Evaluation of brake-actuated haptic device

Yoky Matsuoka
Carnegie Mellon University
Pittsburgh, PA 15213
yoky@alum.mit.edu

Bill Townsend
Barrett Technology, Inc.
Cambridge, MA 02141
wt@barrett.com

Abstract: Brake-actuated haptic devices, a subset of passive haptic devices, are not yet common, so their capabilities and limitations are only superficially understood. Based on thermodynamic theory, we identified an optimal kinematics, and constructed a life-size brake-actuated haptic device. With the new device, we conducted experiments with human subjects to evaluate the efficacy of passively created virtual environments. We identified key performance drawbacks that modern robotics theories fail to anticipate and overcome, and investigated design methods that can avoid such drawbacks.

1. Introduction

Motor-torque-driven devices are widely used in haptics research and advanced teleoperator masters - capable of creating a rich set of virtual environments in the former and recreating physical environments in the latter. Motors, however, introduce the risk of a device striking or overpowering users within reach. With rare exception, safety concerns limit motor-actuated haptic devices to small workspaces.

The replacement of energetic servo-motors with passive actuators such as brakes improves the inherent safety of the system, and expands the range of motion while still allowing us to simulate virtual objects (i.e. to constrain the user's motion inside an object). Safety is essential for acceptance in new applications such as medical procedures, quantitative rehabilitation, advanced exercise training, and entertainment. Even if the device experiences a power, hardware, or software failure, a brake-actuated device is inherently incapable of exceeding the kinetic energy that a user supplies in each motion. Using currently available engineering technology, the workspace of brake-actuated haptic devices can expand to cover whole-body movements without risking a user's safety. With the expanded workspace, a variety of large movements can be trained and quantitatively analyzed.

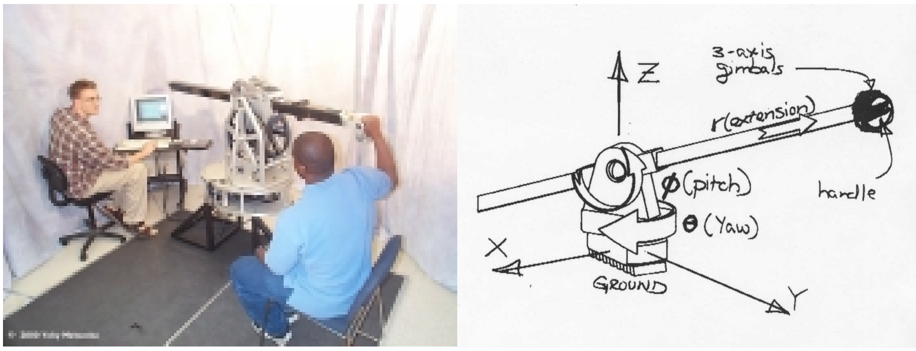

Figure 1. Brake-actuated spherical device we constructed.

In this paper, we describe a novel design of a brake-actuated device, and present theoretical and experimental comparisons to active devices. Theoretically, we demonstrate that brake-actuated devices surprisingly require at least one prismatic joint in order to produce the simplest environments such as viscous fields. A key difference from active devices is that brakes applied at different joints do not add vectorially (unlike torques). As a result, it is difficult to prevent the user from penetrating into an object, and at the same time allow motion in collision free directions ("sticky walls" problem discussed below).

In experiments with our prototype device, we evaluated the machine's efficacy with human subjects, exploring various force fields, including damping, stiffness, inertia, and shape (concave, convex) of virtual objects. Analysis confirms the anticipated problems. Relying on the characteristics of human motor perception, we propose a technique to overcome the device limitations.

2. Prototype Design of an Optimal Human-Scale Brake-Actuated Haptic Device

In 1995, we set out to design and build the best haptic prototype under the following constraints:

1. Life size - workspace size on the order of cubic meters, forces on the order of tens of kilograms, and fully spatial 6 degrees of freedom (DOF) kinematics.
2. Safe - passive actuation only.
3. Economically practical - with today's mechanisms and materials.

