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Survey of Haptic Interface Research at McGill University

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Abstract: *This paper surveys three classes of haptic interface devices that were developed at McGill University since 1993. One class covers devices which output planar forces and explore various ways in which the human hand can input data. Another kind of device is meant to reproduce with fidelity the tasks corresponding to the manipulation of small tools in three dimensions. Lastly, we investigated a new class of tactile display.*

Keywords: *Haptic Interface, Force Feedback, Tactile Device*

1 Introduction

This paper surveys haptic interfaces [1] developed at McGill University since 1993. The research has explored three types: planar devices, those that make it possible to simulate full three dimensional interactions (forces and torques), and tactile displays. Other parts of the research include the prototyping of applications, the development of physical modeling methods as applicable to haptics, and the investigation of specific perceptual phenomena. The paper focuses on the description of devices and how they relate to other aspects of the research.

2 Planar devices

2.1 Pantograph

The Pantograph (Figure 1), initially reported in [2,3], was developed in 1993 in collaboration with C. Ramstein from the Center for Information Technology Innovation (no longer is in existence). This project was motivated by the need to provide visually handicapped users with new means to access *generic* computer applications [4]. Where the audio channel was already well exploited, it was natural to combine it with the haptic channel. Given this, the interface was designed as a planar device able to replace a computer mouse, but not limited to that function. As it later turned out, planar operation yielded a surprising degree of usefulness.

Figure 1: Initial Pantograph Prototype.

The set of requirements included:

I. Efficient form factor (work-area/bulk);
II. Simplicity;
III. Large work-area;
IV. Fidelity (uniform response, wide bandwidth, wide dynamic range).

Item I conveyed the necessity that the device be “table-top compatible” and self-contained. Simplicity (II) implied that the device should be easily duplicated and of potentially of low cost. A large work-area (III) was initially motivated by the desire to create a working region reachable by hand and finger movement; with the forearm resting on the table (100 x 160 mm). Fidelity (IV) was needed since little was known about the ultimate requirements of an effective design. To achieve (II) and (IV), three decisions were made: to use core-less DC motors for absence of torque ripple and for cogging-free operation; to directly drive a linkage without transmission; and to target 10 N peak force at the tip. A number of factors were optimized including inertia minimization and elimination of low frequency structural resonances. The primary figure of merit was uniform acceleration. Not only the peak acceleration had to be high, but it had to change slowly over the work-space; while being constrained in a 3 dB band. A key finding was the much higher sensitivity of the acceleration-related figures of merit (dynamics) with respect to the design parameters rather than Jacobian-based force/torque transfer characteristics (statics).

Figure 2: Set-up aboard NASA’s microgravity aircraft.

The first prototype shown in Figure 1 turned out be over-designed in a number of ways. It became evident that for its intended use it was too large and too strong. Nevertheless, a public demonstration [3] attracted hundreds of visitors who could experience haptically layered GUI elements and haptically enhanced dexterity games.

This initial device could be rapidly adapted to support a human factor study aimed at investigating the effect of haptic feedback during the operation of GUIs for operators subject to extreme conditions in zero gravity (Figure 2). Operators could achieve better performance with force feedback devices than with free moving devices, both in speed and error rate [5].

