Producing Rigid Contacts in Cable-Driven Haptic Interfaces Using Impact Generating Reels

Greg Billette and Clément Gosselin

Abstract—This paper presents a design for a cable reel that allows a cable-driven haptic interface to produce rigid impacts with virtual objects in a virtual reality setting. The haptic interface studied in this article has three degrees of freedom (3 DOF) and acts as a sword-fighting simulator. In order to obtain sharp impacts with this interface, an impact generating reel is proposed to transmit forces across the cables to a user holding the end-effector (sword). A prototype is presented in order to demonstrate the concept. As a method of quantifying the credibility of these impacts, an accelerometer was mounted on the end-effector, where the cables are attached in order to measure the vibrations caused by these impacts. These vibrations are compared with the vibrations caused by an impact with a rigid material such as steel in order to classify the stiffness of the impacts generated by the mechanism.

I. INTRODUCTION

Cable-driven mechanisms have been used in several haptic devices. In [1] Lindemann and Tesar introduced the Texas 9-string, a 6-DOF cable-driven haptic device. Later, a 7-DOF cable-driven haptic device used for grasping virtual objects was proposed in [2]. These two interfaces are only a sample of the vast array of cable-driven haptic interfaces described in the literature. Other examples are the "WireMan" [3] and the Three-Cable Haptic Interface (Williams et al., 2006) [4]. The latter two interfaces are based on three cable reels mounted in a triangular pattern.

The relatively large workspace of cable-driven mechanisms is an indisputable asset for most applications, including haptics. They are less costly than parallel mechanisms with rigid members, they are usually of simple design and are easily reconfigurable by changing the reel positions. These reels are usually located on a stationary base which keeps the end-effector free and adds greatly to the overall simplicity of the mechanisms.

Another important characteristic of cable-driven mechanisms is their low inertia, which is a clear advantage for haptic applications. Indeed, low-inertia mechanisms lead to simpler inertia compensation and hence to better realism. The low inertia of cable mechanisms is due to the use of thin wires or cables instead of rigid members. However there are disadvantages to this last feature. Cables, as opposed to rigid members, can only pull and they are more flexible.

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) as well as by the Canada Research Chairs program. Greg Billette is a graduate student currently working on obtaining a M.Sc. degree at Université Laval in Québec City, QC, Canada gregoire.billette.1@ulaval.ca

Clément Gosselin is a Professor and holds a Canada Research Chair in the Department of Mechanical Engineering at Université Laval in Québec City, QC, Canada gosselin@gmc.ulaval.ca

This paper presents an impact generating reel that was developed in order to simulate sword-fighting impacts with a cable-driven mechanism. This device has all the advantages that other cable-driven mechanisms have —most of which have been already mentioned— while still being able to produce rigid contacts, a feat that is usually hard to accomplish using cable-driven mechanisms. It does however have the disadvantage of requiring an extra actuator for every cable reel as well as the usual disadvantages associated with cable mechanisms such as limited position accuracy and the possibility of cable-user interferences. The overall goal is to produce a haptic feedback that simulates the impact of the end-effector with a rigid virtual object. Various experiments were performed on a prototype in order to quantify the credibility of the impacts generated by the mechanism by analyzing the vibration response at the time of impact. The rest of this paper is organized as follows. First, the modelling of impacts will be addressed. Then, the mechanism designed to simulate impacts will be described. Finally, experimental results will be shown and analyzed and conclusions will be drawn.

