AC 2011-1708: A HAPTICS-ENABLED REHABILITATION DESIGN PROJECT FOR A CONTROL SYSTEMS COURSE

Liya (Grace) Ni, California Baptist University

Dr. Grace Ni received her B.Eng. in Information and Control Engineering from Xi'an Jiaotong University in China, M.Eng. in Electrical Engineering from National University of Singapore, and PhD in Electrical and Computer Engineering from the University of Waterloo. She is currently an assistant professor in the School of Engineering at California Baptist University. Prior to that, she spent three years working for a start-up company in Canada as a senior research scientist and also taught at University of Wisconsin - Platteville for two years, as an assistant professor in Electrical Engineering. Her research interests include controls and robotics, particularly haptics with applications in virtual reality and teleoperation.

Haptics-Enabled Rehabilitation:

A Design Project for a Control Systems Course

Abstract

This paper presents an interesting design project for the Control Systems course offered to Electrical and Computer Engineering and Mechanical Engineering senior students. Students designed real-time control systems that involve haptic effects, meaning force feedback applied to the user by a motorized device as part of the human-computer interface. The main goal of this project is to design haptics-enabled rehabilitation exercises to help post-stroke patients regain their fine-motor skills. The different approaches taken by the multidisciplinary teams are presented, and feedback from students are analyzed. This project familiarized students with the Matlab/Simulink based software platform for the implementation of hardware-in-the-loop systems, and improved their understanding of the social impact of engineering solutions.

1. An overview on haptics and its relation to undergraduate engineering education

Haptics, originating from the Greek word “haptikos” meaning “able to touch”, refers to working with the sense of touch. A haptic interface is a human-computer interface that provides force or touch feedback to the user through a motorized device and haptic rendering software. The haptics technology, combined with virtual reality and/or telerobotics technologies, has undergone rapid development with medical, educational, automotive, industrial and other applications in the past decade, with the contributions of numerous academic and industrial research groups worldwide.

Some engineering educators with a research background in haptics have attempted to incorporate haptics into their undergraduate and graduate curricula. One approach is to use haptics enabled computer simulations to assist the teaching of engineering subjects such as physics, statics, dynamics, control systems, etc. [1][2]. Computer simulations and animations that allow students to feel the responses of systems make learning more engaging and fun, and also help students understand the course concepts better. Another approach is to offer a course on haptics. The advancement of haptics technology relies on the combined effort of electrical and computer engineering, mechanical engineering, computer science, biomedical engineering, and psychophysics. Therefore, haptics courses can be offered to students from different engineering disciplines. However, complete haptic courses are normally offered at the graduate level since it requires undergraduate level courses such as control systems, robotics, C++ programming, computer graphics, etc. as prerequisites.

2. Background of the course and the project

The School of Engineering was established at California Baptist University in the year of 2007. The Control Systems course is a required senior year course in the Electrical and Computer Engineering and Mechanical Engineering curricula. It was offered for the first time in Fall 2010. There were six ECE and four ME students taking this course. They all took Signals and Systems as a prerequisite, in which they gained some experience using Matlab scripts to assist their analysis and design. However, they had no exposure to the software tools such as Simulink, Realtime Workshop, Control Toolbox, that are useful for the implementation of real-time control system. A real-world application based project that requires hardware-in-the-loop real-time control will be an ideal choice to introduce the above tools to the students.

Nowadays, stroke is one of the most frequent causes of severe adult disability in the world. Many stroke survivors suffer from the loss of fine motor skills. The idea of haptics enabled rehabilitation is to assist post-stroke patients to regain fine motor skills through computer-game-like exercises. A patient will either feel the contact of objects in a virtual environment or feel the force that pushes or pulls his/her hand as the response of a game, or guides his/her hand in tracing a contour. Researchers have investigated sophisticated virtual reality systems integrated with haptics for the purpose of post-stroke rehabilitation [3][4][5]. However, the implementation of a virtual environment with 3D computer graphics is beyond the scope of a design project for a course on Control Systems. Therefore the scope of this project is narrowed down to a prototype of a haptics-enabled rehabilitation system which has the essential components and features of such system except the 3D computer graphics part in the user interface.

3. Haptic device and software platform

The haptic device used in this project is the Novint Falcon device (www.Novint.com), shown in Figure 1.

