Handheld Haptics:
A USB Media Controller with Force Sensing

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Abstract

We discuss design principles for a handheld haptic device, scenarios for their use, and our implementation of a portable handheld haptic device following these principles. Handheld devices offer unique challenges and opportunities for haptics: they are compact, simple and consequently low cost, while promising comfort, low fatigue, and affordances for many useful tasks such as controlling digital media. We also describe the implementation of a semi-portable handheld force feedback display consisting of single actuated degree of freedom, orthogonal force sensing, and a USB controller for ease of connectivity to a variety of hosts.

Keywords: Haptic display, handheld control, user sensing, media control, USB.

1. Introduction & Motivation

Handheld haptic devices comprise a promising design space for haptics. Compact and portable, they allow haptic feedback to migrate from the desktop into new environments and applications and are potentially comfortable and more comfortable to use. In this paper we discuss issues related to the design of such devices, offer scenarios for their use and describe a prototype handheld haptic device.

One important consideration for handheld devices is that due to severe constraints in volume and weight, they are permitted few actuated degrees of freedom (DOFs). However, this limitation also presents an advantage in simplicity and expense, facilitating entry into otherwise inaccessible markets. Further, combining low DOF actuation with judiciously located force sensing can improve its utility without greatly increasing size or complexity. For example, by sensing force applied orthogonally to the actuated DOF, the system can infer the user's intent and operational mode and use this information to adapt the system's response.

A natural application of handheld haptic devices is for the control of abstract information spaces, rather than for direct interaction with 3D virtual environments. For example, handheld devices are well suited for the control of digital video and other linear media. In tasks such as video editing, browsing and manipulation, a handheld haptic display can function as a primary control device with no keyboard/mouse present. Eliminating the need for other more grounded input devices allows the user to leave the desk and work in other environments.

Figure 1 shows a prototype handheld haptic device we have developed to experiment with these issues. It consists of an actuated thumb wheel for input and haptic force feedback. Four sites of force sensing orthogonal to the axis of rotation of the wheel provide additional user input. The device is easily connected to any host computer via USB, with control shared between the host and an onboard microcontroller.

The remainder of the paper describes this device and its motivation. In Section 2 we discuss issues in the

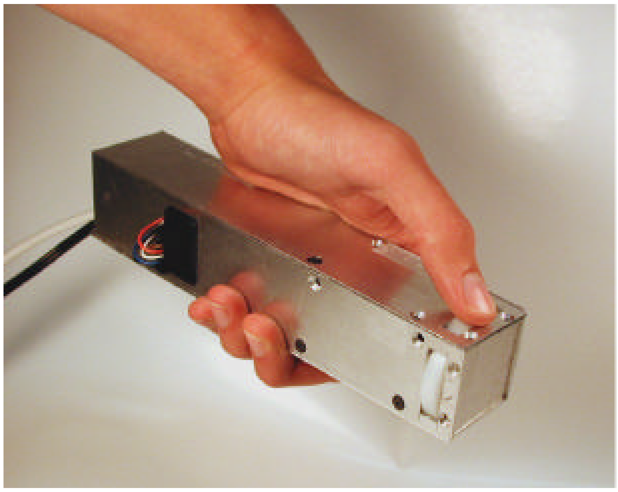

Figure 1: Initial prototype of the handheld haptic display described in this paper

design of handheld haptic devices and comment on related work. In Section 3 we present our approach to the design of a handheld haptic device, and in Section 4 sketch potential scenarios for its use. Section 5 describes the first prototype we have developed for experimentation. Finally, Section 6 summarizes the work and points to future directions.

2. Background & Issues

We preface a discussion of our design approach by considering the application area at which this device class is targeted, the tradeoffs inherent in the choice of a low-DOF, handheld force feedback device, the benefits of supplementary force sensing and related issues of software architectural.

2.1 Haptic Control of Digital Media

Browsing and editing digital media streams is a largely overlooked application for haptic feedback. This sort of one-dimensional data is becoming increasingly prevalent: examples include video and audio streams, or collections of streams such as cable TV channels, audio/video clips or voice mail messages. At present, interfaces to manipulate these streams and collections are generally “button-like”, whether the button is a physical one on a universal remote control or telephone answering machine, or a virtual button on a GUI accessed by a mouse or a keyed code. In the better sort, the user can jump from item to item or between different pre-set browse speeds.

