Math™” will be extended to *“Seeing and Feeling Math”* using a low-cost (<$200) haptic interface device. This two-dimensional applet will be converted into a touch enabled haptic manipulative, so that the haptic virtual manipulatives can then be easily distributed.