Analysis led us uniquely to the device illustrated in Figures 1A and 1B, with brake-actuated spherical kinematics for regional motions terminating at an unactuated and unsensored 3-axis wrist that supports a user hand grip.

In our analysis of the machine design, we begin by defining key terms:

- "Servo-actuation" is the ability to modulate joint torques under computer control in order to create the haptic force field that a user experiences.

- "Energetic" servo-actuation is capable of channeling power from an unlimited external source of energy into the joint torques.

- "Passive" servo-actuation is physically incapable of channeling power from any external source into the joint torques.

- "Brake" servo-actuation is a subset of passive servo-actuation that does not rely on other passive mechanisms, like cobot-style nonholonomic traction-steering techniques or overrun clutches.

- "Sticky-walls" are unique to brake-actuated haptic devices, where a collision with a wall traps the user who becomes stuck behind the wall. There are workarounds, as we discuss in this paper.

Ruling out energetic actuation for its life-threatening safety concerns leaves only passive actuation. One technique was explored by Troccaz et al. [1] who used overrun clutches to brake joint movements. These overrun clutches were not servo-actuated and the applied torque purely depended on the joint angles and speed. An independently developed technique for controlling torques passively was through steerable joints. Substantial progress has been made in building a wide array of steerable robotic joints, collectively known as Programmable Constraint Machines (PCMs) and embodied in cobots [2],[3]. These PCMs have the fundamental advantage of eliminating "sticky walls" (Peshkin and Colgate call them "stuck" mechanisms) by actively aligning the constraint direction with the desired motion. Their disadvantage is the sizable side-slip that traction devices exhibit with existing designs and material technology. That disadvantage however may be overcome when new materials become available in the future.

Our approach to expanding the safe use of haptics to life-size was to replace the motors driving each joint axis of a device with similarly sized servo-brakes. Once settling on servo-brake actuation, the next step was to determine the kinematic structure of the machine. The goal is to control forces in the Cartesian space of the user. So a logical first concept is a Cartesian machine with three orthogonal prismatic joints, such as employed on Cartesian Measurement Machines (CMMs) and vertical milling machines. If such a machine were fully backdrivable (i.e. no friction and no inertia) then a person could move the kinematic tip of the machine in any arbitrary direction with a feather touch. Since these axes are orthogonal, the velocity is easily projected onto the three Cartesian axes and then a desired brake force vector, similarly projected, can control the force resistance.

In fact, projecting force and velocity vectors onto the axes works for any of a large number of mathematically orthogonal coordinate frames, such as paraboloidal, prolate and oblate spheroidal, bipolar, and ellipsoidal. But practical orthogonal kinematic mechanisms are limited to Cartesian, cylindrical, and spherical with the lowing characteristics:

Kinematic Arrangement	No. of Revolute Joints	No. of Prismatic Joints
Cartesian	0	3
Cylindrical	1	2
Spherical	2	1

Table 1 - Classification of spatial mechanisms with orthogonal kinematics

In serial-link robotics, kinematic structures with prismatic joints tend to be more massive for a given work volume than purely revolute structures. The advantage of prismatic joints is that their structures are generally stiffer than revolute structures. A massive structure may be acceptable for a CNC machine in order to achieve the high power and stiffness needed to cut through metal quickly and precisely, but the accompanying inertia and friction, each of which degrade backdrivability, is not acceptable for haptic devices.

So why not build a fully revolute brake-actuated haptic device, and eliminate all prismatic joints? In fact, most serial-link robots do just that, abandoning orthogonal kinematics without penalty. The WAM arm exhibits high haptic fidelity for its 3.5-cubic-meter workspace and 4-kg payload, partly because of its all-revolute kinematics [4].

2.1. Special Restriction against All-Revolute Kinematics

Unfortunately, as we demonstrate with the following thermodynamic analysis, a brake-actuated device must have fully orthogonal coordinates, and so any valid design must have one of the three structures listed in Table 1.

Thermodynamics is a valuable tool in machine design because it quickly narrows the set of feasible solutions; and it elegantly highlights broad truths because its black-box (i.e. control volume) perspective is accomplished without the need to delve immediately into mechanism details.