II. IMPACT MODELLING

Producing the haptic feeling of a very sharp contact with a virtual object is a challenging task. The manner in which the forces are applied to the user is most important. It has been shown in [5] that different materials produce different vibrations upon impact, thus giving a unique force feedback for each material. These transient vibrations are sensed by special mecanoreceptors within the human skin that are sensitive to transient vibrations [6]. Thus humans can distinguish between various materials upon contact. The mathematical model used in [7] for the above mentioned transient vibrations is a exponentially decaying sine wave, namely:

\[ f(t) = e^{-\frac{t}{\tau}} \sin(2\pi ft) \] (1)

where \( \beta \) is the amplitude, \( f \) is the frequency and \( \frac{1}{\tau} \) is the time constant of decay. Each material has its own values for \( f \) and \( \frac{1}{\tau} \) while \( \beta \) is a function of the mass of the virtual object, its velocity as well as its natural frequency and time constant. In a sense, each material can be simulated if its characteristic transient vibration pattern is reproduced. As a general rule of thumb it can be said that the stiffer materials, such as steel, have a higher frequency \( f \) and a smaller time constant \( \tau \). By contrast, softer materials such as wood have a lower frequency and a larger time constant. The material that will be simulated for this sword-fighting simulator is steel.
and the parameters found by Okamura and Dennerlein [5] for this material are: $\frac{1}{\mu} = 0.32$ ms and $f = 1682$ Hz. These values will therefore be used as a benchmark for analyzing the stiffness of the generated impacts.

III. DESCRIPTION OF THE MECHANISM

In order for the transient vibrations to be generated, an impact generating reel has been designed. As in most cable-driven mechanisms, the reels are mounted on the base as opposed to on the end-effector. This implies that the impacts are generated at the base and must therefore be transmitted across each cable. Hence, the compliance of the cables will act as a filter and the impacts that are generated at the base will only be partially conveyed to the user holding the end-effector. In practice, this means that the vibrations at the end-effector are less pronounced. The amplitudes of vibrations are attenuated, the frequencies are diminished and the vibrations take more time to decay. As mentioned previously, in order to produce a credible contact, the frequency needed would have be close to 1682 Hz.

As can be expected, a frequency of 1682 Hz is much higher than what can be generated in practice with the mechanism. However, Westling and Johanson found that the mechanoreceptors in the human skin are only sensitive to vibrations in the range of 50–500Hz [6]. Toma and Nakajima further add that the sensitivity of these receptors increases as the frequencies reach 160Hz and are at peak sensitivity at around 250Hz [8]. This would seem to suggest that in order to produce rigid contacts, it would not be necessary to produce vibrations higher than 500Hz because the higher vibration frequencies will not be perceived by the user.

A. Impact generating reel

The approach that was used to tackle the problem of generating contacts, or impacts, is to use clutches. Indeed, state-of-the-art clutches are able to transmit torque with the smallest possible impacts during actuation in order to protect two pieces of machinery connected by the clutch. Here, the aim is rather to produce a clutch that transmits torque with as much impact as possible. A similar method for producing impacts was first suggested in [9]. Said device was capable of producing impulses on a 1 DOF haptic display in the form of a handle by means of a change in momentum of a spinning momentum wheel. In this case however, the principle has been applied for the first time to a cable-driven mechanism and the impulse has also been augmented by producing an actual impact between two metal parts. These two parts, called the striker and the block, collide with each other to produce an impulse that will travel across the cable to reach the end-effector. Figure 1 shows the impact mechanism that was designed and figure 2 shows a schematic view of the mechanism. In each figure, two servo motors are shown. The first motor is attached to the reel and its function is to keep the tension in the cable. The second motor is the actuator that produces the impacts. This motor, which can be combined with an inertia wheel, rotates at all times in preparation for future impacts. The two motors are separated mechanically by means of two clutches. These clutches can be seen as a single clutch whose purpose is to separate the reel motor from the impact motor and manage the relative angular displacement between the striker and the block.

