Characterising a Novel Interface for Event-Based Haptic Grasping

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Abstract— This paper investigates the capacity of a light-weight haptic grasping interface to convey event-based high-frequency transient forces within a virtual environment. The addition of vibrations based on contact with real-world objects over traditional position-based feedback has shown to significantly enhance the feel of hard surfaces. We describe the design of our prototype grasping system, and experimentally demonstrate the utility of this type of haptic interface. The frequency response of the device was obtained to demonstrate its ability to display high-frequency signals which meet realistic contact requirements. To determine the ability of the proposed device to display the required high frequency vibrations, empirical waveforms were measured by tapping on real surfaces with a high-bandwidth instrumented version of the two finger grasping interface. Empirical models, based on decaying sinusoids were fit to the measured acceleration waveforms to understand the required bandwidth of the proposed device for the particular material properties.

I. INTRODUCTION

Haptics technology provides the means to recreate the sense of touch to a human operator through a virtual environment in a physically realistic way. It aims to provide a transparent interface, which connects to the user through an interface point that is attached to a robotic arm. This arm translates the user’s motions from the real world into the virtual environment and attempts to provide reactive forces to the user’s hand when they have contacted a virtual or teleoperated object. It is this bi-directional channel that distinguishes a haptic device from any other machine interface. The ability to read the user’s motion has demonstrated to be relatively easy, however, the facility to generate the required reactive forces is much more difficult to achieve. In particular, the main function of the haptic interface is not only to generate a force to the user, but to accurately represent objects and their associated physical properties which distinguish them from others. Therefore an ideal device is transparent to the user and nominally has no mass and dissipation, consequently representing a perfect force and position transducer within the corresponding channel direction. With this in mind, this work is specifically concerned with actuated impedance-type (isotonic) devices, which are designed to read position and reflect force to the user [1].

The presented haptic grasping interface is designed with these principals in mind and serves to enhance the ability to accurately represent physical object properties through its novel multi-point design.

Identifying the performance indices of a haptic interface has been approached by several researchers, who have endeavored to characterise the dynamic response of a haptic interface. In characterising this performance, there are several essential criteria that must be considered and are inherent in any mechanical robotic system. These are dynamic and force bandwidth, transparency and perceived mass, and maximum stiffness [1]–[3]. It is the limitation in these indices that induce the inability to provide a realistically stiff representation of contact with hard virtual objects.

When interacting with an environment, the human sense of touch not only reacts to the kinesthetic sensors in the muscles as a result of low-frequency hand motions, but also to the high-frequency vibrations encountered from the contact of hard surfaces [4]. In many tasks we use our fingers to feel for loose or vibrating components which produce a rattle and can thus provide an indication of a defective part. These functions which involve the collision of hard surfaces are accompanied by rich vibrations, that result from the physical properties of the colliding and receiving object that shape the produced high-frequency transient [5], [21]. The act of tapping on a wooden table with a stylus is demonstrated in [5], [21] to produce accelerations with frequencies up to several hundred hertz. This activity stimulates the pacinian corpuscles in the hand and fingertips [6] and actively produces a better understanding of the material’s properties than would be experienced through slowly pressing onto the table’s surface [7]. This single-point interaction with the virtual object should resemble all the physical characteristics of a stylus contacting a hard surface, only current rendering techniques are unable to deliver this realism [8]–[10]. Constraining the user from interacting freely and naturally with the virtual environment is a limitation that is also associated with the use of single-point haptic interfaces. The ability to extract the desired information from a virtual object is a distinct advantage of haptic technology; however the use of single point interaction devices has constrained the natural process to reveal particular object properties [11].

This work explores the use of a novel light-weight grasping interface and its ability to convey vibratory information to enhance the realism of hard surface contact within a haptic grasping perspective. The device provides bi-directional forces to each fingertip, as well as a rotational force to the wrist of the operator, and shows to provide advantages over current approaches [12]–[16]. The nature of this device to deliver bi-directional forces to each finger is of particular importance. The mechanoreceptor nerve endings hold properties which imply that these receptors do not have a localised response, consequently high frequency vibrations
on the skin produced by a single display on each finger will suffice [17]. Our aim here is to present the effectiveness of this type of device and to assess its potential to represent high-frequency event-based transients to the thumb and index finger of a user’s hand throughout grasping conditions. We first present the design of our prototype device, which is based on a cable drive, light-weight ABS plastic construction, and then demonstrate the frequency response of the system. Having determined the device’s frequency capabilities, a replica high-bandwidth experimental system is developed to record several material contact vibrations. Acceleration sensors in the finger tips produce impact vibration measurements during grasping tasks. Modeling these transients for the selected materials provides an understanding of the necessary parameters to replicate them with the proposed interface. We next provide a characterisation of the prototype device and its potential to represent high-frequency grasp contact vibrations.