Applying thermodynamic analysis to mechanisms is a two-step process. First, one defines control volume boundaries, carefully noting all energy exchanges across the surfaces. Keeping the volume fixed simplifies the equations substantially and is generally adequate in the analysis of simple mechanisms that do not include expanding gasses or chemical/nuclear reactions. Second, one applies the laws of thermodynamics. From the first law we derive an energy-balance equation: inflows and outflows of energy during steady-state sum to zero. Then the second law, which forbids the spontaneous creation of power, tells us which energy flows are not permissible.

Figure 2 illustrates the projection perpendicular to the common plane of the inner and outer links of a classic, all-revolute two-link robot. We wish to understand whether servo-braking can support a force directly opposing an externally imposed end-tip motion. For illustration purposes, we impose straight-line motion at a fixed distance from the base of the robot as illustrated in Figure 3.

Three control volumes, represented by dashed lines, are superimposed on Figure 2. The "device" control volume encloses the entire device, including its joints and links, with only the extreme tip protruding. The bottom of the

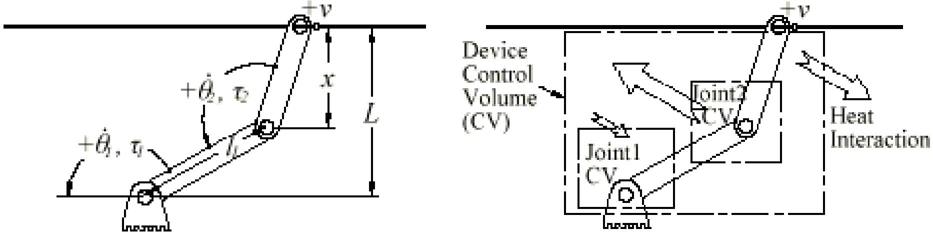

Figure 2. Kinematics of a two-link planar manipulator. We show control volumes around the entire robot and each joint.

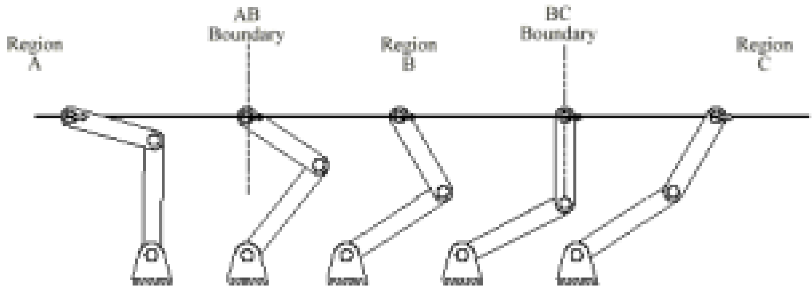

Figure 3. An illustration of how brake-actuated devices fail to create simple environments such as viscous fields. For a brake-actuated device, Regions A and C are impossible to attain.

device control volume passes through a base that is stiffly connected to ground, preventing any load deflections; mechanical work is not possible without displacement, so no work can cross that boundary. This control volume is the same one used in the virtual-work concept for mapping Cartesian forces and torques into a robot's vector of joint torques via Jacobian-Transpose, and defining only this volume adds no contradiction.

Since the force and velocity are opposed and no other useful work energy crosses any other part of the control-volume boundary, the energy must be dissipated inside the control volume and ultimately transferred as a heat interaction across the boundary.

The analysis becomes interesting when we examine each of the two smaller control volumes, which surround each joint. Normal robots can apply arbitrary torques regardless of the direction of energy flows from the motor and into the joint torque or vice-versa. So, in normal robots, these extra control volumes would not yield useful information.

In the servo-brake case, however, useful energy can always be dissipated, but never spontaneously created. And because of the non-orthogonal mapping of the work flows into the joints, some trajectories, can violate this second law constraint. In fact, in Figure 3, the proposed motion could not proceed from A to AB nor from BC to C, but it is permissible from AB through B to BC. Where torque and velocity are opposed at both joints, the motion is permissible. Where they are aligned (as they can be with energetic actuators) in either joint, the motion is not permissible. These permissible areas shift and rotate even for straight-line arm motions, so that most trajectories through the workspace cannot be supported.