Figure 1 Novint Falcon Haptic Device

Being a popular game controller, the Falcon device is actually a parallel-linkage small robot with three degrees of freedom. The user can hold the grip and move it like a mouse but in 3D space, and feel texture, shape, weight and dynamics through the force feedback generated by the three motors attached to the links. The device is connected to the computer through a USB port. It is adopted for our design project mainly because of its low cost. A Falcon device only costs about 200 dollars.

The Matlab/Simulink/Real-Time Workshop platform (www.mathworks.com) and the Quanser QUARC control design software (www.quanser.com) are employed for the software implementation. The Real-Time Workshop generates and executes stand-alone C code from Simulink. The QUARC software provides a big collection of block sets to support third-party devices such as data acquisition boards, robots, haptic devices, etc. so that those devices can be easily integrated in systems designed with Simulink diagrams. The C code generated from the Simulink diagrams can be executed as stand-alone applications with real-time control on the devices. This software platform makes it possible for fast prototyping with real-time control on a physical plant while the algorithms can be implemented at a high level in the form of Simulink diagrams. This hardware-in-the-loop approach is very popular in engineering practice, and the best way to introduced it to ECE and ME students is through projects.

The Novint Falcon device is one of the devices supported by QUARC. The interface, as shown in Figure 2, is simply a block with a 3 by 1 vector input as the force components on X, Y, Z axis (in Newtons) to be generated by the motors, a 3 by 1 vector output as the X, Y, Z coordinates (in Meters) of the device grip position, and a 4 by 1 vector output indicating status of the four buttons on the grip.

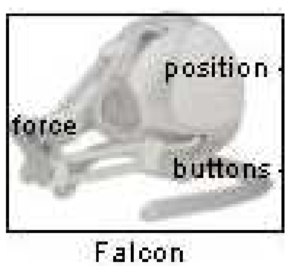


Figure 2 Simulink Block for the Falcon Device

4. Relevant course materials

The lectures in this course are not much different from a standard Control Systems course. Topics covered include modeling, time-domain analysis, frequency-domain analysis (Bode and Nyquist diagrams), root locus, state space method, PID control, phase lead and lag compensators, etc. Haptics and its applications are only briefly introduced with a paragraph on the design project handout. Simulink, Real-Time workshop, and QuaRC are introduced during the lab sessions. Students went through a hands-on Simulink tutorial provided by Mathworks and did lab projects on the Quanser QET DC Motor trainer which has a similar software platform as the design project. However, students were provided with Simulink diagrams for the lab projects and only need to do measurements and parameter tuning instead of design with Simulink diagrams.

5. Requirements of the project

In this design project, each team with three ECE students and two ME students will design their own haptic-enabled rehabilitation system. The assumption is that the post-stroke patient will use this rehab system during the whole recovery period from pretty weak fine-motor skill to almost normal. There was no specific requirement on how the rehab exercises should be. But the following main components/features are required:

- Haptic effects: when the user holds the Falcon device, he/she should be able to feel appropriate amount of force applied to his/her hand to assist the completion of the tasks. You need to apply feedback control in at least one effect.

- User interface: a graphical interface should be provided to the user so that the user can get visual clues of the task and see how well he/she performs in real-time. The user interface can also display instructions and allow the user to choose from some options.

- Data logging and adjustable difficulty level: your application should be able to record the performance of the patient so that the therapist can analyze it. Your application should also allow adjustment of the difficulty level so that the patient can start with easier exercises in the beginning of the rehab period and move on to more difficult level later.

6. Comparison of two team's work

Although the Novint Falcon device has three degrees of freedom, the system will require 3D graphics to match the haptic effects if the rehab exercises are designed for 3D spaces. Therefore, both teams decided to make the rehab exercises to stay on a 2D plane. Since one of the most important fine motor skills is to write and draw on a piece of paper, the value of rehab exercises constrained on a 2D plane can be justified, with the grip of the Falcon device acting like the end-tip of a pen and the virtual 2D plane like a piece of paper on the table top.

The two teams first designed experiments to figure out how the "Falcon" block provided by QuaRC works, in terms of the corresponding axis of the three position outputs of the block, positive and negative directions, position range, and how to send force command to the device through the block input. Each team then brain-stormed about the rehab exercise they are going to develop and assigned tasks to teach team member. With a total of four lab sessions (2 hours per session), the teams developed the following haptics-enabled rehabilitation systems.