II. System Design and Operation

The proposed haptic gripper, shown in Figure 1, attaches to a 6 DOF commercial haptic interface. The gripper interfaces to a user through their thumb and index finger of either hand. The device is cable driven, and has its actuators placed remotely, which eliminates the extra weight that the user must sustain during operation, thus reducing fatigue and simplifying the design. The forces displayed to the users fingers are bi-directional, serving to provide internal and external component forces to each finger and also a rotational force to the operator’s wrist. Each finger attachment arm is connected to a pulley which rotates in the direction of the cable motion, as shown in Figure 1. A single cable is attached to each pulley so that transmission backlash is minimized and the dynamic range and mechanical bandwidth of the system is improved. The cables are routed through sheathes which are fixed to the main body of the gripper and extend along the direction of the cable motion indicated in the figure, through to the force generation system. The added benefits of this design consequently produce a light weight device which weighs 104g, and is focused on transparency and extended usability.

To produce the cable motion, and rotate each pulley on the grasping interface, the force generation device shown in Figure 2 was developed. The device works on the same principles as standard cable and pulley arrangements implemented in current commercial haptic interfaces. This is shown in Figure 2 by the actuator and main pulley assembly. With rotation of the main pulleys by way of actuating the motors, the attached cables which feed to the gripper provide motion to each pulley on the haptic gripper as shown in the figure. The cables and sheathes, which are routed from the gripper’s pulleys and main body respectively, are fixed to the main body of this system and also to each force generation pulley in the direction of the cable motion. As the main system pulleys rotate with respect to the actuators, they serve to drive the cable medium which is attached to them and are used to rotate each pulley on the gripper, thus producing the bi-directional forces to the users’ thumb and index finger. Utilising brushed DC Maxon motors, and placing them remotely, the force generation system is capable of delivering a maximum continuous force of 4.48N per finger, which makes it favourable to various applications which require substantial grasping forces.

Fig. 1: The haptic grasping interface

Fig. 2: The force generation system

III. Structural Response of the Haptic Grasping Interface

Characterising the high-frequency dynamics of a haptic interface must account for the several important criteria mentioned earlier. As haptic interfaces rely on this bi-directional channel, discrepancies occur when trying to understand where the measurement, which dictates these
performance criteria should come from. As an example, the measurement of inertia can be made as seen from the actuator, or the device itself [1]. Traditionally in robotics, these measurements are taken at the joint level, however, as haptic interfaces directly connect with the operator, human dynamics and other factors influence the available choices. An early identification approach for haptic interfaces was demonstrated by Okamura, Howe, Cutkosky and Dennerlein [20], [22], which resulted from limitations experienced in displaying the measured vibrations with their haptic interface. A stylus was attached to the end of a 3GM haptic interface from Immersion Corporation, where they placed the accelerometer on the device itself instead of the stylus, as it is un-actuated. The analysis was conducted by generating a sinusoidal input current from a signal generator into the motor of the 3GM haptic interface that is responsible for producing the vibrations to the user in the virtual environment. The output of the accelerometer was monitored on an oscilloscope, where the signal from the generator was varied to beyond the human peak sensitivity of 250 Hz [20], [22]. By recording the magnitude of the accelerations to the varying input frequencies, the ratio of the accelerometer output, the input from the signal generator produced a normalised magnitude response. Throughout this process the stylus was lightly held by the user to maintain a general tapping position. The analysis of the 3GM device resulted in a resonance at 120 Hz and falls off as frequencies increase. While this approach indicates a measure of high-frequency transient propagation through the device, the technique limits the determination of the relative phase between the input and output to be matched and recorded. As discussed earlier, the distinguishing feature of a haptic interface compared with a robotic system is the direct coupling to the human operator. With this in mind it is necessary to observe the influence of the operator throughout the analysis process. The approach by Okamura et al [20], [22] could not verify the imposed dynamics by the human operator as inconsistency in the light hold of the stylus could result in incorrect performance data [24]. While this work experienced limitations through equipment capabilities, it provides an excellent foundation for investigating the dynamic performance of the presented grasping interface for application within event-based haptics.