2.2. Prototype with Spherical Kinematics

Given that we cannot build a simple all-revolute, brake-actuated device, we settle for one of the three orthogonal kinematic structures of Table 1. And given that revolute joints are preferable over prismatic joints, we chose the option with only one prismatic joint - spherical kinematics.

The device is comprised of backdrivable cable drives free of backlash and friction. The revolute joints are on intersecting yaw and pitch axes with 180 and 90 degrees of joint range respectively. A cable drive is also used to drive the prismatic axis, with 1.1 meters of active stroke. All three axes mutually intersect at the kinematic center of the device and all three drives are terminated at one of three servo-controlled magnetic particle brakes. A high-resolution optical incremental encoder is mounted on the free shaft of each servo-brake. An unpowered and unsensored three-axis handle supports the user's grip at the end of the prismatic link. The machine allows for large, sweeping motions from its user with loads up to 50 kg.

The control of the three particle brakes is done via current amplifiers and an I/O board with encoder counters mounted on the bus of a standard Pentium PC running Windows 95. The machine controller converts the encoder readings to Cartesian coordinates and can respond to a user's musculo-skeletal changes in force, position, velocity, acceleration, power, work, and range of motion in real time. LabView graphical interface software allows the user to specify the training variables in a simple manner. A foot pedal is installed within the user's workspace to make fine adjustments or to send commands during training without stopping the motion.

Finally, to prove that the workspace can provide continuous control free of the type of discontinuities predicted for the all-revolute concept, we attached a weight at the end tip of the robot and dropped it in a viscous field as shown in Figure 4. The weight fell in a straight line with very little variation from a perfect downward trajectory, while the prismatic joint changed the velocity direction.

3. Experimental Evaluation of Brake-Actuated Virtual Environments

With the spherical life-scale device we designed and constructed, we now must explore rigorously whether an effective virtual environment can be constructed.

Previously, purely dissipative devices were used purely to damp human limb movements. To suppress intentional tremor, Rosen and Baiges [5] have developed a tabletop brake-actuated device. It has been demonstrated that

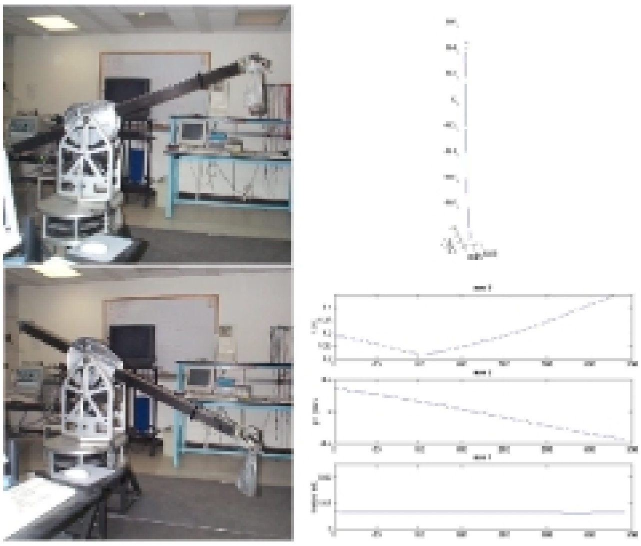

Figure 4. Our brake-acuated haptic device is capable of simulating a perfect viscous force field. We attached a weight at the end of the robot and dropped it in the force field.

mechanical damping on effected joints reduces the amplitude of tremor while allowing slower voluntary movements [6]. The same research group produced viscous joystick [7] and wearable [8] devices to suppress tremor.

We are interested in taking a step further to create a rich set of virtual environments with virtual objects and movement guidance paths. It turns out that movement guidance paths can be constructed the same way as virtual objects. To constrain movements to the outside of an undesired area, we need to construct convex objects covering the undesired area to prevent an entry into the objects. To keep movements within a restricted area, concave objects should surround the area to keep the movements in. To make a tube of path to follow, the tube walls should be a combination of concave and convex objects. If the hand accidentally moves into these objects, the hand should be diverted away from the objects systematically.

