DC Motor Damping: A Strategy to Increase Passive Stiffness of Haptic Devices

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Abstract. Physically dissipative damping can increase the range of passive stiffness that can be rendered by a haptic device. Unlike simulated damping it does not introduce noise into the haptic control system. A DC motor can generate such damping if it's terminals are shorted. We employ a configuration of the H-bridge which can cause this damping to impart stability to our haptic device. This results in an increase in passive wall stiffness of about 33.3% at a sampling rate of 100Hz and 16.6% at 1kHz over the performance of an undamped DC motor. We have also attempted to implement the system on the hybrid haptic control system [1], it was seen that a perceivable change in the performance of this system was not observed by the use of DC motor damping.

Keywords: Haptics, Instability, Passiveness, Continuous Time, Programmable logic devices (PLD).

1 Introduction

The impedance based control system is the most common control system to be employed for haptic devices. However impedance based devices tend to become non passive as the virtual wall stiffness increases. This is due to spatio-temporal quantization of the state variable of haptic control system which leads to an imbalance in the energy flow to and from the haptic device. The buildup of excess energy in the haptic device causes it to become non passive. If we can find a way to dissipate this energy in the haptic device, we can achieve a wider passive operating range for the haptic interaction.

The method presented in this paper deals with the addition of dissipative damping to the haptic control system. Damping is simulated in haptic control system by computing (within the host computer) the damping force. This damping is usually known as 'computer damping'. While this method simulates the damping force, it does not contribute to the stability of the haptic rendering. An enhancement in the stability due to damping can only occur if the damping mechanism is capable of dissipating energy. Since simulated damping is not capable of this it does not contribute to the stability of the haptic rendering.

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In fact due to the noise content in the velocity estimation computed damping often contributes negatively to the stability of the haptic device. This line of reasoning has been described in [2]. DC motor damping or 'electrical damping' achieved by shunting the terminals or dissipating the back e.m.f of the motor, is a simple and efficient means to create physically dissipative damping. This is in addition to the mechanical damping due to friction and inertia of the moving parts which is present in the haptic device. In our experiments it was seen that this electrical damping contributed positively to increase the range of virtual wall stiffness that could be rendered at a particular sampling frequency.

2 Previous Work

Literature on the stability of haptic devices has been mostly limited to the analysis and modification of digital haptic loops. Minsky et al.,[3] investigated the stability of Haptic interaction and derived a condition for the stability of the haptic device based on considerations of sampling rate of the controller. Abbot et al., [4] extended this criterion to include the effects of position quantization. Their treatment of the instability problem involved the coulomb friction present in the haptic device. Miller et al., [5] recognize that passive analog control laws need not necessarily translate to stable digital control laws and derive conditions for such an analog control law to be transformed into a stable digital one. Gillespie and Cutkosky [6] describe energy leaks caused due to the Zero Order Hold inherent in digitally sampled control systems and present control strategies to create the illusion of a passive system to the user. Colgate et al., [7] presented a theoretical analysis of the passivity of the stiff wall and in 2004, Miller et al., [8] provided a condition the haptic device must satisfy to exhibit passive behavior. Hannaford et al., [9] present a "Passivity Observer" and "Passivity Controller" method to track energy movements in haptic interactions with the user and to dissipate the excess energy if it tends to cause active behavior in the system. Lee and Lee [10] explore the use of a multi-rate controller to reduce the ZOH effect in haptic devices and present a mathematical analysis of the same. A more recent paper by Diolaiti et al., [11] accounts for inertia, viscous, and Coulomb friction of the device to the amplifier delay, sampling rate, encoder resolution, and controller stiffness. It also delineates areas of passive, locally stable, limit cycles and unstable behavior of the haptic device. The work on continuous time haptic devices are far and few in between, Kawai and Yoshikawa [12] describe a haptic interface device with an analog circuit which exerts continuous-time impedance within the sampling period of a conventional haptic loop. Though a continuous time circuit is used, it serves only to enhance the conventional digital loop. The continuous time loop is implemented using noise prone analog amplifiers and potentiometers. Niemeyer et al., [13] seek to exploit the electrical characteristics of a DC motor to render virtual surfaces and interface it to virtual environments by means of "wave variables" and analog circuits alone.

Kwon and Song [14] explore the addition of a mechanical damper to their haptic device. The authors report an improvement in the performance of their device. However their method makes use of a additional mechanical damper connected to the actuating DC motors, which is a disadvantage in some situations. Mehling et al., [15] make use of electrical damping that is inherently present in the DC motor. The authors design their circuitry assuming that the DC motor driver is a linear current amplifier. One of the problems the authors sought to overcome by their method is the simulation of free space. The authors seek to eliminate damping in free space simulation by employing a first order resistor capacitor filter. The method described in our paper presents a simpler method of DC motor damping employing H-bridges. Using our method the problem of damping in free space does not arise.