Team A: dynamic trajectory play-back

Team A designed a system that allows the therapist to record a trajectory on a 2D plane and the patient can use it for rehab exercise. They implemented a virtual vertical plane by simply applying a force perpendicular to the plane in direction and proportional to the penetration in magnitude. At the recording mode, as shown by the Simulink diagram in Figure 3, the trajectory data is recorded as arrays representing the coordinates of the Falcon's grip on the vertical plane. The trajectory is played back at the same constant sampling time, the curve and the velocity along the curve are both exactly the same as the recorded one. At the play back mode, shown in Figure 4, feedback control systems are implemented on both X axis and Y axis to generate the haptic effect.

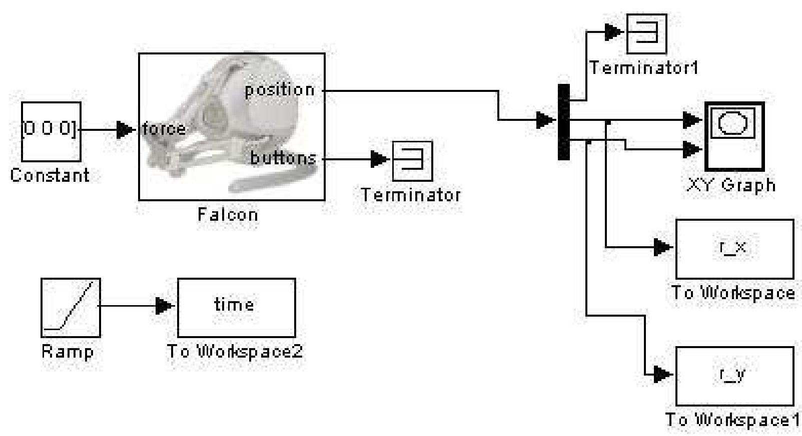
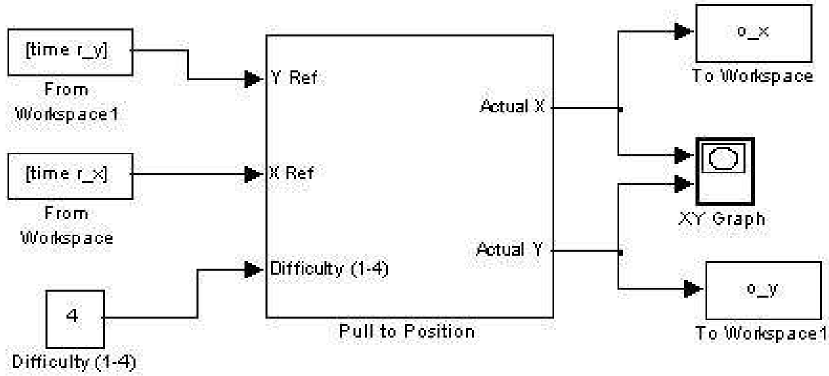
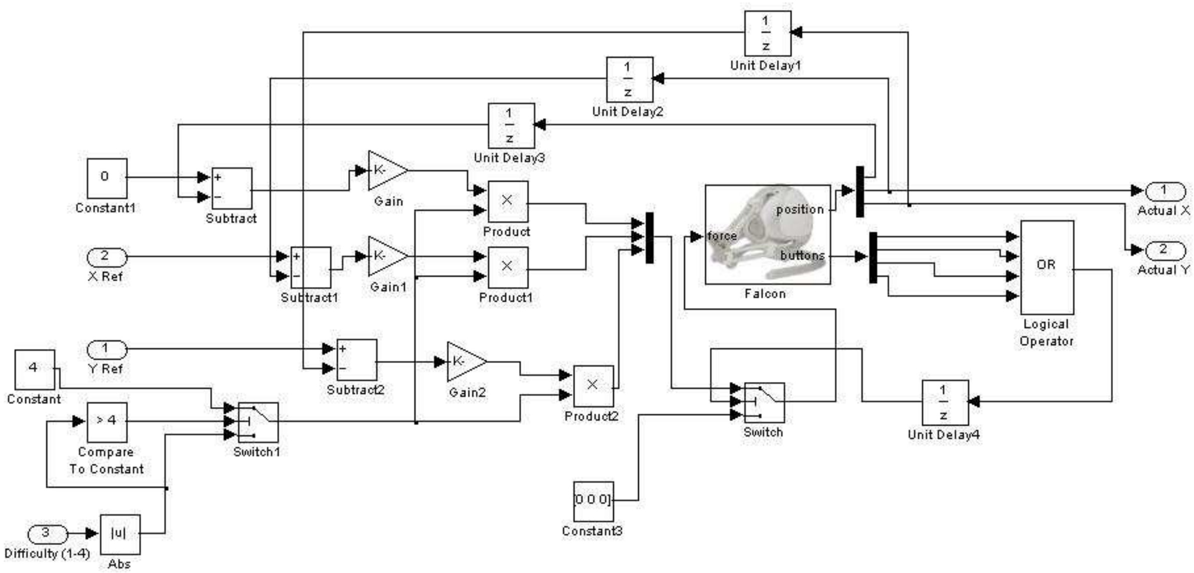