Whenever the mechanism is prepared for an impact, its configuration is as shown in figure 3. In this position, the reel clutch is closed and keeps an angular displacement between the striker and the block and the impact clutch is open to isolate the impact motor from the reel. When an impact is ordered, the status of the two clutches interchanges. The impact clutch closes, which connects the impact motor to the striker. At the same time the reel clutch opens, allowing the striker and the block to move independently. The striker and block will both move relatively to one another over an angular displacement slightly smaller than $2\pi$ rad in order to collide and consequently, produce an impact on the cable reel. During this travel, the two clutches will have ample

---

1Figure 2 shows the block and striker on opposite sides of the reel clutch. This is for illustration purposes only. In reality, the design of the clutch is such that the input shaft coming from the reel can be fixed on the input side of the clutch and then traverse the clutch to finally be fastened to the block located on the output side of the clutch. In effect, this allows the block and the striker to be positioned on the same side of the clutch, namely, the output side. It is very important for these two components to be on the same side because the clutch is electromagnetically actuated and as a result, two electrical wires need to be able to reach it.
time to change configuration. Because these are friction clutches, they can slide a little at first when closing. With this mechanism, the sliding occurs before an impact when the impact motor still cannot produce any forces against the reel. In other words the sliding should occur when the user cannot feel it. The mechanism can be seen in action in the accompanying video.

B. Architecture of the Cable-Driven Parallel Mechanism

The cable-driven parallel mechanism employed as a sword-fighting simulator has three impact generating reels. As mentioned previously and as shown in figure 4, these reels are arranged in a triangular pattern on a plane perpendicular to the ground. All three cable ends are attached to the tip of the end-effector (sword) and the handle is held by the user. Consequently, this mechanism has 3 DOFs, used for producing forces at the tip of the sword. It is essentially the most basic cable mechanism architecture capable of producing forces in a 3-D environment. It is also pointed out that the end-effector is not fully constrained (4 cables would be required) and that there are some limitations on the direction in which the forces can be applied on the sword. These limitations are potentially acceptable in a sword-fighting simulator. The coordinates of the three reels (in metres) are \( P_1 = [-1.01, 0.97, 0] \), \( P_2 = [0, 2.34, 0] \) and \( P_3 = [0.93, 0.97, 0] \). The direct kinematic problem (DKP) for this mechanism is readily solved and yields the position of the tip of the end-effector for given values of the three cable lengths. However, the orientation of the end-effector cannot be determined based on the cable lengths. Therefore, an additional sensor is used to obtain this information in order to be able to draw a graphical representation of the sword in a virtual reality environment.

IV. EXPERIMENTAL RESULTS

Various experiments were performed in order to characterize the effectiveness of the impact reels in simulating rigid contacts. In these experiments, an accelerometer is mounted at the tip of the end-effector, where the cables meet, and the transient vibration response during a contact is measured. The measured vibrations are therefore different from the vibrations that the user would perceive while holding the handle since these vibrations are greatly influenced by the sword’s actual stiffness. The motors are controlled at a servo rate of 500Hz and the acquisition frequency is 10kHz, yielding a Nyquist frequency of \( f_N=5000\text{Hz} \). The maximum frequency of vibration that could possibly occur is 1682Hz, and hence the risk of aliasing is low. The frequency of vibration \( f \) and the rate of decay \( \frac{1}{t} \) was observed and compared with the empirical values found in [5]. The value of the amplitude \( \beta \) was ignored because it is mostly a function of the impact motor and the striker’s inertia as well as their speed just before impact.