3 Our Method

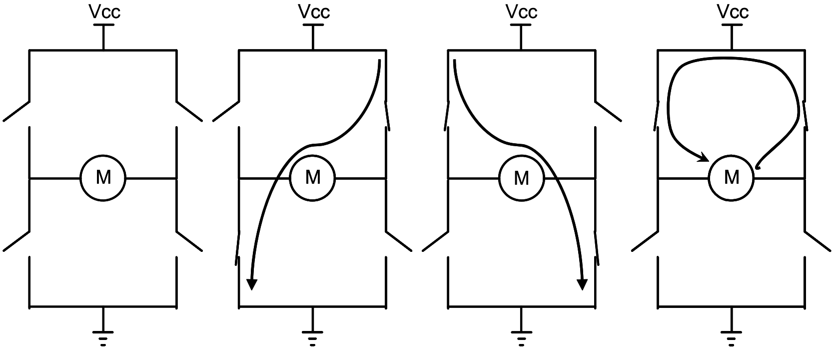
The haptic force law is described by the equation $F = k\Delta x + B_c v$ inside the virtual wall. The term $B_c v$ is called **computer damping**, which is the damping force calculated by the computer. In any control system the presence of a damping term should contribute stability of the system. This is because a damper can dissipate energy. This energy dissipation takes away most of the excess energy that cause limit cycles or instabilities. However damping calculated by a computer, such as $B_c v$ **cannot** contribute to the stability of the system. This is because damping which is computed and introduced into the system as part of a digitally implemented force law cannot dissipate energy. Therefore damping can contribute to stability only if it is implemented as a controlled **physically dissipative** process [2]. In this section we detail a method to maximize physical damping in haptic devices.

3.1 H-Bridge Configurations

We now describe the working of the H-bridge so as to illustrate a method of energy dissipation. An H-bridge can be operated in four different configurations as shown in figure 1.

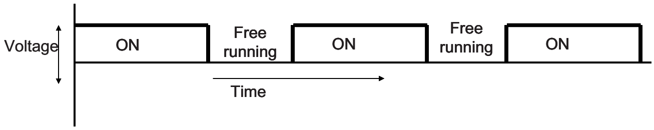
Figures 1(a) and 1(b),1(c) represent the normal OFF and ON states of the H-bridge. The arrows in the figure show the direction of currents through the DC motor. Figure 1(d) shows the damping configuration of the H-bridge. When the shaft of the motor is rotated by a human user, it causes a current to flow through the armature of the motor producing a damping force which opposes the force exerted by the user. The energy input into the system by the human user is now dissipated in the armature resistance by the current produced. We exploit this property of the H-bridge to impart stability to the haptic control system.

A Pulse Width Modulated signal is used to actuate the H-bridge and drive the DC motor connected to the bridge. This actuation brings the H-bridge into two configurations: the ‘ON’ configuration and the ‘free running’ configuration. This is shown in figure 2(a). We can use an alternate configuration consisting of ‘ON’ and ‘Damping’ to introduce additional dissipative damping into the system. This will make the haptic loop more stable and thus capable of rendering stiffer walls.

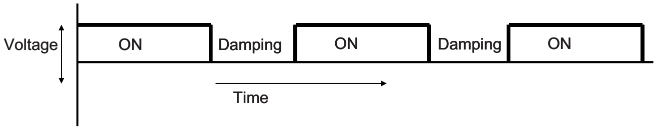


(a) Free Running (b) Clockwise (c) Anticlockwise (d) Damping

Fig. 1. Configurations of an H-Bridge



(a) Typical PWM



(b) Modified PWM

Fig. 2. PWM Strategies

4 Haptic Device Construction

The haptic device consists of a Maxon Re24MAX - 222051 motor coupled to an 1024 cpr encoder. The torque magnification in this device is 1:1. A simplified schematic of this device is shown in figure 3 and an image in figure 4. An Altera Cyclone 2 FPGA was used to configure the electronics for this device as described in Hari Vasudevan et al. [1]. All circuitry for this device involved 11 bit numbers. The PWM resolution was 11 bits and has a frequency of 24.41kHz. The chip LMD18200 is used as the H-bridge driver for the motor, this chip contains provisions to configure the H-Bridge in any of the configurations shown in figure 1. We have implemented two control loops on this haptic device, the conventional impedance haptic control loop and the hybrid haptic control loop as described in Hari Vasudevan et al. [1]. Figure 5 shows the structure of both these control loops. We have however maintained $B_c = 0$. This ensures that the computer damping will not effect the performance of the system. In the figure the term ‘E’ represents the ON, OFF nonlinearity of the virtual wall.