Rarely is the user able to exert intimate, immediate and direct control over the media. Yet this is often desirable, whether the user is an amateur watching a digital video disc (DVD) movie or editing home video from the living room couch, or a videographer or musician cutting and mixing raw video and audio in an editing studio.

Affordances of Continuous Haptic Control

Continuous control offers a constant and fine-grained connection with media that is lacking in button interfaces. In theory a passive knob can provide this too, and much more cheaply. However, such a knob will probably be difficult to use, with no way to manually perceive any but regularly occurring artifacts such as frame edges; whereas we would like to perceive unique features like a stream’s beginning and end, its flow rate and editing cut points. With a passive knob, the user’s motor loop must be closed through the eyes’ or ears’ view of the controlled media, undermining the tight coupling which is the principle benefit of continuous control. The digital media’s feature of random access may be lost completely.

A knob with programmable force feedback can contribute to all of these, through changeable dynamics, edges and textures. It further enables powerful metaphoric operations: interaction with a target via a mediating virtual physical model can be designed to permit seamless, intuitive control [19]. Manually or automatically applied annotations and marks can be signaled haptically, and random access restored through interaction with the virtual model.

Figure 2: Conceptual (form study) prototypes for handheld haptic displays. Media control research described in [12] resulted in these models; the prototype described here is most directly related to the model on the right.

User interfaces for browsing digital media do offer special design challenges. Media collections are often organized hierarchically, and the user may desire to browse both a collection of discrete items, and individual streams within the collection. Supporting this need invites modal interface design, which in turn can make it difficult for the user to recognize the current mode or to know how to change it. This may be particularly hard to address with a low-DOF display and when visual and auditory attention is occupied (e.g. in viewing the video). We suggest, however, that it is possible to achieve *modeless* control when a haptic display is employed, through use of carefully chosen and presented virtual physical models.

Past Work

In a design project aiming to solve the challenge inherent in low-DOF media control, a series of conceptual and engineering prototypes were focused on seamlessly combining discrete and continuous modes of handheld control [12]. This evolution led to the concept of a handheld haptic display such as those illustrated by the conceptual (non-functional) prototypes in Figure 2, distinguished by a finger- or thumb-operated haptic wheel combined with textured surfaces to provide orientation cues. The user operates the haptic wheel while holding the device in particular orientations. The orientation modifies what the haptic interaction means, for example by indicating its target (e.g. video vs. audio) or its function (frame rate or volume). The prototypes shown are abstract, whereas the surfaces of a device designed for a specific purpose would be marked in ways that unambiguously indicate their function.

2.2 Low DOF Force Feedback Devices

The vast majority of current commercial and research force feedback displays have three or more actuated DOFs, designed for applications such as virtual reality, surgical simulation and interaction with 3D graphics models [4, 6, 13, 14]. Their high DOF count imparts the kinematic agility essential for these purposes but also makes them relatively complex, bulky and expensive.

Two-DOF force feedback devices are found most commonly in joystick or pantograph configurations. These are suitable for interaction with 2D graphical environments such as games and generic graphical user interfaces [3, 7, 9, 17]. Being lower on the cost scale, they have had the greatest impact in the commercial consumer market, most notably in gaming devices. The principal paradigm for their use, however, remains interaction with desktop graphical environments.

Single-DOF force-feedback devices are rarely encountered either in research or commercial contexts, and are often discounted by the haptics community as uncompelling. They neither pose interesting kinematic design challenges nor afford the high-DOF interactions on which many current applications are based. However, this simplicity provides important new opportunities beyond the positive impact of 1D kinematics on cost/DOF, display quality and robustness. Their potentially small size and low power requirements make them candidates for embedded and portable applications; and they can be built cheaply enough to enter mass markets. They can replace or augment traditional embedded manual controls such as knobs and switches, and provide interactive control over many kinds of digital media [8, 10].

