One-Dimensional Haptic Rendering Device based on an Audio Loudspeaker *

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***Abstract*— We report overall design considerations and preliminary results for a new haptic rendering device based on an audio loudspeaker. Our application is modeling tissue properties during microsurgery. For example the device would respond to the tip of a tool by simulating a particular tissue, displaying a desired compressibility and viscosity, giving way as the tissue is disrupted, or exhibiting independent motion such as that caused by pulsations in blood pressure. Although limited to one degree of freedom and with a relatively small range of displacement compared to other available haptic rendering devices, our design exhibits high bandwidth, low friction, low hysteresis, and low mass. These features are consistent with modeling interactions with delicate tissues during microsurgery. In addition, our haptic rendering device is designed to be simple and inexpensive to manufacture, in part through an innovative method of measuring displacement by variations in the speaker's inductance as the voice coil moves over the permanent magnet. Low latency and jitter are achieved by running the real-time simulation models on a dedicated microprocessor, while maintaining bidirectional communication with a standard laptop computer for user controls and data logging.**

I. Introduction

Researchers in haptics make extensive use of rendering devices capable of producing the sensation of touch as would occur during interactions with objects in the environment. A broad class of such devices consists of a stationary base supporting a movable component upon which forces and torques are generated relative to the base, in response to translation and/or rotation by an external agent. Most systems presently available to consumers and researchers (e.g. Novint Falcon, Force Dimension Omega, Geomagic Touch) depend on mechanical linkages to generate these forces and torques, which give rise to significant frictional losses and mechanical backlash. To avoid these problems associated with mechanical linkage mechanisms, Hollis developed a magnetically levitated haptic renderer [1], recently commercialized as the Maglev 200 from Butterfly Haptics. This desk-mounted haptic renderer utilizes Lorenz forces to actuate forces and torques in 6 degrees-of-freedom (DOF) on a *flotor* levitated between permanent magnets, while location and angle are determined in 6 DOF by high-resolution optical tracking. Because there are no mechanical linkages, forces and torques on the flotor are rendered without significant frictional losses or mechanical backlash. The Maglev can generate up to 40 N of force and 3.6 Nm of torque over a 2.4-cm-diameter spherical workspace. It also operates at higher frequencies than the aforementioned mechanically linked systems, changing position at 140 Hz and generating forces at greater than 2 KHz.

We have used the Maglev in experiments involving a new surgical tool that augments the surgeon's sense of touch in delicate tissues [2], to understand the control of a needle while puncturing a membrane to minimize damage to the underlying tissues [3], and to differentiate between such punctures performed by dominant and non-dominant hands [4]. While it has been a valuable testbed for these experiments, the relatively large mass of the flotor (~500 g) in the Maglev makes it less than ideal for our purpose of modeling delicate tissue. Furthermore, the Maglev does not directly measure the force and torque applied to the flotor by the user, but rather must infer these from their effect on linear and angular acceleration of the flotor.

We describe here development of a simpler, lighter platform that exhibits many of the advantageous features of the Maglev, albeit with only 1 DOF rather than 6. We take advantage of an existing commercial device with high bandwidth, low mass, low mechanical resistance, and significant force: the audio loudspeaker. In particular, we use low-frequency speakers (woofers). Even a fairly small woofer can have a relatively high displacement (1 cm), and sufficient bandwidth and force for our purposes. The moving portion of a woofer is generally a light but rigid paper cone, suspended in 1-DOF by a ring of elastic material, driven by a voice coil that surrounds but does not touch a permanent magnet. Thus velocity dependent forces (mechanical resistance) are minimal, assuming low air resistance at the velocities we expect the paper cone to be moving. As opposed to the Maglev, whose flotor weighs 500 g, the entire moving apparatus of our devices weighs 23 g, making it more suitable for simulating microsurgery. In the following sections, we review our development thus far of an initial prototype of our speaker-based haptic renderer.

II. Description of Initial Prototype

A. *Scaffold for mechanical user interface and force sensor*

Fig. 1 shows the configuration of the design (SolidWorks) of our initial prototype as well as a photograph of the actual

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device. We have chosen an 80-Watt 5-inch loudspeaker (Faital Pro 5FE120) designed for midrange to bass frequencies, and capable of delivering 10 N of sustained force. The allowable power is less than the manufacturer's reported maximum power for audio frequencies, since at DC all of the energy is dissipated as heat in the coil instead of sound. A custom plastic scaffold, produced using stereolithography, is attached to the central ring of the speaker cone, so as to move up and down as a unit. The scaffold is made of stiff and lightweight hollow beams, supporting an attachment point for user interaction. Users will attach mock-ups of needles, scalpels, etc., to this point, so as to push and/or pull on simulated tissues during psychophysics experiments. We have included a force sensor (Honeywell FS-01) mounted between the attachment point and the scaffold, with a preload spring allowing measurement of push and pull forces exerted by the user at the attachment point (see Fig.1). The sensor has a total range of 6.7 N with an accuracy of approximately ±0.07 N.

