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Toward a Seven Axis Haptic Device

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Abstract

The development of a haptic interface to address the tasks performed by people with small tools is described. Design issues are considered from the requirements, in terms of actuation, kinematics, motion transmission, sensing, and concept design.

1 Introduction

It is a common observation that many tasks performed by people involve the use of small tools such as pens, styli, screwdrivers, cutter knives, lancets, scalpels, and so-on. Common to all these tasks is a person gripping a small handle which is often nearly cylindrical, sometimes knurled, sometimes contoured for finger contact. It is free at one end, while the other end marks the location of the task where the tool interacts with an object. This is such a common occurrence that people have developed a number of specific grip postures well suited for this case. Five of them are illustrated on the Figure 1, but there are of course many others [44]. In view of the versatility of the hand for gripping cylindrical handles free at one end, and of the common occurrence of tasks involving such handles, there is considerable motivation for the development of haptic devices designed from this observation. It is well known that the human upper extremity is extraordinarily sensitive to mechanical stimuli derived from the contact of tools with the skin. While it would be much too lengthy to survey here the capabilities and limitations of the hand (both of the efferent and of the afferent channels) when working with small tools, such a study was carried out by Reynier and Hayward [38] for gaining some insight into the engineering requirements for a high-fidelity device. The conclusions, while not definite, indicate that the task of building a device that can be such qualified, in the sense of transducing mechanical sensations of a large class of tasks in a believable manner is indeed formidable.

2 Problem Statement

Before attempting a summary of these requirements, Reynier and Hayward carried out a number of experiments with an apparatus designed to gain some practical insight in the manner in which people perceive the small displacements of a handle. These experiments are unfortunately not completed at this point in time, but it is worth describing briefly here

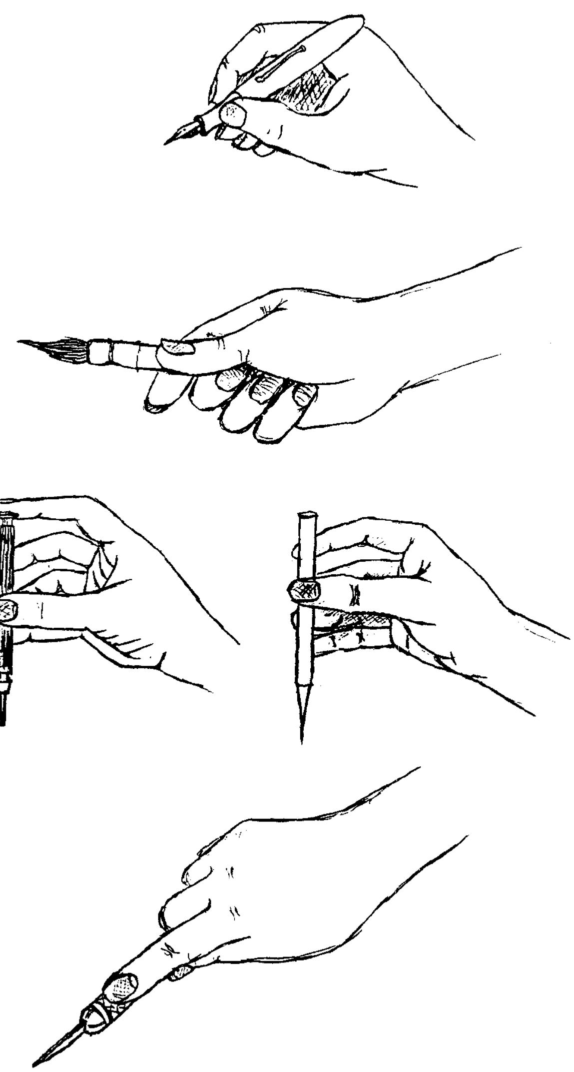

Figure 1: Five postures for gripping small handles

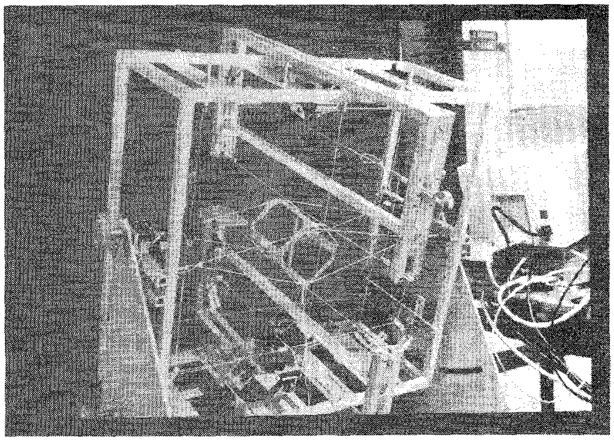

Figure 2: Six DOF Stimulator, the "Cage"

what the apparatus consists of, and some of the results that were obtained.

