A Hybrid Actuation Approach for Haptic Devices

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Abstract

This paper presents a new actuation approach which combines the use of brakes, springs and mini motors to produce a safer and more energy efficient way to drive haptic devices. The applications which can greatly benefit from this new technology include force-feedback interfaces which operate medical robots, an area where safety and reliability are of prime concerns, and small portable devices which can only be powered by limited energy sources such as small batteries. This work also addresses the problems of limited rendering capabilities which today are present on most passive haptic displays.

1 Introduction

The continuing emergence of computer haptics for training, industrial and entertainment applications has increased the need for cheaper, safer and smaller tactile display solutions.

Today most force-feedback interfaces [8, 9, 10, 13, 14] come in the form of small robot manipulators: these systems use electrical motors to generate forces and joint sensors to measure spatial position. The main difference between them resides in their way of operating: while robots are generally programmed to perform active tasks such as moving to a desired position or carrying a load, haptic devices are moved directly by the operator and are programmed to constrain hand motion. The use of electrical motors to reproduce high fidelity tactile sensations has also introduced the risk of striking the user; with rare exceptions, safety concerns have also limited motor-actuated haptic devices to small workspaces.

With the appearance of specialized robots for minimal invasive surgical procedures, important efforts have led to the design of safer and more reliable robotic systems. Today, these new medical devices combine many redundant parts to ensure the safe operating of the system at all times. Despite the fact that redundant design strategies can greatly reduce the risk of incident, there always remains the small likelihood of a system failure where an active element may injure the patient. Such incidents can be caused from a defective part (i.e motor, amplifier, sensor…) but can also be the result of a programming error within a complex control algorithm which may have not been detected during the design phase of the application.

When looking at the field of small embedded haptic devices for micro computers or hand-held devices, electrical consumption and heat dissipation are among the key challenges which need to be addressed before one can manufacture a high fidelity miniaturized haptic device. For instance, a commercial force feedback joystick requires between 10 to 30 watts of electrical power to generate forces continuously in the user's hands. Such energy requirements have imposed the use of external power adapters which are perhaps an acceptable solution for a desktop computer but clearly impractical for portable devices.

In this paper we present a safe and low power actuation approach for multi-degree-of-freedom haptic interfaces which extends previous results developed in the field. This paper is organized as follows: in section 2 we introduce the motivations and background by reviewing and comparing different passive haptic displays. In sections 3 and 4 we introduce our new actuation strategy based on brakes, springs and micro-motors. Finally, the implementation aspects and our initial experimental results are discussed in section 5.

2 Passive Haptic Displays

To overcome safety and stability issues when motor actuators are used, different design strategies using passive actuation approaches have been developed. A first category of passive devices are those where motors are replaced with magnetic particle brakes. A particle brake works as follows: with no electrical excitation, its shaft freely rotates, and with electrical excitation, the shaft becomes coupled to the case of the brake. When the load torque is less than the output torque, the shaft does not rotate, but when the load torque is increased, the brake slips smoothly at the torque level set by the coil input current. In [1, 2] Matsuoka and Al. present a human size 3-dof haptic device where magnetic particle brakes are used to constrain the hand motion of the operator holding the end-effector. This actuation strategy allowed the authors to build a human safe device with a very large workspace, but at the cost of losing some important haptic rendering capabilities necessary to simulate virtual scenes in a realistic manner.

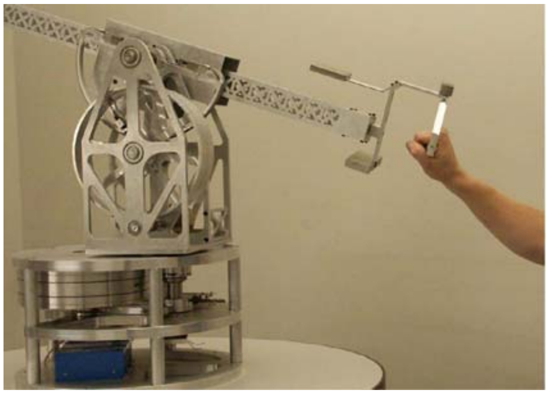

Fig. 1 - Overview of the 6-DOF Dissipative Haptic Device from Matsuoka and Al. The device is actuated by three magnetic particle brakes. A force sensor is mounted at the end-effector to measure the output forces.