With the requirement to demonstrate the high-frequency accelerations shown to enhance the representation of stiff virtual objects, the structural response of the haptic interface, measured in specified conditions can attempt to describe its typically imperfect structure. The two general approaches to achieve this are the isometric and isotonic conditions, where for haptic interfaces, the more appropriate response identification method is the impulse excitation. With isotonic conditions, described by having a free end, a maximum force amplitude impulse is applied to an actuator and the acceleration is measured demonstrating the spectral response [1]. Described previously, the haptic gripper is developed from Acrylonitrile butadiene styrene (ABS), which is generally used to make light, rigid, molded products. Within the overall design goals of this system, attachment of this device onto a 3 DOF haptic interface meant that the grasping interface had to be light weight. Consequently, the contrast between a stiff metallic structure and the ABS system will produce expected differences in the spectral response.

Within the context of this paper, demonstrating the structural response of a haptic device is critical in assessing its potential for application within the event-based haptics approach. Therefore the method making use of the acceleration throughput [20], [22], is explored to characterise the capabilities of the haptic grasping interface. While this method proves sufficient in its identification procedure, our approach was to ensure the best possible synchronisation between the input sinusoidal signal generation and the output measurement of the accelerometer. The sinusoidal input to the motor was generated by a desktop PC and consisted of varying the frequency of the signal in known time intervals. The accelerometer was mounted on the finger attachment point, shown in Figure 3, where its output was measured by the Labjack U3-HV data acquisition system [18].

The input signal magnitude was set to an appropriate force size, which was in the range of general pick and place force requirements, and the frequency was varied from 20Hz to 210Hz with increments of 15Hz per time interval. The experiment was run on one finger interface point as the system is geometrically uniform for both fingers. The initial configuration of the haptic gripper was set to a position in the middle of the rotational area. The input signal is incrementally increased in frequency at approximately 0.7 seconds, and the experiment was run two to three times for other input magnitudes slightly lower than the maximum threshold. Throughout the experiment, a user lightly placed their finger in contact with the finger pad of the gripper, attempting to add the essential dynamics typically experienced within virtual applications. Throughout this process, force sensors
under the finger pads shown in Figure 1 monitored the user applied force. The input signal and finger point acceleration was recorded for the duration of the test and stored on a single file. Figure 4 shows a time domain trial input and typical response output.

![Figure 4: Typical increasing frequency sinusoid force command and resulting handle acceleration](image1)

The output shown in Figure 5 is the ratio of the accelerometer output magnitude to the signal input magnitude, where it is observed that the interfaces’ ability to display the desired magnitude forces exhibits resonance at around 180Hz.

![Figure 5: Normalised magnitude response of the haptic grasping interface to various input frequencies](image2)

**IV. HIGH-FREQUENCY VIBRATION DATA COLLECTION**

A high bandwidth aluminium gripper was developed to record grasp contact vibrations with various materials. The light-weight design of the main system, with its ABS plastic structure is unable to sustain the stiffness required for recording the essential high-frequency transients in order to identify the range of applicable materials for this system. The aluminium gripper was instrumented to collect acceleration and position (velocity) data during grasping tasks with different materials. For this experiment, only one finger interface point (the thumb) was instrumented with the relevant sensors. Mounted to the finger pad interface point is an Analog Devices ADXL321 two axis accelerometer with a bandwidth of 1 kHz and a range of ±18g, where the voltage output of the accelerometer was sampled at 10 kHz. The accelerometer was attached to the top of the finger pad which aligns with the users finger as shown in Figure 6. The aluminium system provides position and velocity data through its interface electronics and encoder, which was coupled to the pulley of the instrumented interface point. A 5mm diameter spherical steel contact point was implemented to impact against the material. The accelerometer and position data were collected through a Labjack U3-HV [18] data acquisition unit connected to a desktop computer at a sampling rate of 10kHz.

A single user was instructed to complete the task of grasping to contact against a specific material. Prior to the experiment the operator was trained to complete the task with
the correct posture and at a consistent contact frequency. The operators height was adjusted for their arm to maintain a horizontal configuration as shown in Figure 7. The collected vibrations were characterised from ten grasp impacts on each selected material. A typical vibration output is shown in Figure 8, which were used to form parametric, empirical models that allowed for an understanding of the different model forms. The identified material frequencies are used to further describe the types of materials which the light-weight grasping interface can generate within an event-based haptics approach.

