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Haptic Feedback Steering Wheel

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Abstract— **In uncoupled steering systems such as drive by wire, it is necessary for the driver to feel a simulated reaction torque related to tire/road interactions. To investigate this haptic necessity, we constructed a simple stationary force feedback steering wheel. This paper describes a low cost force feedback steering wheel system and introduces several driving events to validate the unit's fidelity. Qualitative testing was done without the use of a display to see how the feel of these road events compares to the feel of driving in a car. This low budget solution looks to simply evaluate the torque magnitude and oscillation that is fed back to the driver through the steering wheel.**

keywords: steer by wire, haptics, force feedback

I. INTRODUCTION

Although vision is the most important sense for driving, previous studies have concluded that other modalities such as haptic feedback are second only to vision in relaying vehicle position [1]. It is this reason that in this paper we look at the torque requirements for a force feedback steering wheel separate from the other dynamics that moving base simulators and visual displays provide. And although other studies such as [2] have alluded to the fact that the lack of a proper display hinders the overall simulation, we are proposing only to analyze the magnitude and frequency of the torques that are applied to the steering wheel. Our reasoning for separating the perception of motion from the simulation is for the driver to focus solely on the force he experiences. Perhaps even if the force is unrealistic, it may better suite the drivers own requirements.

The motivation for this research parallels that currently being conducted on steer-by-wire systems. Steer-by-wire systems offer many advantages over common rack and pinion systems. For one, they eliminate complexity i.e. number of parts in the engine compartment and thus allow for greater space and safety of the driving cabin [3]. Also, these systems are considered dry systems in that they do not have any hydraulic pumps, further simplifying the overall system. Perhaps the greatest benefit of steer-by-wire is that the engineer can tune the dynamics of the cars handling simply by using different software [3].

Another area of research related to our project is driving simulators. Driving simulations allow designers and engineers to tune the variables of driving while keeping parameters such as driving speed constant [2]. Designing driving simulators is an extensive process in combining sensory illusions and sensory substitutions [2]. The result allows for the analysis of driving behavior in various conditions fixed by the designer [2]. This paper describes a simple system for a user to experience a sensory illusion but looks at it from a purely analytical aspect. We will use a simple viscous damping model to relay force feedback to the user.

II. SIMULATION

We chose to program our model in C++ allowing us to adequately control the DC motor and the optical encoder. Our model consists of five different events each varying torque according to the position of the steering wheel. Our intent was for the driver to be familiarized with the steering wheel configuration in the first three events and then move on to two tests with and without visual aid. To validate the necessity of haptic feedback and to prove that our equipment is credible, we will run a test comparing force feedback and no force feedback cases. The five trials are described more in depth below:

1) *Slow driving*: This is the most basic of the trials and is made to simulate driving in an open smooth surface area at slow speeds. The speed we are trying to display is between 10 and 15 mph which could model an open parking lot or turning into a driveway. In this model, we counter the drivers motion with a constant torque simulating the inertia of the road/tire interaction commonly felt in coupled steering systems. Because the power steering system is less intrusive at lower speeds, this constant torque has to be higher relative to the other tests for realism.
2) *Freeway driving*: Similar to slow driving in that the driver feels constant force, this model aspires to simulate driving on an open freeway. Because the speeds are higher (50 to 60 mph), the torque acting against the drivers motions is less than in trial one. To further provide realism to the experience, we imbedded a high frequency vibration into the model which strives to simulate a variety of naturally occurring vibrations such as crossing the lane dividing reflectors, sections of rough pavement, etc... To accomplish this, we used a high frequency sin wave to relay torque in the angular range where we felt it was necessary. In each of the first two tests, the driver will be instructed to drive freely for a minute or so.
3) *Off-road driving*: The point of this driving event was to display vibration in a way that it made the driving feel erratic. This event could simulate driving on an unpaved surface such as a dirt road. Trial 3 was an

interesting and fun event more than anything else, as you would never want to feel like you didnt have control of your actual vehicle. However, the method that we used (super imposing sin waves) could be used at different magnitudes and frequencies to display other types of vibrations commonly felt throughout daily driving.