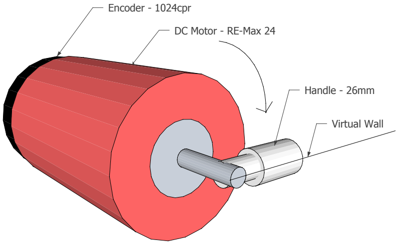


Fig. 3. Simplified mechanical setup of the haptic device

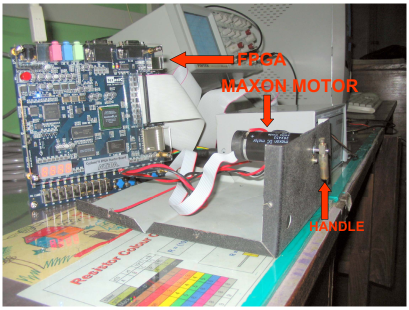


Fig. 4. A picture of the haptic device

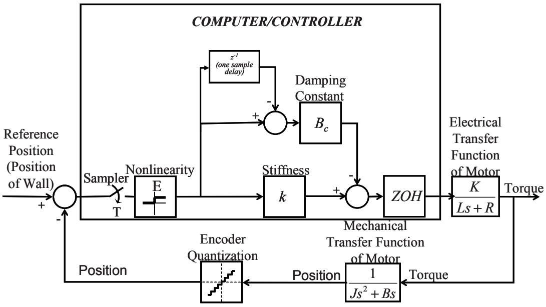
5 Experiment

As the human user manipulates the haptic device, the stiffness which causes the onset of non passive behavior in the haptic device is noted. The user is allowed to use any strategy to find the onset of non passive behavior. The virtual wall is positioned at 0° to the horizontal. The same procedure is followed for haptic loops with and without DC motor damping. The testing is done over a range of sampling frequencies from 100Hz to 1kHz in steps of 100Hz. In addition to this we also test the haptic device when it is configured to implement the hybrid haptic control system [1]. In this control system the spring reaction force is calculated on an FPGA. The computation block in the FPGA is designed using asynchronous combination logic system, which means that the force calculation is almost continuous time (given the gate delays are in nano seconds). This enables it to render very stiff virtual walls.

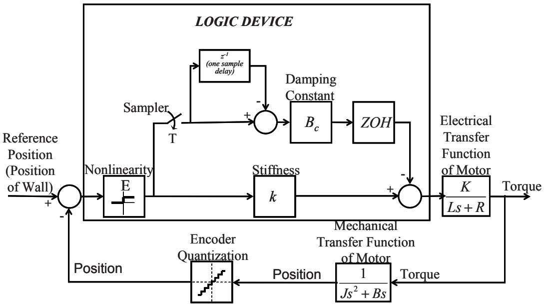
6 Results

The tabular column 1 shows the results of testing the haptic device at various sampling frequencies with and without the DC motor damping.

Figure 6 shows a comparison of the performance of the maximum achievable passive stiffness over a range of sampling frequencies from 100Hz to 1kHz. The



(a) Traditional Haptic Loop



(b) Hybrid Haptic Loop

Fig. 5. Haptic Loops

dotted line represents the passive stiffness achieved with motor damping. It is clearly seen that a higher passive stiffness can be achieved using this method.

Figure 7 shows the percentage improvement of the maximum passive stiffness over the a range of sampling frequencies. This graph however shows a decreasing trend, as seen in the best fit line. Prior to the experiment, it was our expectation that this graph will show a smooth decreasing trend. However the data shows a few peaks in this graph, the reason for this is under investigation. The decreasing percentage improvement, highlights a more important issue. At low sampling frequencies where the system shows non passive behavior at low wall stiffness, it is easy for a human user to see the improvement in performance with the DC motor damping. However at higher sampling frequencies close to 1kHz, even though the improvement in performance is greater in absolute terms, the perception of the improvement is not significant.

After testing the conventional haptic control system, we incorporated DC Motor damping into the hybrid haptic control system[1]. It was seen that the hybrid system **did not** show any improvement in performance even with the DC motor damping. The hybrid system was seen to show non passiveness at $k = 4.589kNm^{-1}$ regardless of whether DC motor damping was present or not.