Figure 3 Simulink Diagram for Recording Mode

In the feedback control system, the Falcon device is the plant, recorded trajectory is used as the reference signal, the actual end-tip position of the Falcon device is the output signal, and the proportional controller serves as a virtual spring attached between the desired position and the actual position. The controller output that sent to the "Falcon" block in the Simulink diagram determines the amount of force applied to the user's hand. The gains of the proportional controllers are basic gain values multiplied by the difficulty level on a 1-4 scale, with 1 being the most difficult and 4 being the least difficult. A smaller gain makes the force smaller due to the same amount of position error, which means less haptic assistance in the task, hence more difficult, while a larger gain corresponds to more haptic assistance hence easier exercise. Also the haptic effects are activated when the user holds down any of the four buttons on the grip.



(a) Main Diagram



(b) Diagram for Subsystem "Pull to Position" in (a)

Figure 4 Simulink Diagram for Play-Back Mode

The test results are shown in Figure 5. The actual curve (dashed) follows the reference curve (solid) except in the beginning when the device grip was pulled from the center of the work space to the starting point of the reference curve. During the test, the user felt that his hand, which is holding the grip of the Falcon device, was being guided through the trajectory.

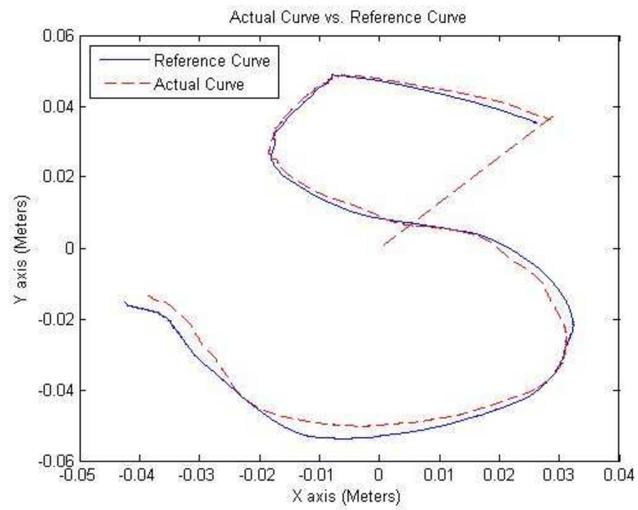


Figure 5 Testing Results of Dynamic Trajectory Play-Back

Team B: a path to trace with virtual walls

To constrain the motion to a vertical 2D plane, team B implemented the force perpendicular to the plane as a polynomial function of the position, such that the force will first pull the grip to the plane and then points out from the plane to generate the contact effect. For the rehab exercise, team B came up with the idea of letting the patient trace a path (only circle was implemented) that is constrained by virtual walls – an inner wall and an outer wall. Figure 6 shows the Simulink diagrams of subsystems that calculate the direction of the force when the grip of the Falcon device penetrates the outer wall. The force will push the grip away from the outer wall in the direction that pointing from the grip toward the center of the circle. Similarly, an inner wall was implemented such that when the grip of the Falcon device penetrates the inner wall, a force will be generated to push the grip away from the inner wall in the direction that pointing from the center of the circle toward the grip. Therefore, the motion of the device will be constrained in a ring between the two virtual walls. Higher difficulty level corresponds to a wider ring which means less haptic assistance, while lower difficulty level corresponds to a narrower ring which means more haptic assistance.