4) *Virtual driving course*: The idea of this trial is to direct a driver through a course without any visual feedback. The motor is purposely set with a high torque and the driver is told to grasp the wheel lightly to emphasize that the wheel is steering them. At the end of the course, the driver will be instructed to sketch the path he was directed through and then the actual course will be shown as a comparison. We feel that this is a most basic haptic test in that the velocity of the steering wheel conveys all of the information within the trial. For instance, the speed of the steering wheel can convey the speed of the virtual car while the change in angle of the wheel and the duration of time for which it is turned communicates the radius and the arc length of the curve. If our model is robust, the track drawn by the participants should match up closely with the actual track simulated.
5) *A basic following task*: The final test uses an on screen cursor to guide the participant through an oscillating path. The path oscillates at a high frequency for 7 seconds and then switches to a lower frequency for the remaining 7 seconds. Another cursor displays to the user their position. As they try to follow the on screen cursor, they can see the difference between their position and the desired path's. Each driver is asked to perform the previous task two times, one without any haptic feedback and then one with haptic feedback. The haptic feedback case couples the drivers position to the guiding position by a virtual spring. Therefore, the more the driver's position deviates from the guiding cursor, the more compensating torque he experiences. An obstacle was added to this test in that the user had to adjust quickly yo a phase change as the sine function changed. We hope to see force feedback aid in this transition. To prove that force feedback is helpful in following tasks, we will compare the error in both tests from within this trial.

III. CONSTRUCTION

Our haptic feedback steering system is a very basic and low cost assembly that can adequately display torque to a user through a steering wheel. The main construction is made from 3/4" thick MDF which is fastened together in a standard box shape. The steering wheel is connected to a 1/2" drive shaft which rotates in two roller bearing assemblies at both ends. The shaft is press-fit into the bearings and is secured further by shaft collars which completely limit thrust movement. The shaft is then connected to a DC motor by a belt and pulley system. For the motor, motor controller, optical encoder and encoder circuitry, we decided to use Phidgets parts due to their low cost and ease of connectivity. The motor was mounted in 1/2" delrin brackets which each have two bolts for adjusting belt tension. All motor circuitry was mounted within the box for aesthetics. To power the motor, a BK Precision AC/DC power supply was used and mounted atop the main box. This steering system is relatively portable at 25"x16"x17"(LxWxH) and can be affixed on any table. We also gave the system a slight tilt (15 degrees) to mimic an actual steering column. Figure 1 shows the exterior of the steering system while Figure 2 shows the interior components (motor control).

Fig. 1. This shows our testing apparatus.

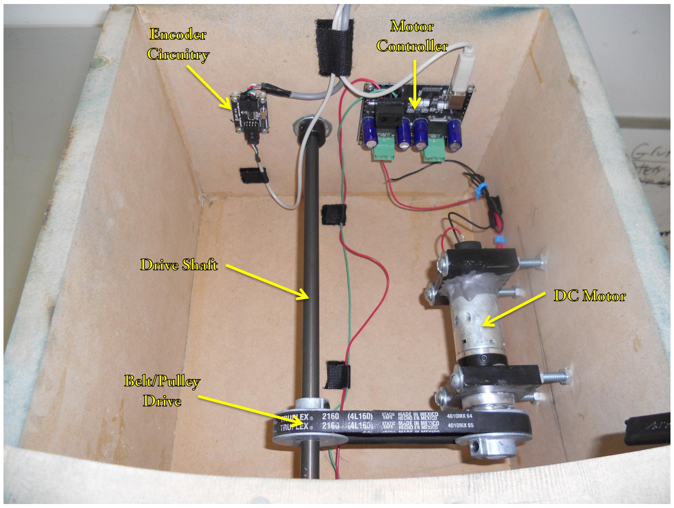


Fig. 2. This shows the internal components of our testing apparatus.