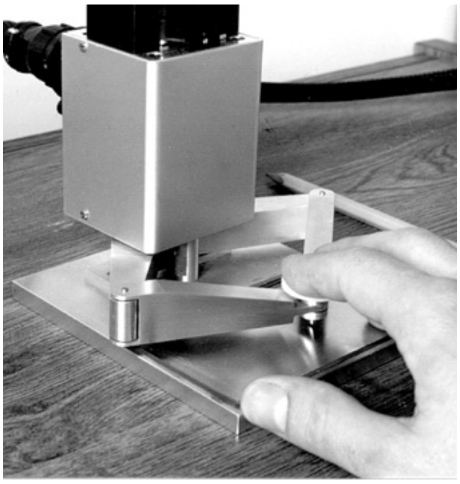

Figure 3: Medium Pantograph

Smaller devices were simultaneously developed in 1995. The first, a reduced version of the initial design, had a workspace 60 by 100 mm (Figure 3). It introduced a hand interface that eliminated the need for grasping, much like track pads of laptop computers. This was achieved simply by taking advantage of the high vertical stiffness of the linkage and of the absence of nominal friction under any load. The user pressed on a plate, very much like she/he would slide an object on a surface. In the context of GUI interaction, one limitation of this approach was the difficulty to combine a pointing task with a designation task. Later, attempts were made to augment the device with load sensitive sensors inserted somewhere within the load path between end effector and the table: at the plate, in the linkage, or between the ground link and the table (pointing and designation functions are separate in track pads: pad/button(s)). While these attempts were later pursued using a different approach, they still remain an interesting possibility.

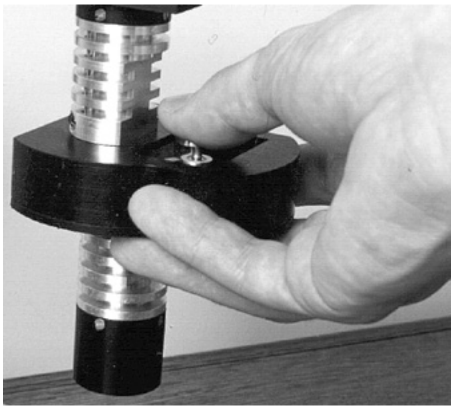

Figure 4. Hand held haptic device.

Hand-held devices (not grounded) were also tried. One of them is shown on Figure 4. The linkage was now completely housed in a case and the case used to hold the device (the actuators housings with cooling fins were a telltale sign of the unfavorable scaling properties of magnetic actuators). Notice that in this type of configuration, the user had to accomplish three tasks: hold the device, perform a pointing task and also designate a target. In the example shown, the shape of the case promoted an opposing grip. The pointing task and the designation task were both given to the thumb which is our most mobile finger. Nevertheless, it was found that it was hard for users to decouple these two tasks. Other more successful configurations were found, such as giving the index and middle finger the designation task, dedicating the thumb to pointing and leaving grasping and stabilization to the remaining two fingers.

Some other designs were tried, one of them had a spherical workspace and was meant to be embedded in the arm of a seat (Figure 5).

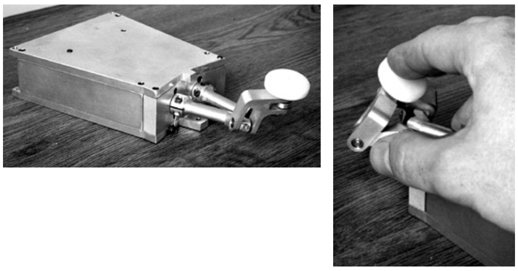

Figure 5. Spherical workspace.device.

2.2 “2D and half” Devices

A commercial realization of these ideas was embodied by the PenCat/Pro^{TM} device. An early version is shown on Figure 6 (Immersion Canada Inc.).

Figure 6. PenCat/Pro

The symmetric five bar linkage was replaced by a more compact design to let the user interact with a protruding cantilevered arm. In addition, sensors and actuators were custom designed for an integrated product. The device retained the concept of producing horizontal forces, but in addition it sensed vertical movements of the pen, thereby creating an input workspace of 100 by 60 by 25 mm. The vertical movement is passively actuated by elastic return. This design was targeted at CAD operators and proved to be very effective. It received in 1998 a product of month NASA award. The rationale behind this concept is that three dimensional surfaces could be perceived by users experiencing only two dimensional forces, as effectively as if they were experiencing three dimensional forces, while navigating in 3D space. This effect was recently confirmed [6,7]. A second version of the device featured full sensing of the pen’s angular position as well as sensing of the user’s grip force, allowing an application developer to account for a rich knowledge of the user’s activity. This idea is applied in our present work to the manipulation of three dimensional medical images.