How well the human hand can discriminate the direction and the nature of small motions, say from a few Hz into the acoustic domain, is a crucial piece of information to determine the needed accuracy of the dynamic response of a haptic device. To our knowledge, such data is not available in any general way. Attempting to separate as much as possible device factors from human factors, a system with a cubic symmetry which, by design guarantees an identical response in any direction of motion, was built [9]. It consists of a handle located at the center of a light and rigid structure designed (1) to provide six anchor points at the centers of the faces of a cube, (2) to have a spherical tensor of inertia, and (3) to provide access to a hand near its center of mass. This structure is suspended from twelve strings linking it via small idler pulleys to six identical voice-coil actuators. These actuators, scavenged from computer disk-drives, have virtually no structural effects up to several kHz, are powerful and rugged, and have no hysteresis since motion is caused by the electromagnetic force present in the windings placed a uniform magnetic field. The result, nicknamed the "Cage", is depicted on Figure 2. It can displace the handle in a workspace of $1 \times 1 \times 1$ cm, $5 \times 5 \times 5$ degrees with a flat response up to 300Hz (improved since the report was written). With this device, stimuli were presented to a number of subjects, varying the amplitude, the nature, and the direction of motion. Rigorous experiments of this kind are difficult to design and their results are notoriously difficult to interpret. We could nevertheless safely conclude that the sensitivity of subjects varies much with their training (the best was a surgeon), and that in certain conditions some subjects are capable of discriminating between two consecutive motions vibrating across orthogonal directions up to 80 Hz, frequency after which the motion is perceived as a vibration without any spatial content. This figure does provide us with an indication of the frequency range within which a high fidelity device should uphold its dynamic accuracy.

It also important to decide the workspace inside which "pen-like" devices are most useful. Since to the author's knowledge, the present device is the first of its kind, there is little experience in this domain. Clearly, it is a human factor issue. The largest workspace possible is evidently a desirable goal, but of course the workspace will be limited by technological factors. Some human factors studies were carried out by Ramstein using another device designed by the author (the "Pantograph", see Figure 2) which features a planar workspace of 10×16 cm [37, 19]. It was felt that an area of that order was slightly too large to be completely used during comfortable work at a workstation, and that a 7×10 cm area was perhaps sufficient. The importance of importance of sufficiently large workspaces has been outlined in a number of studies [27, 47, 18]. However it is always risky to generalize such findings since the tasks and the working conditions can vary so greatly. It was decided for a first prototype to target a workvolume of $10 \times 10 \times 10$ cm which corresponds roughly to the volume reachable by the tip of a tool of the kind described earlier in conjunction with the movements of the wrist alone. A comfortable angular workspace was estimated to be of the order of 90 degrees of pitch and yaw combined with a roll of 180 degrees. Other informal ex-

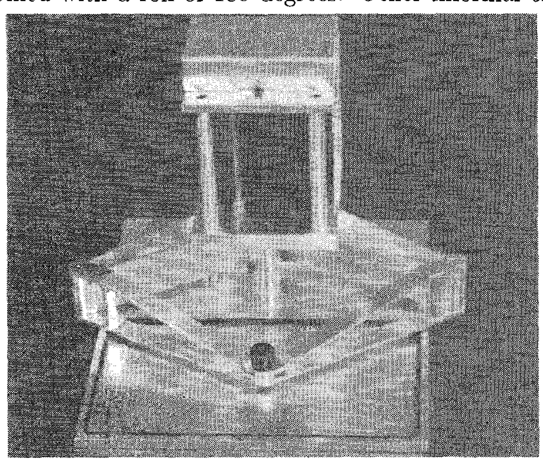

Figure 3: Two DOF Haptic Device "Pantograph"

periments were carried out by the author with the above mentioned "Pantograph". It was used in an attempt to characterize what factors allowed a device to best transduce the sensation of shocks and hard contacts. The extent of the frequency response to small motions (below structural resonances) is a common way to quantify this type of performance. It is, however, an ill defined concept since it depends on the notion of "small motions", which can vary from task to task. Instead, the inertia of the device was varied, while holding all other parameters as unchanged as possible. It was found that the acceleration capability (available actuator effort divided by the inertia) was probably the most influencial factor. This is compatible with the physiological experiments of Johanson and Westling commented upon in [30], which demonstrated the existence of bursts of activity in the skin's rapidly adapting receptors (acceleration sensitive) upon collision of an object held with a precision grip. Moreover, it is obviously compatible with the plain fact that collisions correspond to high rates of change of an object's velocity upon collision (with the corresponding rapid change of the impedance parameters elasticity and damping). From this observation, the sluggish feel of certain force reflective hand controllers or haptic devices can be explained, only partially because of lack of bandwidth (due to structural limitations), but more importantly, because of under-actuation (respectively excessive inertia) which is not conveyed by bandwidth figures (see [39] for similar results).