IV. MATH MODELS

Each simulation has its own specific mathematical model. The mathematics were refined using a trial and error method to get the best "feel" of the simulation for the user. All the mathematics are based upon the rotational position of the steering wheel that is obtained from the rotary encoder. This position is then converted to an angle by using (1).

$$\theta = -position/(1441.8 * 360) \quad (1)$$

The Phidgets' handlers inside C++ use a specified percentage of the torque ($\%torque$) to have the motor controller allocate the correct torque to the motor. The controller also keeps the running $time$ in seconds. The mathematics for each simulation are as follows:

1) *Slow driving*: This maybe the easiest to mimic. What we did for this is have the controller store the previous angle of the steering wheel (θ_{prev}) and the current angle of the steering wheel (θ). We then take the hyperbolic tangent of the difference between the two angles to calculate the percent torque. The reason why hyperbolic tangent was used is because it gives a very smooth transition when applied torque changes direction as the angle changes. Equation (2) shows this relation:

$$\%torque = -100 * tanh(\theta - \theta_{prev}) \tag{2}$$

2) *Freeway driving*: This is very similar to slow driving except the torque has been lowered to better mimic highway driving. Also, after the user turns the wheel past a certain angle a sine wave that oscillates at 15Hz is implemented to simulate the reflectors in the middle of the highway. Equation (3) shows the percentage of torque when driving straight and (4) shows the percentage torque for the simulated reflectors.

$$\%torque = -60 * tanh(\theta - \theta_{prev}) \tag{3}$$

$$\%torque = -100 * tanh(\theta - \theta_{prev}) * sin(2 * PI * 15 * time) \tag{4}$$

3) *Off-road Driving*: To simulate this trial, the torque applied was found by multiplying the torque percentage by a sinusoid with a frequency of 5Hz (5).

$$\%torque = 100 * sin(time * 2 * PI * 5) \tag{5}$$

4) *Virtual driving course*: This simulation was done by making a virtual road course by using a sinusoid at a given frequency ($freq$) for a portion of it's period. We have the steering wheel go to the angle we want by multiplying our desired angle(θ_{des}) by the sinusoid (6). The percent torque that the user feels is a spring force between the current angle and the desired angle (7 and 8).

$$\theta_{give} = \theta_{des} * sin(time * 2 * PI * freq) \tag{6}$$

$$\theta_{error} = \theta_{give} - \theta \tag{7}$$

$$\%torque = \theta_{error} \tag{8}$$

5) *A basic following task*: This maybe the most complicated of our simulations. The pupose of this simulation is to have the user follow a cursor by turning the steering wheel. The cursor's postion is a sinusoid that moves at a certain frequency ($freq$) shown in (9). The percent torque is once again a spring force that is a function of the given angle from the sinusoid (θ_{give}) and the user's position (θ) shown in (10 and 11). We then multiplied the torque by a spring constant of 0.75 to give us the correct magnitude.

$$\theta_{give} = 110 * sin(time * 2 * PI * freq) \tag{9}$$

$$\theta_{error} = \theta_{give} - \theta \tag{10}$$

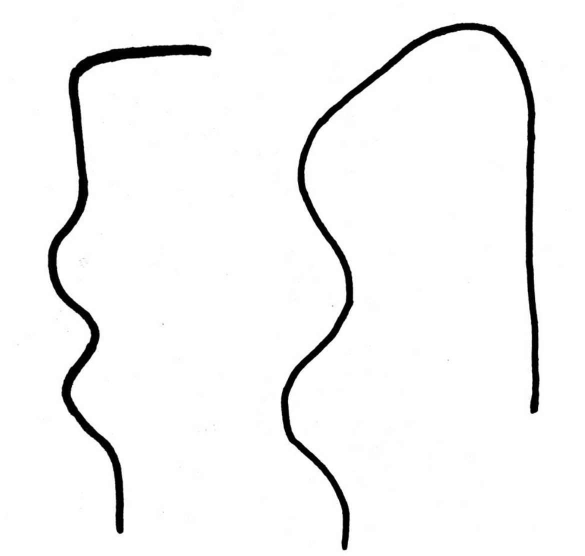
$$\%torque = 0375 * (\theta_{error}) \tag{11}$$