V. MODELLING THE GRASP IMPACT VIBRATIONS

The task of tapping with a vibration display on an objects surface has been shown in [19] to enable the user to distinguish between virtual materials through the recreation of vibrations which are composed of particular material properties. This work is further extended in [20] to measure a larger array of materials and simultaneously provide both force and vibration signals to the user. We utilise the empirical model used in [20] which is an exponentially decaying sinusoid shown in Figure 8, as its form relies on the material properties that we attempt to model. This is given by

\[ Q(t) = A(v)e^{-Bt} \sin(\omega t) \]  

where \( Q(t) \) is the frequency of the impact vibration, \( A(v) \) is the amplitude, and is correlated with the attack velocity, \( v \), for a particular material. The decay constant \( B \) is chosen to follow the observed decay of the vibration waveform, and \( \omega \) is the frequency of the impact vibration [22]. Five grasp contact experiments were completed for each material, and showed consistency in these parameters. The choice of the decaying sinusoid model is based on the simplistic response of a second-order mass-spring-damper model [22]. While Figure 8 demonstrates extra component frequencies within the empirical result for balsa wood, enhancing the model will not enhance the realism due to human sensing constraints [20]. The first cycle of the vibration transient provides the attack amplitude which represents the maximum acceleration. This is shown to vary linearly with the attack velocity, and is depicted in Figure 9 for contact with balsa wood across 10 grasp impact trials. Due to this approximately linear result, the amplitude parameter is the product \( A \cdot v \), where \( v \) is the velocity of the gripper prior to impact. The scalar \( A \) is called the amplitude slope parameter [20], and is determined from the relationship formed by each material through the incoming velocity and the acceleration amplitude. Using least squared technique, the decay rate \( B \) parameter was determined for each impact trial and averaged. The fast fourier transform was used to determine the frequency \( \omega \) of each trial impact, which was found constant for each material. Table I lists the parameters for grasp impacts on several materials. This approach allowed us to determine the range of materials that can be applied to the ABS grasping interface through the resulting frequencies and the device’s frequency response. Figure 10 demonstrates the measured and modeled vibration data for the balsa wood sample.

![Fig. 8: Typical acceleration impact transient from contact with balsa wood](image1)

![Fig. 9: Attack velocity and Acceleration amplitude for balsa wood](image2)

![Fig. 10: Modeled acceleration transient for contact with balsa wood](image3)

### Table I: Tapping model parameters for the selected materials

<table>
<thead>
<tr>
<th>Material</th>
<th>( A(s^{-1}) )</th>
<th>( B(m/s^{1.5}) )</th>
<th>( \omega ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>15000</td>
<td>5618</td>
<td>2222</td>
</tr>
<tr>
<td>Plastic</td>
<td>8200</td>
<td>2700</td>
<td>305</td>
</tr>
<tr>
<td>Hard Wood</td>
<td>6900</td>
<td>1976</td>
<td>714</td>
</tr>
<tr>
<td>Hard Foam</td>
<td>2400</td>
<td>5617</td>
<td>109</td>
</tr>
<tr>
<td>Balsa Wood</td>
<td>2300</td>
<td>157</td>
<td>280</td>
</tr>
<tr>
<td>Thick Foam</td>
<td>1600</td>
<td>212</td>
<td>145</td>
</tr>
<tr>
<td>Styrofoam</td>
<td>1400</td>
<td>102.1</td>
<td>227</td>
</tr>
</tbody>
</table>

Observing the frequency ranges in Table I, it is obvious that from the previous frequency response results, the ABS gripper can demonstrate the frequencies of only a few of the sampled materials. However, through human evaluations of
vibration sensing ranges, the peak sensitivity is around 250 Hz and the complete rage is between dc to over 1000 Hz [23]. As identified in [22], psychophysical experiments can be used to scale the identified model parameters to within the range of the gripper’s bandwidth. Consequently representing a larger range of materials.

VI. CONCLUSIONS

A novel prototype haptic grasping interface was presented and experimentally evaluated for its capacity to produce high-frequency vibrations to enhance the realism of hard virtual contact. Experimental results produced empirical vibration waveforms which were measured and modeled from contacting different material surfaces. A simplified model demonstrated the use of a scalar parameter, formed from the relationship between incoming velocity and the amplitude acceleration to adjust a simple decaying sinusoid for various incoming grasp velocities. The light-weight gripper was characterised through the normalised magnitude response and showed to preserve a significant amplitude for the appropriate frequencies, which in comparison with systems evaluated in the literature proved to satisfy a significant standard. This work has demonstrated the ability for multi-point haptic interfaces to enhance the realism of hard contact within a virtual environment through an event-based haptic approach.

REFERENCES