A. Results for 1-DOF system

The first part of the testing consisted in obtaining the vibration response of one impact generating reel. For this test, the impact motor and its corresponding clutch were replaced with an electromagnetic friction brake. The cable was extended at a relatively low speed and when it reached a certain length, the brake closed and the reel clutch opened to allow the striker and the block to move independently and collide. This experiment was meant to simulate a collision between a sword and a fixed rigid surface, e.g., a wall. The
results are shown in figures 6 and 7 for impacts generated at distances of 0.5m and 1m, respectively. The average frequency measured at a distance of 0.5m was 181.01Hz and the average time constant of decay was \( \frac{1}{\mu} = 13.2 \text{ms} \).
At 1m the average frequency was 162.26Hz and the time constant was \( \frac{1}{\mu} = 41.30 \text{ms} \). A quick glance at the measured time constants reveals that in both cases the values obtained were much higher than the targeted time constant of steel \( \mu = 0.32 \text{ms} \) and it was also noted that the values obtained varied greatly from one test to the next. As for the frequency it is apparent that it decreases as the length of cable increases, which was expected since the natural frequency of a cable changes with its length. For this application, the maximum cable length will most likely be shorter than 2m, therefore the vibration frequency should stay in the range of 100–200Hz. It is interesting to note that although — as predicted — the vibration frequency of steel was not attained \( f_{steel} = 1682 \text{Hz} \), the frequency obtained is however slightly higher than the vibration frequency of acrylic \( f_{acrylic} = 128 \text{Hz} \) [5]. It is also interesting to note that it is in this frequency range that the mechanoreceptors in the human skin start to become most sensitive to vibrations [8]. On that account, by observation of the measured frequencies alone it can be said that although it was not possible to simulate an impact with steel, it was possible to produce an impact with what can be considered a rigid material.

B. Results for 2-DOF and 3-DOF systems

For these experiments, the mechanism is as shown in figures 1 and 2. The impact clutch and impact motor were put back in place and the operating principle is as explained in section III-A. Obviously, the production of three dimensional impacts requires all three impact reels. As explained earlier, the three reels are arranged in a triangular pattern on a plane. The impact motors are controlled using the coordinates of the direction of the desired impact. Hence, the system will adjust the speed of reels consequently so as to produce an impact in the desired direction. The characteristics that are observed in these trials are the impact frequencies and rate of decay. Another important characteristic to be observed in the experiments is the synchronization of the impact reels. Indeed, in order to have a credible impact, all impact reels have to produce their impacts at the same time in order to avoid a "machine-gun style" impact.

1) 2-DOF Results: After testing the reels individually, two reels were used to produce a 2-DOF arrangement. In order to accomplish this, the end-effector was placed at \( x = [0, 0.97, 0] \) which is located on the centre line of the isosceles triangle shaped reel configuration. In the first test, an impact with a velocity of \(-2 \frac{\mu}{s}\) in the \( x \) direction and \(2 \frac{\mu}{s}\) in the \( y \) direction was performed. Because of the limited inertia of the impact motor and striker of the reels, a rather small angular momentum is produced at this speed. Due to the position of the effector, two reels were required to produce the required impact. The vibration response is shown in figure 8. A fast-Fourier transform was performed on this signal in order to analyze the frequencies involved and the results can be seen in figure 12. The second test involved a more considerable speed of \(-4 \frac{\mu}{s}\) in the \( x \) direction and \(4 \frac{\mu}{s}\) in the \( y \) direction. The results are shown in figures 9 and 13.

In both cases the vibrations obtained were in the range of 140–160Hz with a peak at around 156Hz. However, at reduced impact speeds there were also vibrations in the range of 30–50 Hz. In both cases, the rate of decay was estimated in the range of 11ms to 16ms. As for the impact synchronization, it was observed that both impact reels generated impacts roughly at the same time. Obviously this statement is not very precise but synchronization was the most difficult characteristic to determine. The method used to estimate whether there was one impact or two distinctive impacts consisted in observing the shape of the vibration response curve. Indeed, when the transient vibration curve does not have the characteristic shape of an exponentially decaying envelope — such as in figures 8 and 9 for instance — it can be conjectured that there is most likely a slight delay between the impacts. Such variations occurred in all the tests that were performed but it must be noted that two completely distinctive impacts were never observed in these experiments.
Fig. 8: Vibration response during a low-speed 2D impact.

Fig. 9: Vibration response during a relatively high-speed 2D impact.

Fig. 10: Vibration response during a relatively high-speed 3D impact.

Fig. 11: Vibration response during a hard 3D impact.

Fig. 12: Vibration frequencies during a modest 2D impact.

Fig. 13: Vibration frequencies during a relatively high-speed 2D impact.

Fig. 14: Vibration frequencies during a relatively high-speed 3D impact.

