The **WHaT**: a Wireless Haptic Texture Sensor*

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Abstract

We describe the **WHaT**, a wireless device for haptic texture measurement and interaction. The **WHaT** is designed for simultaneously measuring contact force and acceleration in a hand-held probe. The probe is small and can be comfortably held, like a pen. It transmits contact measurements to a host computer over a wireless link, with low latency. We discuss the design and initial evaluation of the device.

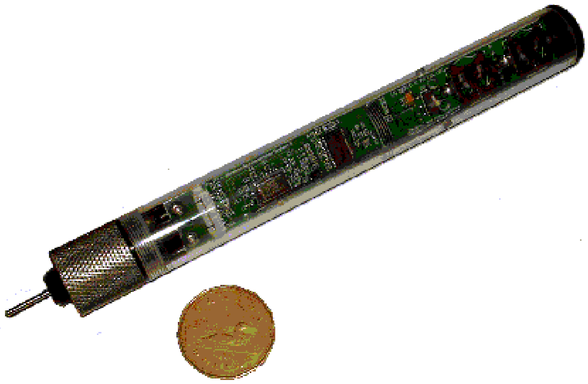

Figure 1: WHaT prototype

1 Introduction

To build realistic haptic virtual environments, we must measure real world surfaces. However, measurements of these surfaces are difficult to obtain for several reasons. First, the mechanics of contact require that both motion and force have to simultaneously measured to construct accurate physical models. Psychophysical research also shows that haptic texture perception is influenced by the parameters of both motion and applied force. Second, a real world surface could be a part of a large or complex shape. Traditionally, surface measurements have been performed on small samples of material [16], for instance, in metrology labs. Recently, the UBC Active Measurement facility [20] demonstrated the ability to acquire surface measurement on curved surfaces of entire objects, but it is limited to small objects and requires careful robot motion planning to measure surfaces that are difficult to reach. What is needed is a small hand-held device that can be used by humans to directly sample surface properties.

In this paper we describe a new wireless haptic texture sensor, the **WHaT**, designed for contact measurement. The **WHaT** is a hand-held device that can measure acceleration in all 3 dimensions, as well as the magnitude of contact force between the probe tip of the device and solid surfaces, at 400Hz[1]. The device is wireless, and can transmit the recorded data to a computer over an RF link. A picture of the device is shown in Figure 1. The device is roughly the size of a whiteboard marker, and can be held comfortably with a pen grip. The global position of the **WHaT** can be tracked by visual markers attached to it; for instance, we intend to do this with a Vicon motion capture system [27] capable of measuring position with sub-millimeter accu-

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[1] Higher sampling rates are possible, but are currently limited by the wireless link.

racy at 250Hz.

The WHaT is also designed for communicating the contact force and acceleration measurements to a host computer with very low added latency (2 ms). Therefore the WHaT can be used interactively as a human interface, for instance to detect contact and interaction parameters using just the onboard sensors, without external position measurement. These contact parameters could used to synthesize contact sounds [26, 25], for instance.

We will provide a live demonstration of the device at the symposium.

The rest of the paper is organized as follows. In Section 1.1 we discuss some related work. Section 2 discusses contact texture models from the point of view of the constraints it imposes on a measurement device. Section 3 describes the design of the WHaT and Section 4 describes preliminary results on the performance of the device. We conclude with Section 5.

1.1 Related Work

Haptic textures have been investigated extensively, in both engineering and psychology. In psychology, the perception of haptic texture, particulary roughness, has been investigated by [14, 11]. Traditionally, engineering metrology has been aimed at characterizing surfaces produced by manufacturing processes as they relate to assembly and wear, and not for haptic renderering [24]. Haptic texture rendering is an important theme in haptic interface research; see, for instance, [22, 8, 5, 9, 20, 4].

Recently there has been growing interest in reality-based modeling for haptic rendering, by measuring texture parameters of real world objects [16, 9, 7, 17, 21, 13, 20, 18]. Most of this work is concerned with measuring properties of small samples of material or small parts of a surface. A notable exception is [13, 20] in which it was shown how ACME, a robotic active measurement system, could measure haptic texture on curved, real-world surfaces. Other physical properties of contact, such as deformation properties, have also been measured (e.g., [6, 20, 12, 19]).

Ottensmeyer and Salisbury's TeMPeST 1-D [19], designed for in-vivo measurement of tissue visco-elastic properties, has some similarities with our device; we use the same force sensor in the WHaT. Another related device is the hand-held haptic media controller [10], which used a different force sensing approach for measuring low-frequency forces applied by humans; in the WHaT we use a stiff force sensor for measuring fast contact force transients.