One of the few examples of an embedded single-DOF interface is the haptic knob employed by BMW with Immersion Corp for user control of automobile cockpit secondary functions [1]. This tool was motivated by concerns for compact, simple yet informative manual control. Much remains to be learned about how to make these constrained interfaces work well.

Handheld Devices

Many classes of haptic displays, both grounded and ungrounded, can be viewed as "handheld" in some manner. A Phantom is typically operated with a stylus, emulating the use of a handheld tool such as pen or a scalpel by allowing 6-D motion [15]; however, the stylus is constrained to move within the device's workspace and thus bound to the desktop. Some ungrounded devices are hand-mounted, such as the Rutgers Hand Master [2]. They can move more freely in space, but conversely do not give the sense of holding or manipulating a tangible tool; and are distant from a potential consumer market in terms of cost and complexity. The sense of "handheld" that we seek here is that of picking up, carrying and containing within the palm an internally grounded, reactive tool.

Vibrotactile Feedback

Tactile feedback provided by modulated vibration is an attractive approach to haptic feedback when cost, weight and power consumption is critical. One approach to the design challenge outlined here is to put a thumbwheel in a handle and program vibrations based on user-directed motions of the wheel. However, our feeling is that our design goals require a richer palette to paint with, including the display of static forces and expression of dynamic models.

2.3 Orthogonal Force Sensing

Sensing the force a user applies in a direction other than a haptic display's actuated axis creates an additional manual control channel at lower cost and complexity than would another actuated DOF [5]. This extra channel can be exploited in many ways [19] and is particularly valuable in low-DOF devices where the single control channel might otherwise be too restrictive. Examples of how this feature can be exploited are given in Section 4.

2.4 Architectural Considerations

Two choices must be made in specifying the software architecture of any haptic system: the distribution of model computation and sensing, and the mechanism for communication among the system's computational units.

These decisions are influenced by several factors, including whether the system is for research/development vs. retail (the former generally requires low-level access to haptic primitives, while hard-coding usually works better for the latter); the complexity of the virtual model and of coordinated non-haptic parts of the system (e.g. a graphical or auditory display); cost constraints; and the performance and tightness of integration demanded of the whole [11].

Resolving these constraints in the face of limitations in computational hardware and communication protocols often demands unattractive tradeoffs. A common approach for research systems, where the haptic model must be accessible whereas cost and modularity may be less critical, is to put a high-performance (and expensive) I/O card in a desktop host and perform all digital signal conditioning and haptic model updates locally on the host CPU. The only communication required is among processes, either locally or over fast ethernet when multiple CPU's are required (e.g. to serve compute-intensive graphics or video handling).

However, even for a research system this can be

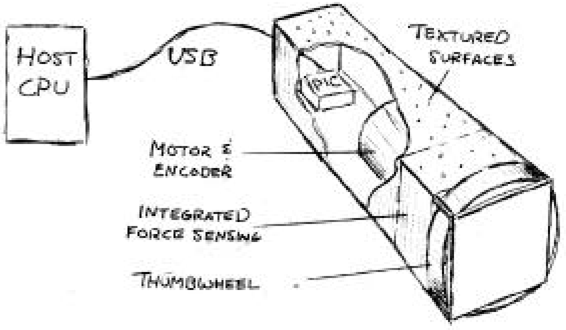

Figure 3: Overview of proposed system. Key elements include the host CPU and microprocessor data client, connected bidirectionally via USB; handheld thumbwheel display with actuator and encoder; textured case walls; and 2-axis force sensing integrated into the display's case walls.

undesirable, for example if one wishes to use the haptic device with different machines and operating systems – every host must have the expensive I/O board and appropriate drivers.

USB Communication

What's needed for research systems is a more generic way to get sensor and command data rapidly in and out of the host. Serial I/O is an obvious candidate, since hardware connections are available on most computers and many microprocessors, and drivers are common. Its early protocol, RS-232, could not manage the 500-1000 Hz update rates that haptic displays require. However, the Universal Serial Bus (USB) offers a viable answer. So-called "Slow" USB 1.1 can achieve barely-adequate loop rates of 500 Hz while transferring 8 bytes in each direction, and increasingly available USB 2.0 can poll about 8x faster [21]. Conventional microprocessors such as Microchip's PIC product line [16] currently have USB 1.1 support in some models, easing the development burden, and PIC USB 2.0 support is anticipated shortly.