Here, we examine virtual objects with three different force characteristics, namely inertial, viscous, and stiff forces, by conducting simple experiments with human subjects. Inertial, viscous, and stiff forces are proportional to the acceleration, velocity, and position of the machine handle respectively: F=Ia, Bv, or K(x-x0), where I is a inertial constant, B is a damping constant, and K is a stiffness constant. We are interested in understanding how each force field affects the hand movement, and whether these force fields can prevent movements into a certain region (i.e. inside objects). To compare with equivalent objects created by an energetically servo-actuated device, we used PHANToM to also produce inertial, viscous and stiff virtual objects.

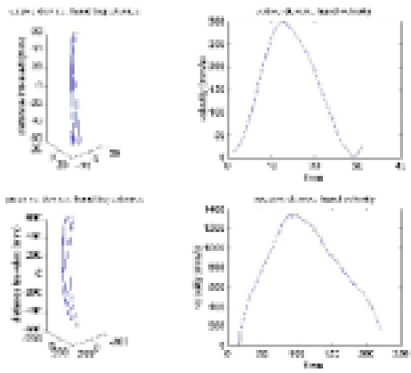

Figure 5. Baseline hand trajectories for both active and passive devices.

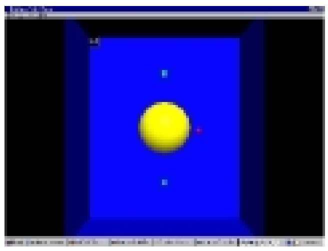

Figure 6. A virtual object placed in the hand path. Subjects did not see this object.

Four human subjects participated in this study. The computer screen displayed a visual feedback of their hand location in the workspace. There were two targets within the workspace, and subjects were instructed to move from one target to another with a sound cue. For the energetically actuated device, the movement was 10cm long and had to be executed within 650 milliseconds. For the brake-actuated device, the movement was 100cm long and was executed within 1.20 seconds.

To establish a baseline movement for all subjects, we first recorded ten hand movements for each subject for each machine without any virtual objects in the workspace. The baseline movements were straight between two points, and their velocity profiles had a single bell-shaped curve for both devices, as shown in Figure 5.

Once the baseline movements were established, we placed a virtual sphere in the baseline hand path as shown in Figure 6 (2.5cm radius for the energetic device and 25cm for the brake-actuated device). The virtual object was introduced unexpectedly, and visual feedback was suppressed to assure that subjects did not alter their movement.

First, we studied viscous objects placed in the middle of the hand

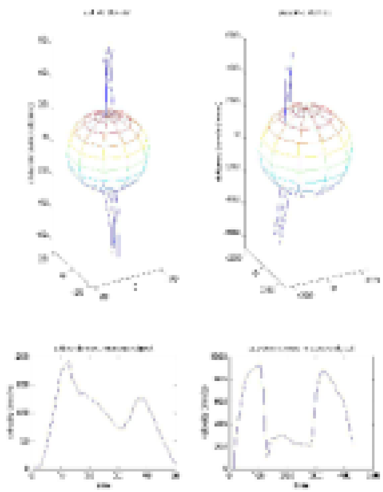

Figure 7. Hand paths and their velocity profiles when subjects interacted with a viscous sphere.

path. With low viscosity[1], subjects continuously executed straight movements through the virtual objects for both devices, as shown in Figures 7A and C. The effect of the viscous objects was obvious in the velocity profiles (Figures 7B and D); the velocities were reduced while the hand was in the object, and resumed to finish the original bell-shape curve after the hand exited the object. In both energetically and brake servoed devices, viscous objects acted as a tool to slow down movements but the hand trajectories were not deviated from the intended paths.