V. RESULTS

We performed a predominantly qualitative study in the USF TECO energy hall (Hall of Flags). This location gave us a diverse crowd with a variety of different knowledge sets and a large age deviation. In this study, we presented the subject with a poster which included still photos of the terrain in which they would be driving over, and a computer monitor to display Trial 5. Each subject was given time to drive freely in each terrain type (Trials 1-3) before moving on to the next trials. For the first three trials, we asked each subject what they thought about the magnitude and oscillation of the force compared to their driving experiences. Overall, 80 percent said that the force displayed in the slow driving event was more than they are used to experiencing while driving. For Trial 2, the consensus was that the magnitude of the torque was sufficient, but the vibration felt through the steering wheel simulating lane dividers was greater than in an actual vehicle. In the off-road trial, the subjects were asked if they felt that they had control of the vehicle. Most responded that it felt realistic, but without a visual display they could not discern controlling the vehicle.

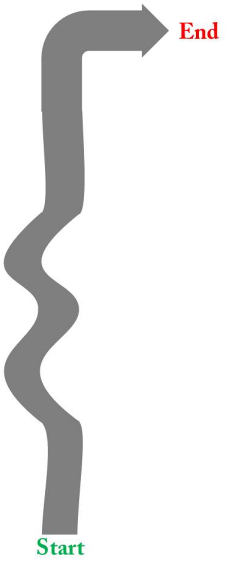
In Trial 4, participants were informed that they had one attempt to guess a simple road course that was displayed to them through the steering wheel. They were also told to grasp the steering wheel lightly and not to resist its motions. After the trial they were immediately told to sketch the course that they were directed through. After testing 14 participants, the results were promising. Most of the participants came very close to drawing the exact road course with only two that were not accurate. The two main problems that the subjects had were identifying the straightaways and the arc length of the final curve. We feel that this is due to the lack of a visual to display speed. Some of the subjects sketches are displayed in comparison to the actual course seen in Figure 3.

For Trial 5, we tested 14 subjects in a basic following task both with and without force feedback. Each subject was giving a visual of what the cursors looked like and the general idea of the experiment prior to testing. Each person was given a preliminary trial on each test (with and without force feedback) before data was recorded. Qualitatively, the results varied. On some subjects it was clear to see that force feedback helped track the target while others were constantly out of phase with the cursor due to overshooting the position. To quantify our results, we measured the error in angle between the on screen cursor and the driver's movements. We then plotted the error of force feedback vs. no force feedback. Just as our qualitative results showed, it was not conclusive that force feedback helped in the following task. We observed each graph and decided if the subject passed or failed. Pass



(a) A subject's sketch of Trial 4.

(b) Another subject's sketch of Trial 4.



(c) Actual course that we designed.

Fig. 3. This describes the sketch representation of Trial 4 by two subjects in comparison to the actual course .