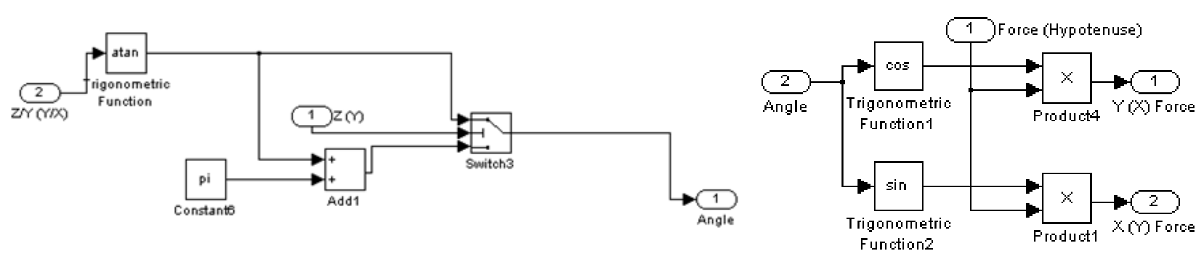


Figure 6 Simulink Diagrams Showing the Calculation of Force Direction

Test results with the grip of the Falcon device (solid) moving along the outer wall (dashed) is shown in Figure 7. During the test, the user felt the force pushing the grip away from the outer wall.

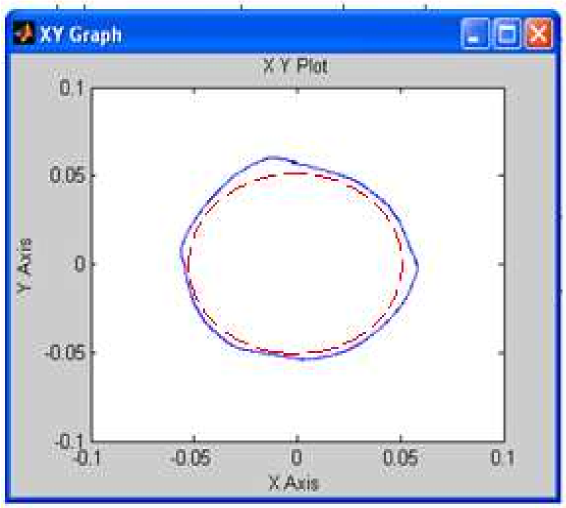


Figure 7 Testing Results for Tracing a Circle with Virtual Walls

In the end of the semester, each team demonstrated and explained their work to the other team and the instructor, and submitted a technical report with the distribution of tasks among the team members. Besides the technical details on the project, students also reflected on the possible impact haptics-enabled rehabilitation could have on post-stroke patients, therapists, and the society.

7. Student feedback and future improvements

In the end of the Fall 2010 semester, the following questionnaire was filled out by every student.

****

This project increased my understanding or improved my skills in the following areas:

(Rating on a scale of 1-5 with 1 being strongly disagree and 5 being strongly agree.)

1. How engineering solutions can help people and impact the society.
2. Matlab and Simulink.
3. Hardware-in-the-loop real-time control system.
4. Analyze a problem and evaluate multiple solutions.
5. Design experiments to determine properties of unfamiliar equipment.
6. Issues in designing a system that involves human-computer interface.
7. Trouble shooting and problem solving.

8. The need for life-long learning.
9. Work in a multidisciplinary team.
10. Technical communication orally and/or in writing.

What could have been done to make this project more interesting and successful?