B. Displacement via induction and optical reflectance

We have developed a new method of computing displacement from the inductance of the speaker voice-coil, which changes as the voice-coil moves over the permanent magnet. Our system to measure speaker inductance uses a 30 KHz sinusoid superimposed on the lower-frequency voltage used to generate force in the speaker, as shown in Fig. 2, left. Our preliminary results indicate this is possible, although confounding effects with inductance occur due to the current in the voice coil used to move the speaker, probably as a result of non-linearity in the ferromagnetic core. Since the currents used to effect displacement are known in advance, we expect to be able to calibrate our measurement of displacement so as to be independent of this effect. Our present prototype also includes an independent measure of displacement based on a reflective optical sensor (Vishay TCRT5000L), which we have calibrated against a mechanical gage, and will use to effect dynamic calibration of the inductance-based displacement. (Fig. 2, right).

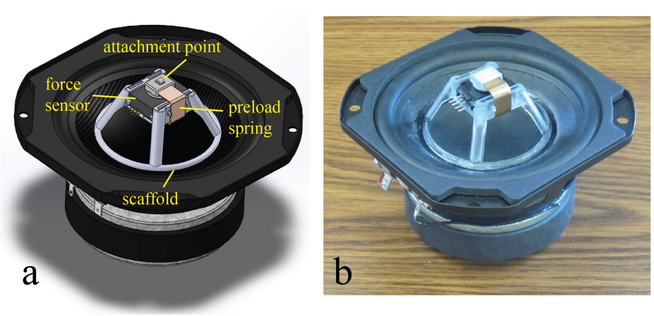

Figure 1. (a) Design showing custom scaffold with supporting attachment point for user interaction, and force sensor with preload spring, allowing measurement of both push and pull forces; (b) Actual device.

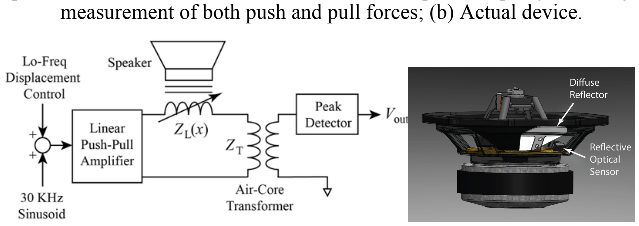

Figure 2. Designs for determining displacement using (left) voice-coil inductance; (right) optical reflectance from diffuse reflector.

Initial measurements indicate a signal-to-noise (S/N) of 61 dB for the optical system and 39 dB for the inductance system over a -3 mm to +3 mm displacement range, corresponding to precisions of 0.005 mm and 0.07 mm respectively, although accuracy is clearly less.

C. Real-time computation and control

We have implemented an inexpensive computational architecture that provides high bandwidth, low jitter, and low latency for real-time operation, while preserving flexibility in the user interface and data logging capabilities. The system includes a dedicated microprocessor (Analog Devices ADuC7026) with 12-bit analog-to-digital and digital-to-analog interfaces, performing reasonably complex models of tool-tissue interaction at 5 KHz. The microprocessor communicates to a standard laptop computer through an intervening programmable interface (Pololu Wixel) permitting the computer to log data synchronously and allowing low-bandwidth commands from the researcher without interrupting continuous real-time operation of the model being run on the microprocessor.

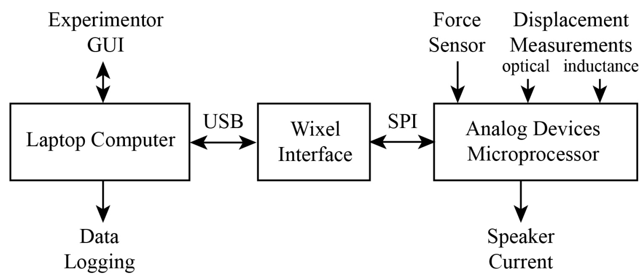

Figure 3. Computational platform for real-time operation.

III. Conclusion

We are developing a novel 1-DOF haptic renderer based on a readily available inexpensive electronic device, the loudspeaker. The renderer exhibits high bandwidth and low friction, which are advantages it shares with the Maglev haptic rendering device from Butterfly Haptics. It also exhibits low mass. Ongoing work includes further refinement of our new method of displacement measurement based on voice-coil induction, and development of models and applications for haptics research.

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