From other numbers gathered in the literature (reported in [38] and other publications [30, 25, 28, 10]), we may know attempt to summarize those requirements.

- The frequency response must be wide since humans are known to perceive force stimuli well above 300 Hz.
- The device must also be accurate since the amplitude of force signals are sensed by most operators over four orders of magnitude, say from 1 mN to 10 N.
- The device must present properties that enable its mechanical impedance to be programmed over several (~ 3) orders of magnitude.
- The workspace must be free of intrusion by linkages, strings, etc...
- The inertia must be small and well behaved everywhere inside the workspace.
- Dynamic response (including structural dynamics) must be precise, up to 50-100 Hz.

As often discussed, this means that the device must be characterized by the absence of backlash, friction, and other disturbing dynamics; in particular structural dynamics in the low range. It also requires uniform dynamic conditioning inside its workspace. It is amazing to observe from a historical perspective that the proposed requirements for hand-controllers (now called *haptic interfaces*) have never ceased to increase, and apparently follow, rather than precede, what technology can offer [13, 15, 36, 12, 45, 4, 5, 39, 40, 6, 8, 16, 17, 21, 33, 46, 1, 42].

3 Approaches

3.1 Actuation

Actuation is such a critical problem that there are opportunities for the application of about every type of actuation to create haptic devices operating at various scales, and to take the best advantage of their respective properties. Here we outline some of the arguments which led us to consider electric actuation at the exclusion of any other type.

For the purpose of this discussion, actuators may be classified in three categories: electric, fluid driven, and strain based actuators (electrostatic actuators are not considered because they are too weak at the needed scale. More exotic techniques, such as contractile polymers, are not available in a practical way yet). Strain base actuators, e.g. piezoelectricity, magnetostriction and shape memory effect, were discarded at the outset because they all have in common limitations including non-linear dynamics (hysteresis) and/or small strain. Their appeal is mostly for the creation of small amplitude stimuli, in particular vibrations. None of those, alone, can address the required range of displacement and frequencies.

Fluid actuators have been applied to hand controllers and haptic interface designs. As far as compressed air is concerned, some impressive performance figures have been reported [41]. This technique was nonetheless discarded on the grounds of application complexity. Much of the complexity is owed to the fact that the device must be used in the vicinity of human operators, and as such, comfort and safety issues must be considered. Compressed air presents presents much inconvenience because, by principle, it stores a large quantity of potential energy in the conduits. In case of failure, this energy is suddenly released causing a great deal of noise: the sudden transfer into kinetic energy results in an explosive noise particularly annoying near operators working under stressful conditions. Pneumatic systems are also noisy in normal operation. Passive protection against these effects is bound to add a great deal of complexity to the final system. Hydraulic actuation was successfully used in the design of haptic interfaces, most notably in the Sarcos dextrous master arm. The safety issues are not quite as severe in the case of hydraulics since catastrophic failures are in fact quiet and can be shielded against rather easily. Power and compactness of hydraulic actuators make them actually quite attractive, however the services needed to support hydraulic systems precludes its use in commonplace workstation environments.

This leaves us with electric actuation. Electric actuators in turn come in great many kinds, but many conspicuously exhibit adverse properties. In particular all types involving magnetic field reversal in a magnetic circuit have hysteresis. This precludes high frequency operation and causes adverse effects when feedback is applied. Most types having moving polar pieces, such as moving magnet brushless motors additionally exhibit cogging and torque ripple. This effects are difficult to be compensated for with precision. The type found most appropriate for the device about to be described is the coreless motor with fixed magnets which resembles in its operation a voice coil actuator. Its main disadvantage is the presence of brushes for supplying and commuting the windings. The resulting friction in quality models is however quite small. The near absence of torque ripple as well as of hysteresis, combined with low rotor inertia largely compensate for the friction disadvantage. Models of that type are available from several manufacturers.