3. Approach

One way to enhance manual control over digital media is to combine a handheld haptic display augmented with force sensing as suggested by the form studies of Figure 2, with new interaction behaviors [12]. Here we will discuss engineering issues in building a prototype to test this idea. Figure 3 provides a schematic overview of the system, the key elements of which are described below.

3.1 Form Factor

A handheld concept was chosen over a desktop version to enable new contexts of use: for example, from a living room easy chair, with no keyboard in sight, and with a digital video monitor or audio speakers rather than a computer screen as the principal target of manipulation.

A typical haptic display actuator (e.g. a 20-Watt Maxon DC motor) can be accommodated in a handheld format in a direct-drive configuration with a thumbwheel mounted directly on the motor shaft. The device's case or "handle" becomes an elongated structure of square or circular cross-section, with the wheel mounted on the end.

The user holds the device in the palm and rotates the wheel with the thumb. Pushing radially on the wheel – towards its center of rotation – excites one of the two force sensors. As described in Section 3.2, the system is able to determine which side the thumb pressed from, making the identity of the "active" face, i.e. the one closest to the thumb, an additional user input channel.

The user must therefore know what function each face enables. This can be accomplished, for example, by covering the faces with easily distinguished textures and, for learning purposes, colors, symbols or text.

Ergonomics

Any device intended for frequent manual use raises concerns for its ergonomics, and those that rely on thumb motion must be scrutinized with particular care. The form factor described here employs the thumb in two motions (rolling and pressing); and is somewhat sensitive to hand size. We can address some of these concerns superficially by adjusting overall case size (within actuator constraints) to fit an "average" hand and rounding its edges, and refining the pressing forces and scroll gains to comfortable levels. However, once the prototype is in regular use these issues must be considered and other form factors evaluated.

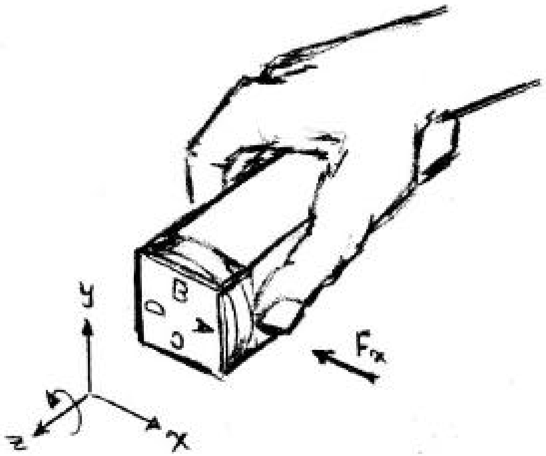

Figure 4: Two-channel force sensing scheme. When the device is held in the orientation shown, the user presses the thumbwheel from Face A and thus excites the x-axis force sensor.

3.2 Force Sensing

Force can be sensed on two orthogonal axes by mounting strain gages on the two pairs of facing walls of the handle housing, such that each pair will be activated by a force applied radially to the thumbwheel (i.e. normal to the actuation axis). This concept is illustrated in Figure 4, and an implementation is demonstrated in Section 6.2. A force applied on the wheel from the center of any face will activate just one pair (e.g. A-D activates the x-axis sensor), while a force applied from an edge made by two intersecting faces would activate both pairs equally. Because the thumbwheel is not accessible from these edges, one pair of sensors will always be activated more strongly than the other pair. The system can determine which pair of faces is activated based on the x-y force values. Further, it can infer which of the pair is active, since it is easy to push the wheel radially but not to pull it.

3.3 Model Distribution & USB Communication

For a research prototype that tightly couples a potentially complex virtual model to other display subsystems, we felt it was critical to maintain our haptic model computation on a powerful host processor rather than on a local microprocessor embedded in the handheld device. At 500 Hz roundtrip communication for up to 8 bytes of data each direction, USB 1.1 marginally supports this with promise of near-term rate improvements with USB 2.0.