2 Contact texture: models and measurement

Haptic interfaces are designed to render the feeling of contact with physical objects, but how exactly to model that contact for realistic 3D objects is still not well understood and is the subject of ongoing research. It is not yet clear what physical models of contact are best suited for haptic interaction, how such models are related to psychophysical percepts such as roughness [14], and how model parameters are to be acquired for real objects. The WHaT is designed to make it possible to explore these issues. Broadly, contact texture models suitable for synthesis can classified as deterministic contact dynamics models and stochastic models. In this section we discuss some of the constraints imposed by both types of contact texture models on the design of the WHaT. The WHaT is meant to be a multi-purpose measurement device, which could be used to support the construction of a variety of contact models, as well as for general user interaction.

Perhaps the most significant feature of contact interaction is its intermittent nature. When you run the tip of a stylus over a rough, textured surface the tip rapidly makes and breaks contact with the surface. Figure 2 illustrates this. Dry friction on the surface also leads to intermittency as the tip can alternate between sticking and slipping on the surface. Thus realistic surfaces impose non-holonomic constraints on the dynamics of the stylus.

We can model such intermittent contact dynamics using complementarity methods [23, 2]. We describe this for the case of single particle of

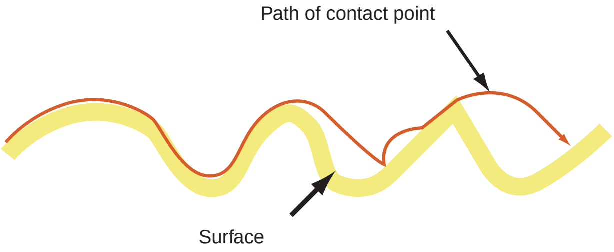

Figure 2: A cartooon view of contact. As the contact point moves from left to right on a rough surface, it could break contact several times.

mass m here; the generalization to rigid bodies and chains is known but will take us too far afield to describe here. The position $x \in \mathbb{R}^3$ of the particle is constrained to non-interpenetrating contact with a rigid surface by the inequality

$$g(x) \geq 0. \tag{1}$$

In free space ($g(x) > 0$), the particle is subject to Newton's laws of motion, but when in contact ($g(x) = 0$) the equations of motion can be derived from the augmented Lagrangian as

$$m\ddot{x} + G^T\lambda = f, \tag{2}$$

where $G = \frac{\partial g}{\partial x}$ is the constraint Jacobian matrix, λ is a Lagrange multiplier, and f is an external force.

The mechanics of contact can therefore be formally modeled as a nonlinear complementarty problem:

$$\begin{aligned} m\ddot{x} + G^T\lambda &= f, && \text{(3a)}\\ g(x) &\geq 0, && \text{(3b)}\\ \lambda &\geq 0, && \text{(3c)}\\ \lambda g(x) &= 0. && \text{(3d)} \end{aligned}$$

The last equation is the *complementarity condition* which says, informally, that either the contact force λ is zero, or the "distance" $g(x)$ from the surface is zero (or both).

This shows that an object's contact state is characterized by both the trajectory of the object and the contact force. It is therefore necessary to measure both these quantities.

When the particle is already in contact with $g(x) = 0$ and $dg/dt = G\dot{x} = 0$, the above nonlinear complementarity problem reduces to a linear complementarity problem (LCP):

$$\begin{aligned} m\ddot{x} + G^T\lambda &= f, && \text{(4a)}\\ \ddot{x} &\geq 0, && \text{(4b)}\\ \lambda &\geq 0, && \text{(4c)}\\ \lambda\ddot{x} &= 0. && \text{(4d)} \end{aligned}$$

This is the form which is often used to solve contact problems (for instance, see [3]). In contrast with nonlinear complementarity problems, LCPs can be efficiently solved, for instance, using Lemke's method. Hence for continuous contact, directly measuring acceleration $\ddot{x}$ is useful.

Coulomb friction can be incorporated into this complementarity formulation. We refer the reader to [15, 3, 23, 1] for more details.

The models we have just discussed are deterministic models of contact dynamics and could be used for direct numerical simulation of the contact forces and motion of a haptic interface. For many applications, such a detailed model may not be necessary, and a stochastic model of the contact forces and motion may be sufficient [22, 8, 13, 20]. Constructing such models, with correlated forces and accelerations, also requires that both quantities are simultaneously measured.