Table 1. Effect of DC Motor damping

Sampling Frequency	**k(Nm^{-1}), without motor damping**	**k(Nm^{-1}), with motor damping**
1000	*764.88*	*892.36*
900	*733.01*	*860.49*
800	*637.40*	*764.88*
700	*605.53*	*733.01*
600	*509.92*	*573.66*
500	*414.31*	*478.05*
400	*318.70*	*382.44*
300	*223.09*	*286.83*
200	*159.35*	*191.22*
100	*95.61*	*127.48*

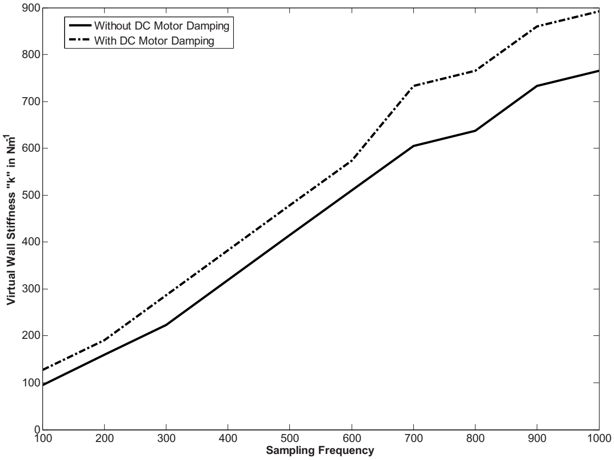


Fig. 6. Effect of DC Motor Damping

A possible explanation for this is as follows. Traditional haptic control systems are only able to render virtual walls of very low stiffness. Therefore the PWM duty cycle corresponding to the first unstable controller gain is low. Let us assume that figure 8(a) represents one such PWM. The green region is the dissipative region that uses the DC motor damping. Haptic control systems such as the hybrid haptic control system are able to render virtual walls that have a much higher virtual wall stiffness. Higher stiffness implies that the onset non-passive behavior only occurs at a higher PWM duty cycle. This is shown in figure 8(b)

Comparing the PWMs in figures 8(a) and 8(a) we can see that amount of time for DC motor damping is lower in the second figure. This implies that a lower amount of excess energy can be dissipated. Because of this reason there is

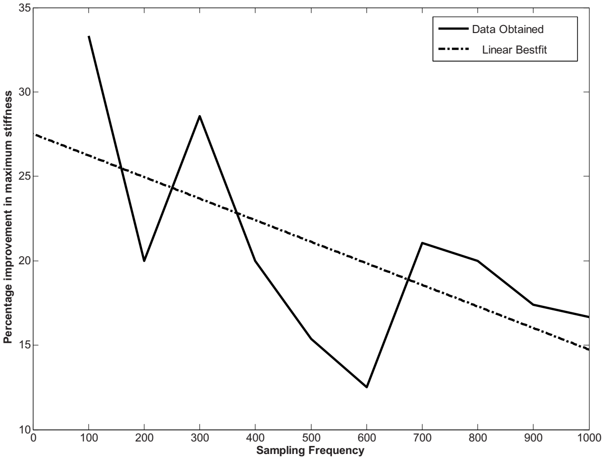
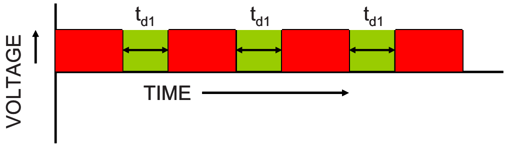
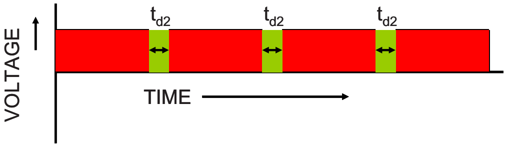


Fig. 7. Comparison of Relative Performance Increase



(a) Maximum PWM at Low Virtual Wall Stiffness



(b) Maximum PWM at High Virtual Wall Stiffness

Fig. 8. PWM behavior

no improvement in the hybrid haptic control system performance either with or without DC motor Damping.

7 Discussion

In our earlier work [1] we have shown that our hybrid haptic loop has better performance than conventional haptic loops. This is because we can execute the haptic loop in continuous time in our hybrid haptic system as opposed to sampled implementations in conventional haptic loops. However we do not find an improvement in the performance of this hybrid system if we employ DC motor damping. A possible reason for this can be that at the on-set of non-passiveness the hybrid system operates at a higher PWM duty cycle. Consequently there is less time available to dissipate excess energy. Whereas in the conventional haptic loop the onset of non-passive behavior occurs at lower PWM duty cycles, hence more time is available to dissipate excess energy. This is further supported by the fact that as we increase the sampling frequency the percentage improvement in the maximum passive stiffness decreases as shown in figure 7.

8 Conclusion

The DC motor damping method presented in this paper presents a method to improve the performance of conventional haptic control systems. Using this technique the percentage improvement in performance becomes lower as the sampling frequency increases. This system is suitable in situations where a high sampling rate cannot be maintained due to computational constrains. However it is seen that a significant increase in performance is not obtained when the same technique is employed on the hybrid haptic control system.

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