3 Six Axis Devices

There is interest in devices that can replicate with some fidelity tasks actually performed in the real world. With this in mind, a full 3D device was developed with MPB Technologies Inc., Montreal. The initial design is described in [8].

3.1 Laboratory Prototype

A device of this nature inherited from telerobotic master arms and its design was much inspired by early systems such as CEA’s MA-23 force reflecting manipulator, a project that was headed by J. Vertut and JPL’s FRHC designed by J. K. Salisbury. A worry was the limitations of electromagnetic actuators. Again it was decided to initially use existing core-less DC motors although they were clearly sub-optimal for this task. Consequently, accurate static balancing was required for all six degrees of freedom.

The requirements were:

I. Static balancing;
II. Uniform dynamic response both inertially and structurally.
III. Wide dynamic range.
IV. Work-area compatible with a “resting elbow” posture.
V. Low visual intrusion.

Item V meant that the design had to adopt a “wrist partitioned” arrangement which in turn implied remotization of actuation. Thus partitioned into a grounded “positioning stage” and a distal “orienting stage”, the design could be better analyzed. For the positioning stage, a pivoting four-bar linkage was found which could achieve both static balancing and uniform inertial properties. It was first observed that mass concentration would occur at the actuators and at the wrist. Static balancing required that the center of mass remained invariant under any movement of the device. Uniform and minimal inertial properties was achieved by placing each actuator such that each would experience an inertia dominated by just one single actuator plus that of the distal orientation stage, in all three directions.

Referring to Figure 7, and ignoring the links, the moment of inertia experienced by Motor-1 is due mostly to Motor-2 and to the distal stage. Motor-2 experienced a moment of inertia due mostly to Motor-3 and the distal stage, and Motor-3 experienced his own inertia and that of the distal stage. Taking advantage of the geometric properties of a four bar linkage, proper dimensioning allowed us to locate an invariant center of mass on the axis of Motor-1, thus realizing static balancing.

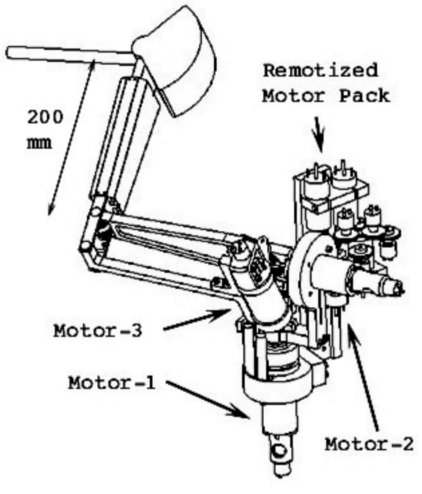

Figure 7. General Arrangement

The design was also considered from the view point of its structural response. This follows from the observation that temporal resolution of the sense of touch, while not being as keen as that of hearing, is nevertheless sensitive to the high frequency details of the force applied. This is exacerbated by the fact that force feedback devices face conflicting requirements. On one hand, there is an advantage in increasing rigidity to enhance crispness but this is usually accompanied with more pronounced structural resonances. For this reason, a box design was selected for some of the links instead of pocketed solid beams since they yielded higher inherent damping. Studies were also made to shape the structural response the links used advanced composite materials [9]. Similarly, to promote distortion free high frequency response all joints were preloaded and yoked.

The distal orientation stage posed a different set of challenges. For the laboratory prototype, a "double five-bar" mechanism was developed. With this parallel mechanism, it was possible to achieve three axes of orientation (with optionally a fourth sliding action) with significant working range (90° X 100° X 120°) using only 15 parts, and it could be made very light (50 g). This mechanism was driven by four identical pulleys, Figure 8.

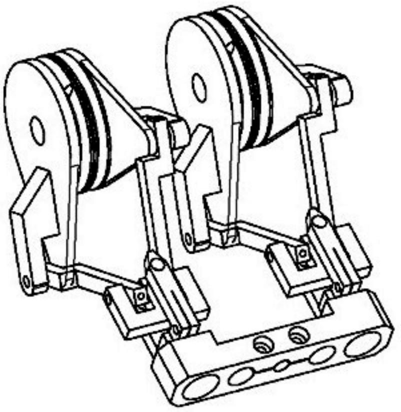

Figure 8. Distal orienting stage.