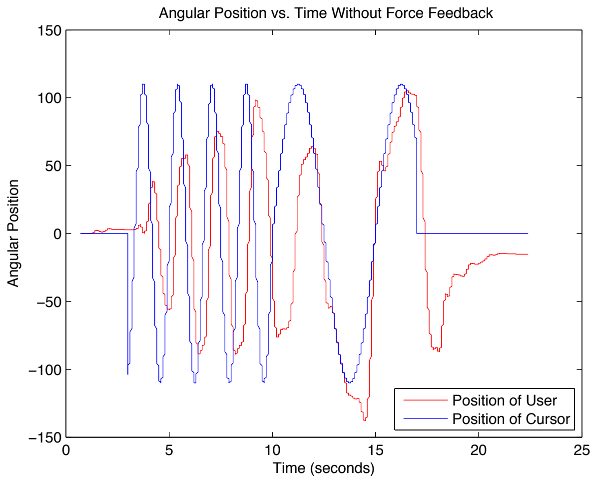
declared that force feedback helped while fail designated that it was not beneficial. We observed the error at multiple points along the graph and decided if the error was significant. From here we concluded that 43 percent passed and 57 percent failed. Therefore, without conducting more experiments, it is said that haptic feedback for a basic following task performed on our testing apparatus is not beneficial. From our plots, however, we did find some interesting trends. The first trend was that force feedback improved the subject's performance throughout. It can be seen in Figure 4. Figure 5 shows the second trend which shows that the subject was aided by force feedback when the cursor changed speeds this happens at ten seconds. Finally, the third trend shows virtually no improvement from the purely visual following task. It is shown in Figure 6.

VI. CONCLUSION

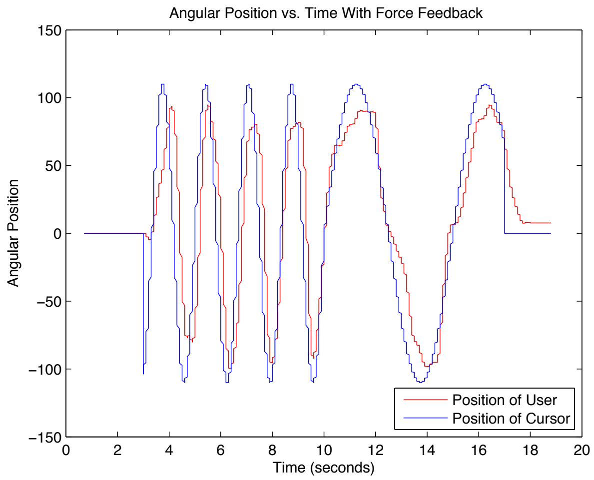
To conclude our study, we found that our model has some flaws, but was ultimately successful in displaying different conditions to the user. When asking subjects to compare our steering system to the one that they experience daily in their own cars they overwhelmingly said that while these events feel realistic, they do not match up directly with their experiences. We expected these sorts of results based on our limited resources and lack of visual display. The torque applied for the first three trials was found using a basic torque model and a trial and error approach. From our results, we found that the magnitude of the torque percentage for the slow driving simulation needs to be decreased, as does the magnitude of the vibration in the freeway driving simulation. Trials 4 and 5 showed some interesting results. It is clear from our analysis that our steering wheel can accurately display a basic driving course, but it is limited by the person's memory as there are no visuals. Trial 5 did not prove that our system is robust, as only 43 percent of the subjects benefited from force feedback, but an overwhelming amount of the testing population preferred it to purely visual feedback. We hypothesize that the lack of benefit comes from the fact that our testing was limited in sample size and our on screen graphics are not sufficient. Perhaps adding more randomization to the cursor path (it is solely oscillatory) coupled with better graphics and a larger sample size could change the significance of force feedback in our study. What we have learned however is that the majority of subjects appreciated having force feedback even if it was not realistic. This may prompt other researchers to not just look at the realism of their steering models, but to experiment with other models that either aid in the performance or comfort of driving as it is displayed to the driver.