In the next set of experiments, we created an inertial object in the subject's hand path. For all subjects, the hand path again penetrated through the object, and the movement speed was reduced. However, the force exerted by the device was quite different for the energetically and brake servoed devices. As shown in Figure 8, the hand acceleration changed its sign in the middle of the movement. When the acceleration was positive, the force was the same for both machines. In contrast, when the acceleration became negative, the brake-servoed device could not apply negative force, so it produced a mirror image force profile. Subjects perceived the inertial objects created by the brake-servoed device to be viscous, while energetically created objects were perceived to be inertial. Indeed, the force profile for the brake-actuated device resembles more of a bell-shape velocity profile than the acceleration profile. Despite the difference in forces, neither device was able to divert the subject's hand movement from the original path.

As a last set of force fields, we created a stiff object in the hand path. Stiff objects apply forces that are proportional to the distance from the boundary of

[1] When the viscosity was set high, control instability was experienced for both devices when the control loop frequency was 1kHz.

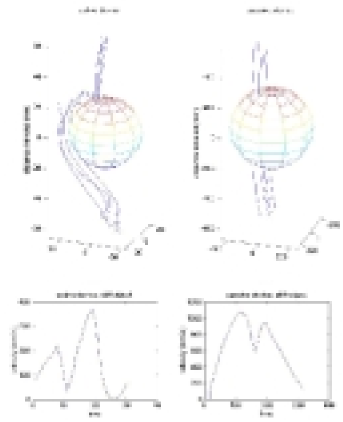

Figure 8. Hand paths and their velocity profiles when subjects interacted with a stiff object. For the active device, the hand path changed its direction.

the object. The deeper the penetration, the stronger the force applied. For a sphere object, the force was inversely proportional to the radius from the center. With the brake-actuated device, the subject's hand still projected a straight movement, as shown in Figure 8A. When the stiffness was set low, the hand went through the object, and when the stiffness was high the hand stopped just inside the object. When the hand was stopped inside the object, the resistive force was strong for all moving directions. Therefore, when subjects attempted on pulling their hand out of the object, they experienced a "sticky walls". "Sticky walls" are inherent to the servo-brake mechanisms, and cannot be eliminated without a use of external parameters such as the interacting person's movement or perception.

In contrast, when the energetically-servoed device created stiff objects, the hand changed its course, as shown in Figure 8C. The hand penetrated the object slightly then slipped off to the side of the object before continuing to the target. This type of movement deviation was observed for a variety of stiffness, and subjects perceived a wide range of object hardness corresponding to the stiffness of the object. This is the behavior we want to reproduce using brake-actuated device, but we must first get around the "sticky walls" problem.

As a first attempt to remove the sticky walls, the velocity vector orientation was monitored throughout the program. When the hand penetrates the object, ideally, the hand should not get stuck if the velocity vector is differently oriented from the velocity vector used to enter the object. This technique was effective at a high velocity, but at a lower velocity, singularities were experienced. Singularities occurred when the velocity vector did not specify the moving direction (i.e. velocity equaled to zero). At singularities, without predicting the next moving direction prior to the move, brakes could never respond correctly. For example, if the brakes are turned on, regardless of the next move, the user experiences a sticky sensation. On the other hand, if the brakes are off

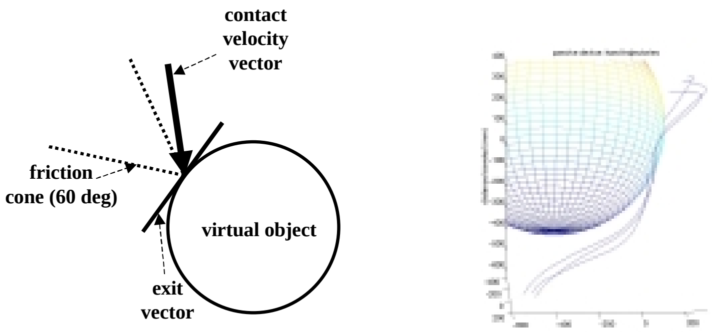

Figure 9. A way to create non-sticky objects, machine axes were aligned with exit vectors of the virtual object. When they are aligned, passively created objects can divert hand movement as shown on the right.

and if the next move is into the object, the hand penetrates into the object further before the brakes turn back on. Therefore, without being able to predict the next movement, the sticky walls cannot be eliminated with this technique.