Thus, our design for the haptic system control calls for a local microprocessor on the haptic device which:

- samples the two analog force sensors
- latches the decoded encoder value
- sends this data via USB to the host
- receives a motor command via USB from the host
- converts the command and sends it to the amplifier.

Products with these capabilities are currently available; e.g. in Microchip's PIC line. The result is a hardware interface one step closer to "plug and play" access, requiring no specialized hardware in the host computer, and device drivers easily adapted for a variety of operating systems.

4. Scenarios for Use

What is a single-DOF, handheld haptic display good for, and what should it do? Building on the thoughts developed in Section 2, we present several scenarios in which we believe this type of device could be valuable; and provide initial specifications for haptic behaviors we will create. Some of the scenarios have been partially implemented in the past in other form factors [19]. All will benefit from further innovative development of underlying haptic interaction models and behaviors.

The specifications given are based on past experience with earlier prototypes; we anticipate that user testing of the current version will lead to evolution of both morphology and programmed behavior, perhaps in multiple directions. For example, a physical design issue likely to require iteration is the coupling of the three control motions (handle rotation, thumb rolling, and thumb pressing).

4.1 Universal Language

We begin with the observation of a need common to the following scenarios. There are several kinds of media stream, and it is desirable to develop a set of haptic behaviors that applies seamlessly to all of them. By illustration, digital video will soon enter the home as:

- commercially produced digital video (a rented disc from the corner store or piped in from an external server);
- hundreds of digital cable TV channels;
- live camera feeds, from the internet or private sources like the daycare center or an elderly relative's home;
- home video shot from the user's own camera and stored on a local server or hosted remotely.

All are one or more stream of digital video, each a linear sequence of frames which can also be accessed at random. They also *differ* significantly in ways that will affect how the user may want to access them. The most obvious distinctions, which hold for audio and other types of media as well, are:

1. **Realtime vs. stored data**, e.g. a live camera feed vs. a DVD. Any part of a stored stream may be accessed at any time, while realtime data is only available as it is delivered. Thus fewer *temporal* operations exist with realtime data – but other functions may apply, like zooming, volume or track switching. The boundaries between these two are being relaxed with products like ReplayTV™ and TiVo™ [18, 20] which permit "elastic" viewing of live cable feeds via short-term buffering. That is, one can pause a live TV program, then later fast-forward to catch up to real-time. However, one can still not view material before it has been broadcast.
2. **Single sources vs. collections**. Viewing a DVD movie is a different experience than TV channel surfing. A user is likely to view the movie in entirety and in sequence; whereas she may skip rapidly through collections of channels (favorites, categories or any) looking for interesting snippets or a place to settle down. In the latter case, organization and navigation of the collection may be more critical than browsing the stream itself – over which little navigational control may be possible.

How can a single simple manual controller support these different models of use? We propose that by applying a small set of physical metaphors, we can provide seamless, intuitive movement between navigation of collections and streams, and between different control functions like rate, jumps, volume and zoom. This is possible because the integrated orthogonal force sensing allows the user to continuously modulate a motion command; at the same time, he can select different objects of or tools for manipulation via the device's orientation and by using applied force as a switch.

Metaphors and Modes

Various metaphors have already been proposed [19] and more will be developed. For example, the concept of a virtual clutch allows intuitive and smooth multirate navigation through a stream when wheel motion is combined with force pressure: the rolling media is perceived haptically as a spinning mass, selectively engaged by the external wheel when the user presses down on it. Rotating the device within the hand and engaging the wheel from a different face could initiate navigation of a collection: now scrolling means progressing through a linked list with detent feedback (stronger at frequently visited "favorites"), and pressing moves one to a new level of the hierarchy with a haptic click for verification. A third face might permit creating and jumping to marks or annotations.

4.2 Visual Browsing: Video & Broadband Cable

A first scenario is in the living room, away from the computer screen as we know it. The user is sitting on the couch and wants to look, not modify. His attention is focused on the video display, and it may not be a comfortable place to use a keyboard and a conventional mouse or any tool that requires grounding.