VII. FUTURE WORK

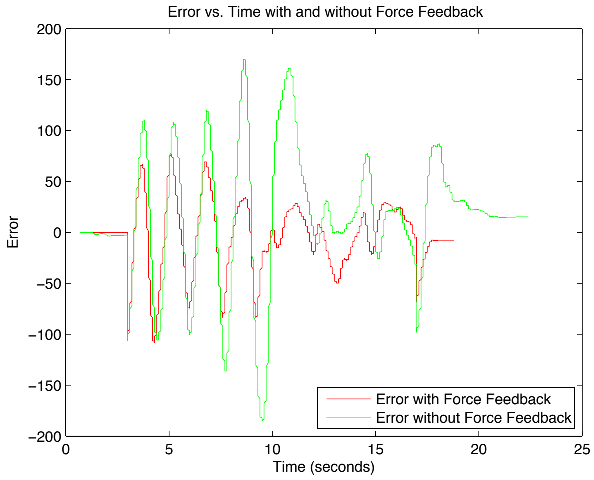
Because of limited time and resources, we feel that our model could be improved in many different facets. For one, we would like to utilize a more advanced model and take general suspension components into account. Once sufficient adjustments have been made to the model, we could possibly incorporate our system into a fixed base driving simulator such as in [4]. This would give us the ability to use visuals and inertial feedback currently missing from our simulation. However, a logical next step for our project would be to improve our on screen graphics for the fifth trial to at least employ different colors for each of the cursors as well as definitive boundaries for the edges of the driving surface. For the earlier Trials (1-3) we would like to incorporate velocity damping into our feedback model as well as have the wheel center itself to simulate the natural effect experienced when letting go of the steering wheel of a moving car.



(a) Angular Position of user without Force Feedback.

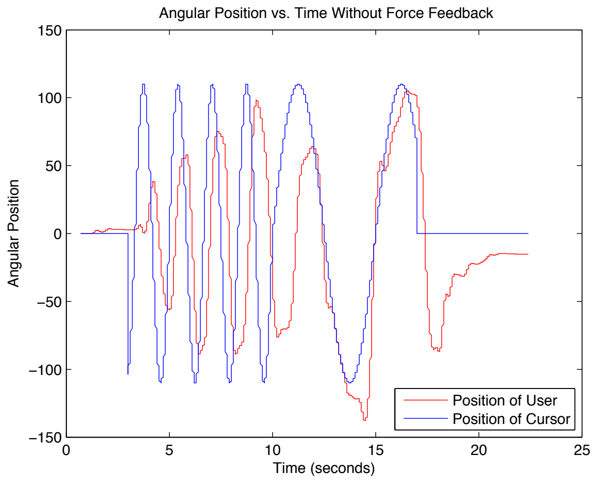


(b) Angular Position of user with Force Feedback.

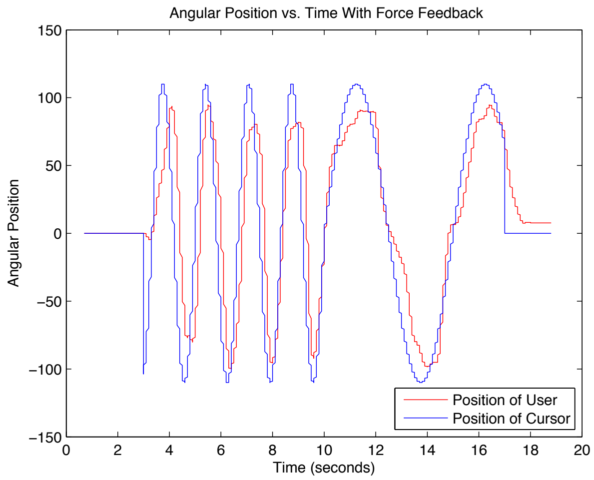


(c) Error Between with and without Force Feedback.

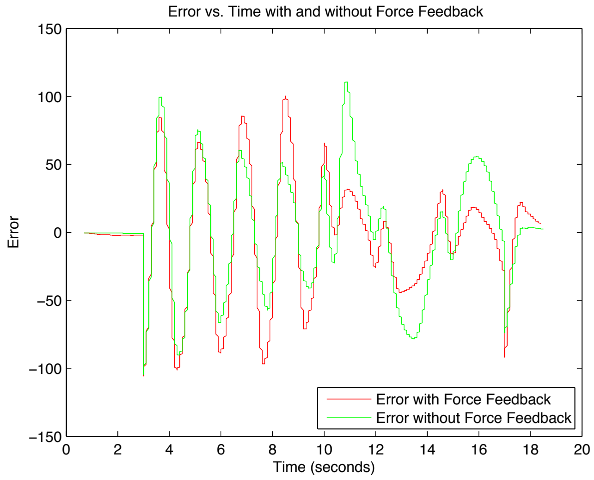
Fig. 4. This describes the angular position with and without force feedback for subject 9.