Fig. 15: Vibration frequencies during a hard 3D impact.
2) **3 DOF Results**: Experiments with three cables were then conducted. For these experiments, the end-effector was close to \( x = [0, 0.97, 0.5] \) which is still located on the centre line of the isosceles triangle shaped configuration of the reels with an offset of 0.5m in the \( z \) direction. The speed of impact was also increased and the direction of the impact was the \( z \) direction. This direction and end-effector position was chosen because it required an equal amount of work from all three impact reels to accomplish the required impacts. The first test involved an impact speed of \(-6.32\) and the results are shown in figures 10 and 14. The second test involved an impact speed of \(-8.2\) and the results are shown in figures 11 and 15.

First, it can be observed that vibrations in the frequency range of 140–160Hz were always measured. Additionally, vibrations above 300Hz are also recorded during fast impacts (figure 15). The frequencies observed varied greatly between 300 and 500Hz. Even though these results were rather inconsistent, they are also encouraging because they suggest that the target vibration frequency of 500Hz is perhaps attainable, albeit only when the impact is hard enough. It was also interesting to notice that the time constant of decay \( \frac{1}{\mu} \) varied between 11.6ms and 20ms which is still too high compared to steel. As for the the impact synchronization, it can be seen in figures 10 and 11 that the signals did appear to be in an exponentially decaying envelope. This was generally the case for all experiment attempts, which suggests that the synchronization was better than in the 2-DOF case. A possible reason for this is that the control of the impact motors is more precise at higher speed, where friction has less importance and where the optical encoders produce less noise and therefore allow a more precise synchronization.

**V. CONCLUSIONS AND FUTURE WORK**

**A. Conclusions**

The comparison of the impact vibrations measured experimentally and the typical vibrations that would be obtained with steel leads to the conclusion that, although the benchmark was not reached, it was possible to achieve stiff impacts. Vibration amplitudes in the range of 160Hz were recorded in all experiments and it has been shown that when the impact speed was increased it was possible to achieve vibration amplitudes in a range close to the target of 500Hz. It was noted that vibration frequencies in the range of 160Hz resemble those that would be measured during an impact involving acrylic (\( f_{\text{acrylic}} = 128\)Hz). Although these vibration frequencies suggest that the stiffness of these impacts is fairly high, the rate of decay of the impact vibrations however is rather long and mitigates the sensation of stiffness. Just how much this longer rate of decay affects the sensation of stiffness is not well known. For comparison purposes, it is noted that the typical rate of decay of vibrations from the simulator are normally between 11.6ms and 20ms while the typical rates of decay for real collisions are: steel (\( \frac{1}{\mu_\text{steel}} = 0.32\)ms), acrylic (\( \frac{1}{\mu_\text{acrylic}} = 2.13\)ms) and wood (\( \frac{1}{\mu_\text{wood}} = 6.48\)ms) [5]. The tests performed in this work show that although the impacts do not feel as if they were impacts with steel — which was the original objective — they feel like impacts with a material that has a stiffness somewhat close to acrylic. These results are very encouraging considering the typical low stiffness of cable-driven mechanisms. It is therefore conceivable to use cable-driven mechanisms for the purpose of producing rigid impacts.

**B. Future Work**

Future work will include the integration of the cable-driven haptic device in a sword fighting simulator. A virtual environment will be built and in this environment the movements of the user’s sword will be represented graphically. The goal is to enable the user to use his sword for the purpose of hitting various objects, some that are moving and some that are immobile. The working principle of the impact generating reels necessitates an anticipation of the momentum of the virtual object. Since a virtual object’s movement can be described as a combination of a translational movement of its centre of mass and a rotational movement, the velocity at the point of impact can vary greatly depending on the position of this point. As a result, one of the objectives is to develop an algorithm (or implement an existing algorithm) that anticipates the point of impact on the virtual object and on the user’s sword in order to simulate impacts that are as realistic as possible.

**REFERENCES**