****

The average ratings to the first ten questions are shown in Figure 8:

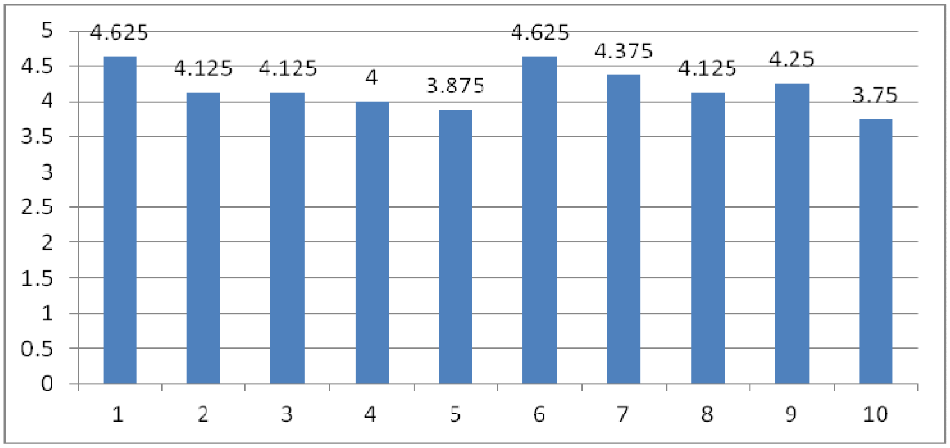


Figure 8 Average Ratings of Students Feedback

Regarding the last question, most students commented that the project could have been more successful if they were given more time. The main obstacle we faced during this project was that the upper division ECE lab, which was used for the lab and design projects of the Control Systems course, was not ready in the beginning of the semester. After the computer setup, hardware and software installation, and other issues were solved, we only had less than two months left to do the lab projects and design project. With their senior design, other courses, and part-time jobs, the students didn't have time to work on the projects outside the dedicated lab sessions.

Another comment by the students is that some training on GUI design and S-function in MATLAB will be helpful. They did some work on GUI design with the GUIDE component of MATLAB. However, they didn't complete the integration of the GUIs with their systems because they didn't have time to figure out how to display multiple dynamic trajectories (for team A) or static shapes together with dynamic trajectory (for team B). Ideally, the GUI should contain an embedded axis showing 2D trajectory of the Falcon device grip position, and the reference trajectory for team A or inner and outer circular constraints for team B, together with options such as difficulty level or shapes to trace. Seven of the ten students are currently in a Robot Modeling and Control course and are able to use some of the lab sessions in this course to continue the GUI design part of the haptics-enabled rehabilitation project.

For future improvements, evaluation by real post-stroke patients, therapists, or experts with research background in rehabilitation will be valuable for this kind of projects.

8. Conclusions

A haptics-enabled rehabilitation project for a Control Systems course is presented in this paper. Students learned skills for designing hardware-in-the-loop real-time control systems on the Matlab/Simulink/Real-Time Workshop platform. This project also improved their awareness of issues in the design of human-computer interface, the social impact of engineering solutions, the need for life-long learning, and collaboration among different engineering disciplines.

Acknowledgement

The author would like to acknowledge the following students for their hard work on this design project and contributing their system diagrams and testing results to be presented in this paper: Zachary Bowman, Nick Braden, Mark Davenport, Patrick Dietz, Kellan Frericks, Benjamin Lee, Bobby Magby, Robert Maystrovich, Brandon McGaffey, Scott Rendel.

Bibliography

1. Grow, D.I., Verner, L. N., & Okamura, A. M., “Educational Haptics”. AAAI 2007 Spring
2. Symposia – Robots and Robot Venues, Resources for AI Education.
3. Williams, R. L. II, He, X., Franklin, T., & Wang, S., “Haptics-Augmented Engineering Mechanics Educational Tools”, World Transactions on Engineering and Technology Education, Vol. 6, No. 1, 2007.
4. Rozario, S. V., Housman, S., Kovic, M., Kenyon, R. V., Patton, J. L., “Therapist-mediated Post-stroke Rehabilitation Using Haptic/Graphic Error Augmentation”, IEEE Engineering In Medicine and Biology Conference (EMBC), Minneapolis, MN, USA, 2009.
5. Boian, R. F., Deutsch, J.E., Lee, C. S., Burdea, G. C., Lewis J., “Haptic Effects for Virtual Reality-Based Post-Stroke Rehabilitation”, Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003.
6. Yeh, S.-C., Rizzo, A., Zhu, W., Stewart, J., McLaughlin, M., Cohen, I., Jung, Y., Peng, W., “An Integrated System: Virtual Reality, Haptics and Modern Sensing Technique (VHS) for Post-Stroke Rehabilitation”, Proceedings of the ACM Symposium on Virtual Reality Software and Technology, 2005.