Fig. 2 - Picture of a magnetic particle brake (model B1) from Placid Industries. This model was used on the Hybrid Haptic Device which is described in section 5 of this paper.

A Haptic device using magnetic particle brakes works particularly well to render forces which are in opposite direction to the instantaneous velocity of the end-effector. In practice this would include, for instance, simulating a virtual tool plunged in a viscous liquid. Because particle brakes also present low time constants which are in the order of a few milliseconds, many types of high-frequency texture effects can be rendered in a very realistic manner by modulating the current driving the coils of the actuators.

Despite the fact that brakes offer a safe alternative to motors, serious limitations occur when one wants to generate forces with arbitrary direction and magnitude.

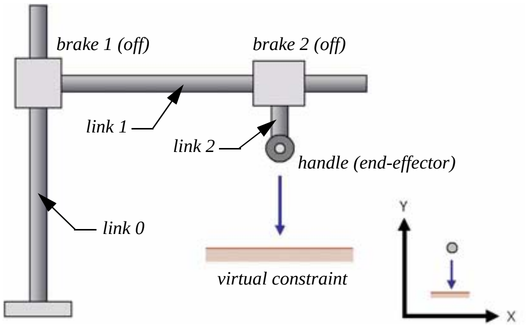

Fig. 3 - Illustration of a 2-DOF haptic device that is actuated by magnetic particle brakes instead of motors. When no constraints are programmed both brakes are released and the operator can move the end-effector freely.

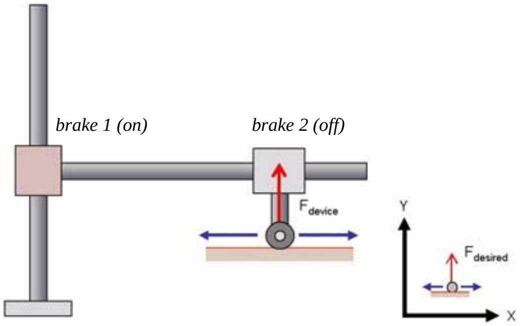

Fig. 4 - In this illustration the operator programs a horizontal constraint by engaging the brake of link 1. A force sensor is mounted at the end-effector to measure the output force. The same stategy can be applied to simulate a vertical constraint by enabling brake 2 and disabling brake 1.

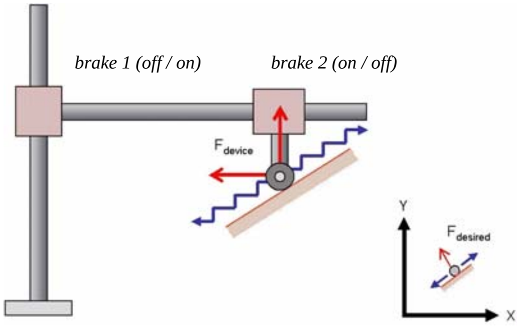

Fig. 5 - In order to program a constraint of arbitrary angle, both brakes need to be engaged consecutively so that the motion of the end-effector can approximate the virtual wall along a step-like trajectory. We notice that the reaction force oscillates between the horizontal and vertical constraints as the operator moves the end-effector along the tilted wall.

Such a situation occurs in simulated environments where a virtual tool interacts with objects of variable shape and stiffness. In the following figures we illustrate this problem using a 2-DOF haptic device which is actuated by two magnetic particle brakes [3]. When both brakes are disabled (Fig. 3), the user can freely move the end-effector or handle within the physical workspace limits of the device.

To simulate a vertical constraint, the controller needs to simply engage the brake 2. The same procedure is performed on the opposite brake to simulate a horizontal constraint; this case is described in Fig. 4. A much more difficult situation occurs with constraints of arbitrary slope; this case is illustrated in Fig. 5. The only way to achieve this task is to approximate the virtual wall by a series of small steps where both brakes are engaged consecutively. While the end-effector will physically follow the stair-like trajectory, the operator is certain to perceive these increments as undesired vibrations.