Furthermore, monitoring the velocity vector did not cause any movement diversion that we desire to produce. How can we make an environment that can impose a restriction into a selected region? As a way to constrain movements into a certain path, we could eliminate a joint from the device and make a two DOF robot. With this elimination, the movement would be restricted to a two dimensional workspace. If one of the brakes on the device is locked, the simulated environment should be reduced to a plane as if eliminating a joint. If two of the brakes are locked, the environment should be further restricted to a line. Even though these planes and lines are restricted to the machine constraints, if there are ways to use this locking technique with respect to virtual objects, we may be able to divert movements using purely dissipative devices.

To combine the locking technique with virtual objects, as a way to create non-sticky objects, an object contact point was first defined as illustrated in Figure 9A. We defined a contact point on the object and defined a contact velocity vector as the hand velocity at contact. In addition, we defined a tangential plane with respect to the object at the contact point. This tangential plane is a collection of tangential vectors, defined as exit vectors, that the hand movement should follow immediately after contacting the object. Friction cone was defined to be 60 degrees wide. When the contact velocity vector was within the friction cone, then the movement was not deviated. If the contact velocity vector is outside of the friction cone, *and* any of the exit vectors was closely aligned with one of the machine axes, then an appropriate joint was locked to move the hand along the exit vector. After the hand deviation was completed, the joint was unlocked. Figure 9B shows an example where hand trajectories were diverted from an objected created by a brake-actuated device.

We tested various movement cases with a virtual sphere, and found that we cannot consistently align the exit vector with the machine axes. As a way to overcome this issue, we created a workaround that utilizes the discrepancy in human visual and proprioceptive perception. When humans are given perturbed visual information, their motor behavior adjusts to match the visual input. Martin et al. [1990] put a prism-goggle on subjects and asked them to throw a dart at a target. Because the prism distorted the target to the right for 15 degrees, subjects adapted to throw the dart to the left for 15 degrees to compensate for the perturbation. Subjects did not perceive that their muscles were commanding different forces to produce the compensatory movement. This experiment suggests that the resolution of the proprioceptive information is lower than the one for the visual perception. Due to this perceptual gap, some haptic inaccuracy may be tolerated if the visual feedback is consistent.

To increase the chance of an alignment between an exit vector and a machine axis, the subject's movements were projected for 50 milliseconds in advance using the movement velocity profiles. This projection estimated the contact point with the object and the exit vector. If the projected exit vector did not align well with the machine axes, the closest point along the movement trajectory with an alignment was searched. When the point was found, the object was moved to that location and the visual feedback sped up or slowed down proportionally to match the proprioceptive object location. With this search algorithm, we were able to divert a hand movement on a virtual sphere for all cases.

A limitation with this technique was the shape of the object. A sphere was a convenient example because the tangential plane was always outside of the object. However, problems arose as the object surface produced a situation where the entire tangential plane was in the object (i.e. concave objects). Therefore, concave objects have spots that cannot be declared as a contact point. The same search algorithm was implemented to find the nearest non-concave points, but the technique was ineffective for large concave surfaces.

4. Conclusions

Using the optimal life-scale brake-actuated haptic device we constructed, we created a large and safe haptic environment. We were able to create virtual objects and guide movement path in this new environment, but the non-energetic nature of the brakes imposed limitations on the virtual environments. Perhaps, the most exciting part of this investigation was the development of algorithms utilizing human movement and perceptual information, but there were still limitations that we could not eliminate. We illustrated the overall capabilities and limitations of a brake-actuated device in Table 2. While viscous objects can be created without any limitations, inertial and stiff objects do not simulate the energetically created objects perfectly. The limitations for stiff objects are devastating because stiff objects are implemented to divert hand movements. While it is easy to divert movements for the energetically actuated device, the brake-actuated device had to overcome the "sticky walls" problem.

We intend to improve the design by adding a force sensor in the handle. If we could detect the movement direction before the device joints starts moving, then we may be able to eliminate the sticky walls. Furthermore, we plan to add weights and springs to produce negative inertial and stiff forces for some applications.

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