The actuators driving the distal stage were remotized by a set of tendon drives. These were distinct from conventional tendon drives in the sense that a design was found to operate them in "pull-pull" mode using a single motor per axis (Figure 8). This was achieved by separating the torque generating capstan from the tensioning mechanism. The tendons were made of a polymeric material (Spectra™ fibers) which have excellent transmission characteristics, comparable to steel cables. One disadvantage is that they creep under load. This tendency has no effect on the "pull-pull" design since the tensioning mechanism could take up large variations in the tendon length. The tension at rest was only a fraction of a Newton.

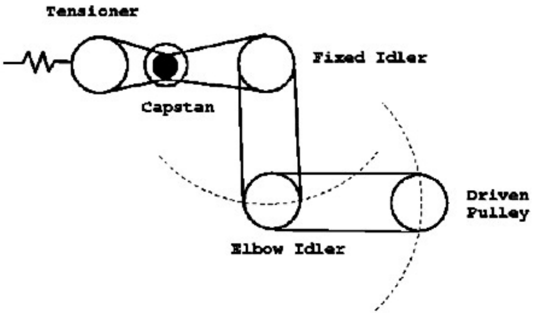

Figure 8. Pull-Pull tendon transmission.

The combined result of these techniques was quite satisfactory. The resulting inertia at the tip was bounded by 0.09 kg under and 0.15 kg above along any axis and anywhere in the workspace. The friction level is around 0.1 N in any direction. It can be verified that inertial forces generated by humans moving a 0.1 kg mass in a reduced volume also generates inertial forces of this order. It could be concluded that this figure stood for the "noise floor" of the device. It was possible to achieve nearly 1:000 dynamic force range in translation and 1:100 in angular movements. The dynamic response was measured at the handle under isometric and isotonic conditions. Some axes were more satisfactory than others but in general the isotonic response was fairly flat up to 50 Hz.

3.2 Commercial Version

The commercial version differed from the laboratory prototype in a number of ways. The use of the box design for the links was generalized resulting in a much "cleaner" feel. It integrated position sensing in the driven joints, making it easier to achieve high control stiffness. In the commercial version, this parallel orienting design was found to be too costly to manufacture, given other requirements such as resistance to abuse and was replaced by a more sturdy serial structure. Instrumentation was also much improved. An early version can be seen on Figure 10. Since by static balancing, the device operated equally well under any orientation with respect to gravity, it was possible think of attaching it to a isometric orientation stage that would provide an infinite orientation range, so-to-speak, by servoing orientation so as to always keep the distal stage within its range of motion.

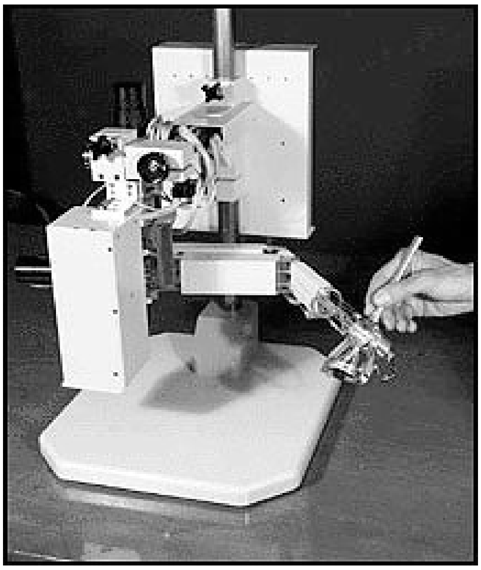

Figure 10: Freedom-6s

4. Tactile Display

The laboratory developed tactile displays, which are devices capable of distributed application of mechanical signals directly on the skin, as if the skin were in contact with the surfaces of objects. Tactile stimulation is especially interesting if the simulated interaction of the skin with an object can represent relative sliding, since this corresponds to the typical manner in which we experience the surfaces and edges of objects. The observation behind our designs is that such interaction results in stimulation patterns which are rich not also in spatial details but also in temporal details. The question was asked whether these stimulation patterns needed to be reproduced with their full complexity.