3.2 Sensing

Although precision is of no particular importance due to reasons including postural persistence and other phenomena in the human perception and control of the position and motion of limbs [11], instrumentation must be noise free and resolve about four orders of magnitude. The choice of sensors is critical. It is known that quantization has adverse effects on the various aspects of of the performance of a haptic device: high frequency noise, creation of limit cycles, and so-on. If the sensors are analog, noise control and anti-aliasing must be carefully studied.

In this project, all sensors were custom designed for packaging, statiblity and smooth response. They are based on analog optical techniques to measure displacements and forces. In the two cases, they rely on differential IR light intensity measurements.

3.3 Motion Transmission

Direct drive precisely means absence of transmission. Such an approach is exemplified by Salcudean's six axis "flotor" system [42] or by Cadoz's keyboard [8]. Because of the absence of transmission, such a device is likely to provide the highest amount of fidelity. However its small workspace (limited by the the air gap) cannot be increased without severe penalty in under-actuation, which we saw earlier is critical. This lead the authors to consider a dual stage design [42].

Other motion transmission techniques offering high frequency response include the use of linkages, flexible elements (cables, steel belts, or polymeric tendons), shafts plus gears, or fluid lines connected to bellows. Since transmissions work by exposing structural elements to stress, the best results will be obtained when the largest amount of material is exposed to the most uniform stress, or in other terms, when the strain energy is maximized for a given amount of material. Friction and backlash aside, gears offer the worst case among the techniques listed above since at any given time only one tooth (at best, a small number in an epicyclic design) is exposed to stress. Bellows connected to each other by fluid lines were also eliminated for reasons of complexity.

This leaves us with linkages and flexible elements. Both have advantages and limitations, and both were used for making haptic devices[1, 2, 5, 7, 9, 14, 15, 19, 21, 23, 31, 32, 34, 35, 39, 45, 22], and both are used is the present device. Linkages will work best under the condition that bending moments and out-of-plane stresses are minimized, and that bearings are exposed to simple loadings. This puts limits on the kind of mechanisms that can use linkages at high frequencies. Serial linkages were eliminated at the outset and the reason is as follows. A serial structure driven by cables can be made efficient [2], however, by principle the response of each joint is bound to degrade as the driven joints become more distal due to cummulative routing. This works against the response uniformity requirement. Spatial parallel linkages, on the other hand, have the well known problem of poor bulk/worskpace ratio which conflicts with the intrusion minimization requirement.

As far as flexible elements are concerned, durability and stiffness are the primary factors to be considered. Cable and steel belts have been used traditionally in the making of force reflecting devices from Goertz' early manipulators, Vertut's MA23, and Salisbury's FRHC. Recently introduced polymeric tendons have proved to possess unique durability properties [29], and stiffness [24]. The principal disadvantages of polymeric tendons over cables or steel belts are creep under permanent loading [43], and higher dissipation when routed around idlers. On the other hand, idlers diameters can be made small, eight times the tendon diameter, without causing fatigue.

4 Concept Design

The concept is driven by an attempt to progress toward the goals stated earlier with a single stage design: grounded actuation coupled by motion transmissions to the active end. From the discussion above it is likely that no single motion transmission technique is capable of providing for six axis of motion with the requirements outlined earlier. Therefore, the proposed design combines the two most promising techniques: linkages and tendons into a single unit.

To reduce system complexity, two principles were applied: separation of functions and replication. This means that no wires are routed in the kinematic structure which transmits only mechanical signals. All actuators are grounded and grouped together, and so are all the sensors. The largest number of parts with similar functions will be made identical. This leads to a design which consists of an actuator pack, a set of identical sensor packs and a kinematic structure with tendons routing. See Figure 4 for a picture of the resulting device, called the "Stylus".

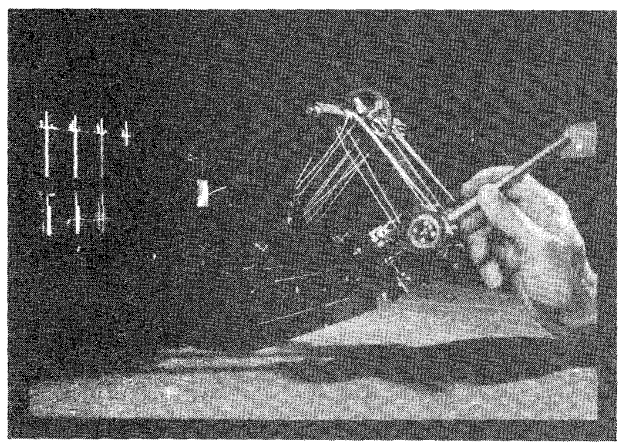

Figure 4: Miniature Hand Controller: the "Stylus".