Thus the primary design goals of the WHaT were to simultaneously measure contact forces and acceleration at the contact point, augmented by external position measurements. These measurements can then be used to develop a variety of haptic texture models.

3 Design of WHaT

In addition to the measurement goals, it is important that the device have the physical feel and affordances similar to a commonly used handheld tool, like a pen. This allows natural interaction with the surfaces to be measured. A pen-like feel is particularly important since widely used haptic display devices like the PHANToM are designed for interaction with a pen-like stylus.

Another important design goal was to make the device wireless. This allows the device to have a large workspace and to be easily maneuvered into tight corners. It also eliminates extraneous forces from tension in the connecting cable from contaminating measurements.

The WHaT employs twin miniature 2-axis accelerometer chip mounted at right angles to measure acceleration, and a miniature piezoresistive force sensor chip to sense contact (see Figure 3).

The accelerometers used are the ADXL202E chips made by Analog Devices, with range of (-2 g, 2 g), linearity ± 0.2% of full scale, and accuracy of 8×10^{-3} g, where g is gravitational acceleration. The two chips are epoxied into a precision-machined aluminum bracket within the "grip" section of the device. Since each chip measures acceleration in two orthogoal axes, acceleration is measured along four axes. The chips are arranged so that two axes are aligned with the principal axis of the WHaT. The acceleration is measured at the approximate location of the fingers during grasping.

The force sensor is an LPM562 piezoresistive force sensor chip made by Cooper Instruments. We chose this type of force sensor because of the high stiffness and small size. However, it is a single axis sensor and measures force along the principal axis of the WHaT.

Figure 3 shows an assembly view of device components. The force sensor sits in a milled pocket within the grip section of the devices. The probe at the end of the device transfers load to this force sensor. A delrin guide constrains the motion of the probe in all but the longitudinal direction. The low coefficient of friction between delrin and stainless steel ensures that the load applied to the probe is accurately transferred to the force sensor. A narrow circuit board containing a Microchip PIC 16F876A microcontroller and a RFM TR1000 916.5MHz RF transceiver is rigidly attached to a bracket on the grip section of the device. A plexiglass cover protects the circuit board and allows the user to hold the device anywhere without causing damage. Snap-together cables bring the signal from the sensors to this circuit board (that also contains signal-conditioning hardware for the sensors).

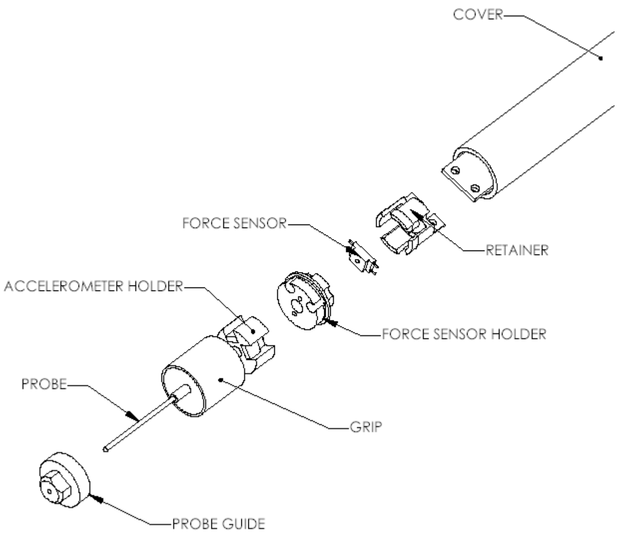

Figure 3: WHaT assembly.

The built-in 10-bit analog to digital converter on board the PIC is used to decode the analog voltage from the force sensor and the three analog voltages representing acceleration in the x, y and z direction. A precision 1.2V voltage reference on the circuit board allows the device to account for fluctuations in battery voltage.

The built in CCP module of the PIC is used to decode the acceleration for the redundant z-axis (there are two, two-axis accelerometers) allowing for accelerations below 2mg to be detected.

The heart of the RF section is the TR1000 transceiver. A Manchester encoding scheme is used to transmit data at a baud rate of 88,000 bps. A piece of wire inside the plexiglass cover is used as the antenna. The device transmits data at well over 3m using only a few milliamps of current. The microcontroller sends packets of data containing the acceleration reading along three axes and a force reading. Our preliminary results show that 400 packets per second can be sent with a latency of little more than 2.5ms.