Media targets for control are likely to be those listed in Section 4.1 above. At minimum, the user will want to both move through a stream at smoothly changeable rates and to jump at intervals or to marked points within the stream; and to navigate flat or hierarchical collections of streams (e.g. cable TV channels).

4.3 Home Video Editing

In a second concept, which could apply as well to audio editing, an amateur user composes a new video segment by combining clips from several other sources. Again, she may be doing this from the living room rather than a desk; and our goal is to give her basic, lightweight functionality rather than expert or sophisticated capabilities. For example, she should be able to:

- browse within the current segment
- switch between new segment & original source
- select a new source
- choose, mark and adjust cut / insert points
- paste a source clip into the new segment
- apply simple effects, like fades and dissolves.

This list is characterized by random access within streams (creating edit marks and jumping to them), as well as the previous selection of collection items and continuous-browsing needs. These functions can be accommodated with selectable faces, distinguished with haptic textures and/or visual indicators.

For this more complex task, the user will probably need visual information displayed on the screen in addition to the video target, such as a list of sources and an overview of the target's evolving structure.

4.4 Audio MP3 File Setup

In this scenario, the user has a large collection of audio files stored on a server in his home from which he wishes to choose several and set them up to play while he does something else – in the same way you might load several CD's into a carousel then go away. Although he has GUI access to his digital jukebox from his home office computer, his sound system is piped throughout the house and he'd like to access the collection from other rooms. Current multi-room audio systems allow you to switch CD trays, volume or channel from a wall switch in linked rooms, but accessing a large digital collection is difficult without some kind of additional feedback.

Thus, this user might want at least three classes of functions (hierarchical collection navigation, track skipping and volume control) to be associated with the faces of his haptic remote. The tricky part is comprehensible navigation of the collection in the absence of visual feedback: audio feedback composed of samples from the set would probably be slow and annoying. Instead, we might try using easily recognizable haptic icons ("hapticons") to represent major subgroups (e.g. rock, classical, jazz and hip-hop) such that the user can scroll until he feels the desired icon. Within the subgroup, items might be organized by artist or title and distinguished by major and minor detents, accompanied by short clips. Alternatively, an approach such as the "alphabet browser" described in [19], combining letter utterances with haptic detents, could be employed.

5. Initial Prototype

We have recently constructed a first prototype of the handheld, USB-connected system specified in Section 3; it is shown photographed in Figure 1and again in Figure 5 as a CAD model with key components identified. The aluminum case's external dimensions – constrained by the motor bore – are 200 x 40 x 40mm. The nylon thumbwheel has a thickness of 7 mm and diameter of 46mm, such that it protrudes a maximum of 3mm from each face. This prototype's overall weight is approximately 600 g, reducible in future iterations with material substitutions and use of a smaller actuator.

The microprocessor and amplifier circuit are located

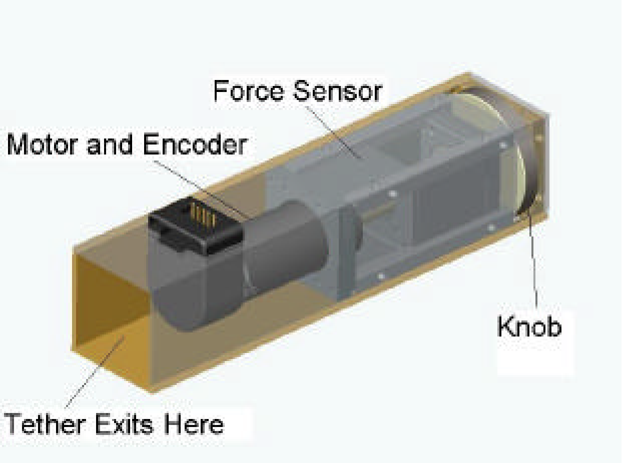

Figure 5: CAD model of implemented handheld system. Shows cutaway of rectangular housing with motor/encoder, force sensing unit and thumbwheel

on a printed circuit board in the cavity behind the encoder visible in Figure 5; a USB tether leaves this cavity and connects to the host USB port, and a second wire brings power to the motor and circuit from an AC adaptor.