A project was initiated in 1997 to develop a tactile display that reduced the stimulation of the skin to the re-creation of surface strain fields, ignoring indentation. This is supported by several observations. One of them relates to deformation patterns of the tissues as a whole. For example, the patterns caused in a finger pad exploring an object have combined components. In other terms, skin indentation patterns, not just punctuate ones but also those having a spatial extent and temporal variations, must result in changes in all entries of the deformation field. Since it is not known whether human touch responds specifically to only some, all, or combinations of these components, it was thought that useful tactile sensations could be created by causing lateral skin stretch/compression at the surface of the skin and ignoring indentation.

Interestingly, all previously reported tactile displays only were concerned with distributed indentation, hence their name “shape displays”. There are numerous examples of technological displays which take advantage of similar observations, in the sense that the detailed specification of the stimulus does not correspond to what is experienced. Two notable examples are found in the visual domain. Rapid sequences of stills can result in an experience of movement, or the relative proportion of two or three narrow light spectral components give rise to the experience of continuous hues. Informal experiments described in [9] seem to support the possibility that skin surface strain fields are very effective stimuli in this sense.

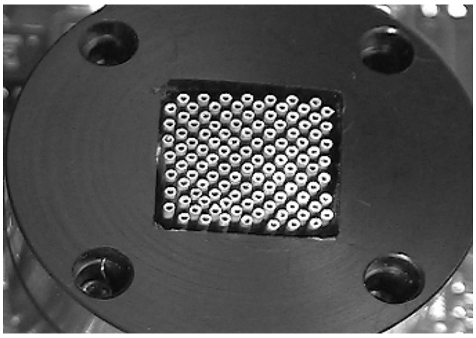

Figure 11: Active area is 12 x 12 mm, 36 “tact-cells”. White circles are contactors.

A device was built that could create such lateral stress patterns [9] (Figure 11). The higher the density of lateral “tact-cells” (small patches of skin being individually deformed), the smaller the movement of the contractors for an equivalent strain. This allowed us to realize a rather dense display using simple technical means. Perhaps more importantly, because of the small required movements of each individual contractor, piezoelectric actuators could be used. They do not limit the device in the temporal domain as other actuators do.

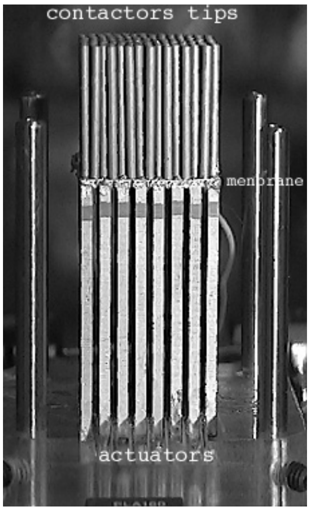

Figure 12. Tactile Display, cover removed.

Briefly described, referring to Figure 12, an array of piezoelectric actuators (1 mm^2 cross section) deformed a membrane which had been structurally relieved by an array of perforations. A second array of contractors were connected to the upper side of the membrane so as to swing laterally when the membrane deforms. They also perform lever amplification of movement. Judicious activation of the actuators allowed us to program arbitrary lateral strain patterns (in space and time) of skin in contact

The results are preliminary [9] but sufficiently encouraging to justify the development of other generations of such devices with simplified manufacturing and larger movements.

5. Conclusion

This paper surveyed devices which occupy distinct niches in the large space occupied by past and future haptic interfaces designs. We also became interested in a fourth niche, that of vibrotactile displays. At present, we have experimented with devices that can be worn on the finger like rings or on which one can stand. These were explored in a effort to assist computer music performers interact via open air gestures with electronic equipment [11].

Acknowledgments

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