(a) Angular Position of user without Force Feedback.

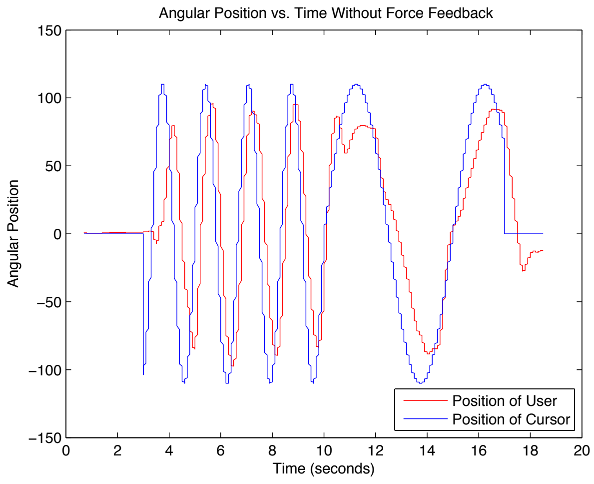


(b) Angular Position of user with Force Feedback.

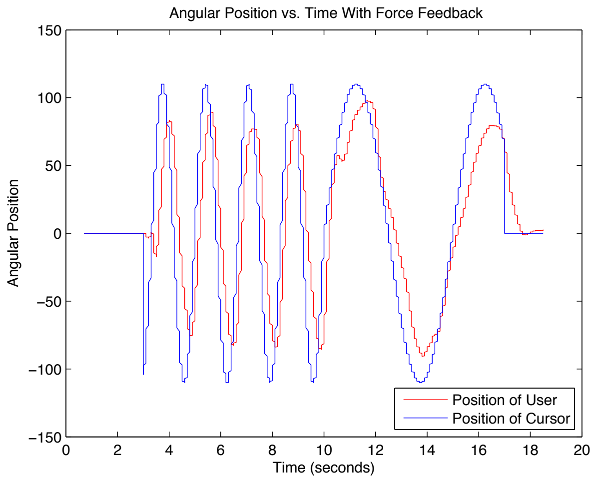


(c) Error Between with and without Force Feedback.

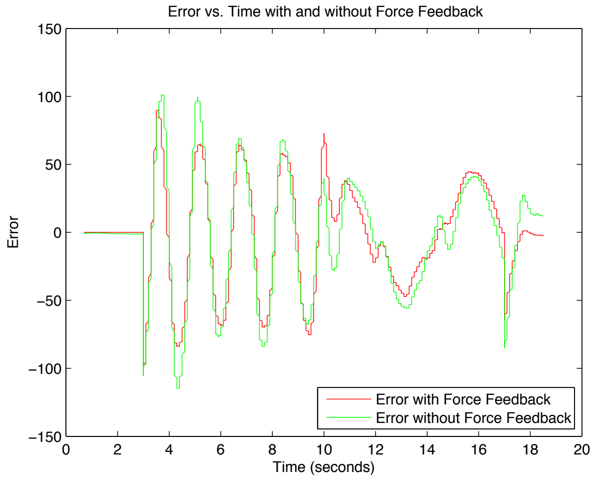
Fig. 5. This describes the angular position with and without force feedback for subject 10.



(a) Angular Position of user without Force Feedback.



(b) Angular Position of user with Force Feedback.



(c) Error Between with and without Force Feedback.

Fig. 6. This describes the angular position with and without force feedback for subject 11.

For data collection, we would like to do a full ANOVA study on our current data separating it into two distinct test groups. One aided by force feedback and the other purely visual feedback. We could then see the statistical significance between the two. At this time, we feel that we have a very basic haptic feedback steering system with a lot of potential to be furthered in software simulation.

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