6. Local Microprocessor and Sensor I/O

Device I/O is coordinated by a Microchip PIC 16C745, which features USB 1.1 conversion, digital I/O, two 8-bit A/D channels (used for force sensing) and a single D/A for the motor command. The encoder is decoded and latched with an HCTL 2016 and read digitally by the PIC.

6.1 Haptic Display

A 20-W Maxon RE025 brush motor in a direct-drive configuration provides the system's actuation. With a 23-mm radius knob, this motor produces a tangential stall force of about 10 N and a maximum continuous tangential resistance of 1.2 N.

Knob position is measured by an HP HEDM 5500, 1024-line 3-channel encoder.

A power supply provides 4 Amps at 12 V to the motor via an H-bridge amplifier circuit heatsinked to the device's aluminum case; and, rectified to 5V, to the other circuit electronics.

6.2 Force Sensing

Details of the force sensing implementation are seen in Figure 6. A bisected aluminum cage isolates the x and y deflections; each of the two units is a 31.75 mm cube. The flexion plates are each 2.4 mm thick and have a design spring constant of 8 N/mm, producing a maximum deflection of 1.8 mm from an applied force of 15 N.

A strain gage is mounted on each of the four flexion plates, and each pair produces a 0-4V force signal which is sampled by one of the PIC's 8-bit A/D converters. The sensor's active voltage range is closer to 2.5 volts, resulting in an actual converted range of a little under $2^8/2$ or ±128 counts per sensor: i.e. a saturating pressure on any face will result in a signal of nearly +128 or –128 counts, depending on which face it is.

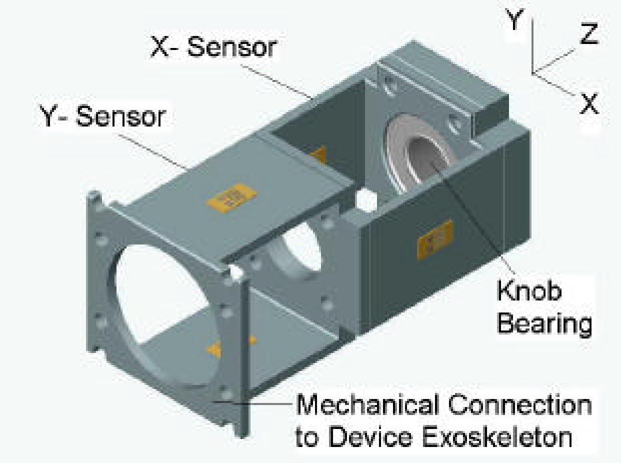

Figure 6: Force sensing detail. A close-up of the dual-axis strain gage mounting system shows the locations of the x- and y- axis strain gage pairs, the motor shaft extension and the force sensor's loading by the pressed shaft through the bearing at the distal end of the sensor. The sensor's proximal end is fixed to the housing and grounded in the user's hand.

6.3 Host Communication: USB

Because Microchip had not released its USB 2.0 model at the time of this construction, we chose to proceed with USB 1.1 support and upgrade the microprocessor when available.

USB 1.1 support permits a minimum polling rate of 1 msec with corresponding data transfer of 1.5 Mbps; the poll rate is halved to get a roundtrip communication rate of 500 Hz. 8 bytes of data may be sent in each direction at this rate. This system described here sends 7 bytes from the device to host every cycle (4 bytes of force, 2 bytes of position and 1 byte of header); and receives 2 bytes of motor command. Thus, it is polling-limited and close to data-limited in one direction, but does provides adequate performance.

USB 2, for which Microchip support is expected within the year, can poll at 125 µsec (8x faster) and transfer 12 Mbps. Thus while the current prototype may exhibit marginal stability for challenging environments, we expect the situation to improve drastically with minimal redesign.

7. Summary & Future Plans

This paper describes the motivation, anticipated use and initial implementation of a handheld haptic display designed for intuitive manipulation of digital media streams in non-desktop environments. As such it represents the beginning of an ongoing project that will include prototype iterations and experimentation based on implementation of the usage scenarios described in Section 4.

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