The RF data sent by the WHaT is received by a bridge device that employs the same RF subsystem as the WHaT. A PIC microcontroller onboard the bridge decodes the Manchester encoded RF data, and then sends this data to a computer over the serial port at a baud rate of 115,200 bps. The DS276 RS-232 transceiver chip

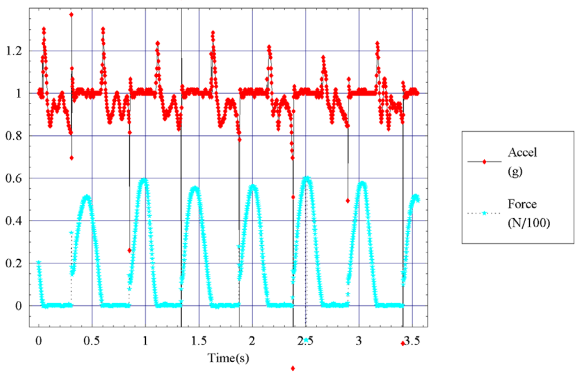

Figure 4: Data recorded when the WHaT was held vertically and tapped against a desk. The acceleration shown is along the principal axis of the device, aligned with the force axis.

made by Dallas Semiconductors is used to convert from the 3V CMOS levels that the bridge operates at, to levels that can be detected properly by a computer's serial port. The bridge device draws all of its power from the DTR and RTS pins of the computer's serial port.

All power needed by the WHaT is provided by four 12mm diameter coin cell batteries installed on the circuit board.

4 Results

We built a prototype version of the WHaT, and conducted a preliminary evaluation of its performance. We describe these results here, and will provide more extensive evaluation and a demonstration of the device at the symposium.

Figure 4 shows a plot of data recorded when the WHaT was held vertically and tapped against a desk about 2 times per second. The data clearly capture the complementarity between force and acceleration for contact with a hard surface. Impacts are clearly seen at the initiation of each contact. Somewhat more surprising is a small impulsive spike in acceleration when contact breaks; this could be due to adhesion, some feature of human motor control, or other reasons; but it is highly repeatable.

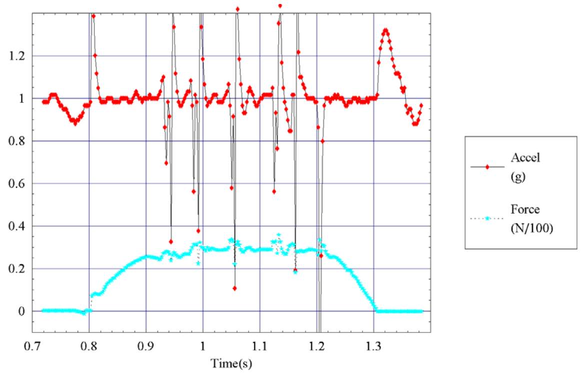

Figure 5: Data recorded when the WHaT was held vertically and moved across a piece of ribbon cable.

Figure 5 shows the data recorded when the WHaT was moved across a piece of “ribbon cable” at an approximately constant speed. The ribbon cable is compliant, and shows a constant loading force on which variations due to the ridges on the cable are seen. The force variations are seen to be highly correlated with the accelerations.

We conducted the experiments with both an early version of the device, using wires instead of RF to transmit the readings, and using RF wireless transmission. In the wireless mode, the sampling rate in these tests was 400 frames per second (1 frame = 1 force reading + 3 acceleration readings). When using RF, however, a small percentage of the packets are corrupted during transmission. The error rate seems to depend on specific conditions in the environment; our RF chips operate in the widely used 916.5 MHz band that is also used by cordless phones, etc., which can cause interference. But the errors can be easily detected and rejected since they show clear jumps in all 4 bytes; we are also investigating the use of well known error correcting codes. Finally, using this inside a shielded environment like our Haptic, Auditory, and Visual Environment (HAVEN) should minimize the problems with interference.

5 Conclusion

We have described a new, hand-held, wireless haptic texture sensor, the WHaT. The device should be well suited for both measurement of real world surfaces for modeling, as well as for low latency interaction. The design of the device was discussed and some preliminary results were presented.

The constraint of making the device small and wireless have imposed some limitations on the device that we hope to address in future work. The WHaT can only sense force along a single axis, since it was difficult to find a sufficiently small but stiff 3DOF force sensor. Therefore measurement of Coulomb friction and the surface normal is difficult using only the on-board sensors. However it may be possible to measure this indirectly using off-board position sensing and suitable assumptions about friction variation. In future work, we also plan to investigate improvements to the bandwidth for wireless communication, by using Bluetooth radio.

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