The kinematic design is hybrid combining a positioning structure and rotating structure. Figure 5 shows the positioning structure which provides three degrees of translation freedoms and the possibility to route tendons to a distal orienting structure, and high structural integrity. Referring the figure, the ground link supports two driven pulleys which permits, by differential action, the control of the forward and lateral movements of the end link. The pulley on the elevated shaft controls the vertical movements of the end link. The corresponding tendon is roouted via a dual idler located on the bottom shaft. A dual idler can route the two strands of one tendon using one single unit and keep the path length constant regardless of the movement of the corresponding joint. This structure has been selected because it is stiff and can be implemented with simple components. Two sets of four idlers located on the ground shaft and the elevated shaft transmit motion to the distal part of the mechanism. The displacements of the positioning structure have a small but noticeable effect of the tendon path lengths. How this is handled is discussed below. The orienting structure, based on a mecha-

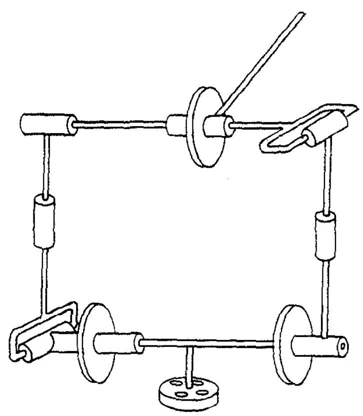

Figure 5: Positioning Structure.

nism that we call a "double five bar", is shown Figure 6. It has many interesting properties, having a large orientation workspace with quasi-constant kinematic conditioning, high structural integrity, and possible dynamic balancing. Its control is also acheived via tendons routed through the positioning structure as just described. Throughout its orientation workspace ($90^o \times 90^o \times 180^o$) the four driven pulleys swivel around a fixed axis causing no change in the tendon path. All four distal channels are thus driven through only two dual idlers per channel which minimizes friction and complexity since all these parts are replicated. The combination of these two structures provide both for the routing of tendons and the required uniform response workspace (see Figure 7). It must be noticed that the orienting structure is in fact actuator redundant, and this explains, at last, the title of the paper. The large orienting workspace of this mechanism is moderately affected when the end member is permitted a fourth translational freedom. This seventh freedom can be taken advantage of for actuating an end effector having, for example, a pinching motion capability. All tendons are routed through identical sensor packs assembled side by side and interposed between the actuators and the kinematic structure. The initial design included a spring loaded tensioner

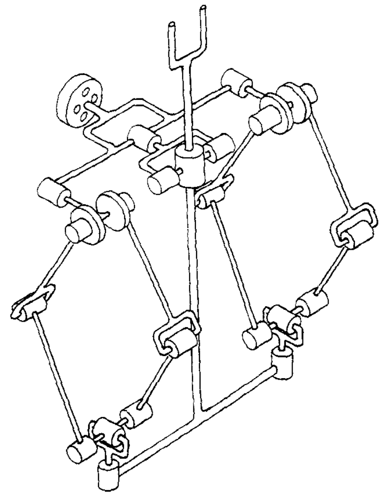

Figure 6: Orienting Structure.

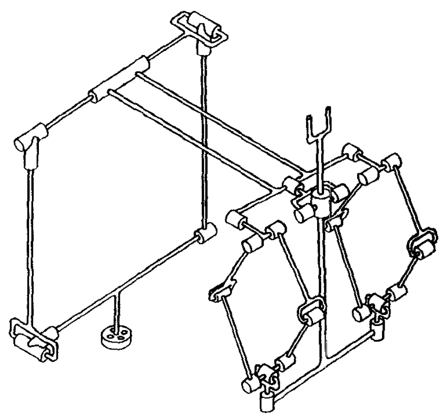

Figure 7: Kinematic Structure

for each channel. This did not perform correctly for a number of reasons that cannot be discussed here. The system now uses a differential drive technique which eliminates the need for the static tensioning of tendons. It also can also accommodate slight tendon path changes, tendon creep and aging, and other mechanical imprecisions. Its characteristics are discussed in a separate paper [20].

5 Conclusion

In this paper we describe a system that achieves a sizeable portion of the requirements needed to create a high fidelity haptic interface with seven degrees of freedom: three displacements, three orientations of a handle plus an additional degree of freedom for pinching tasks. The control of this device is currently under development and experimental results will be subsequently reported.

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