Another example which illustrates the limitations of brakes is presented in Fig. 6 where we simulate the interactions between a virtual tool and a deformable elastic body. In this scenario a force is applied through the use of a tool onto a deformable sphere. When the sphere deforms, potential energy is stored internally in the same manner as a linear spring is compressed. When the operator moves the tool away from the object, the object regains its original shape and the reaction force applied onto the tool diminishes gradually to zero. Such behavior can be rendered haptically using almost any type of motor actuated haptic device. But with a device actuated with brakes only, the reaction force can only be modeled correctly during the initial phase of the simulation when the operator pushes against the object. As soon as the user moves the tool away from the sphere the force abruptly falls to zero giving the illusion that the object is not elastic and therefore cannot regain its original shape. This perceptual inaccuracy comes directly from the fact that brakes can only dissipate energy and never produce any. This problem leads to important limitations in the way virtual environments can be rendered realistically.

A second category of passive devices are those which use passive and frictionless actuators. These actuators include hysteresis or Eddie current brakes [5] and they provide an elegant solution to control the torque with higher accuracy and with a higher bandwidth compared to magnetic particle brakes or clutches. The downside of these actuators is that torque cannot be maintained when the device is in a static configuration and therefore these approaches need to be combined with other types of actuators to handle static situations. In [15] Kwon and Al, present a hybrid approach by mounting motors directly onto the shafts of the brake. Difficulties in sensing the output force when the brakes are engaged have limited the overall performances of such system.

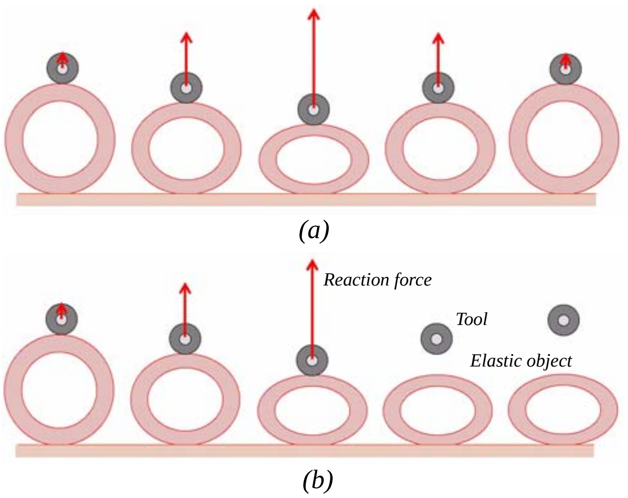

Fig. 6 - This illustration describes the interaction between a virtual tool and an elastic body represented here by a sphere. In (a) the use of a motor actuated haptic device (i.e. Phantom, Omega …) allows one to realistically simulate the interaction forces between the tool and the deformable object.

In (b), when the motors of the device are replaced by brakes, a discontinuity in the force is observed when the operator moves away from the object. This limitation is caused by the fact that brakes cannot restitute potential energy stored during the compression phase of the object.

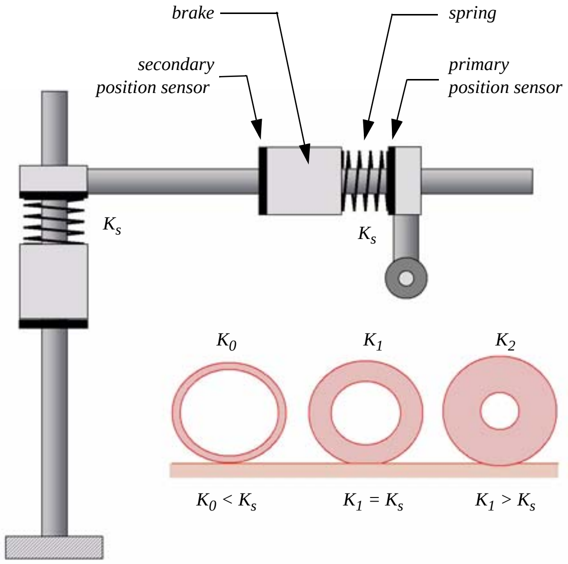

Fig. 7 - This illustration describes the addition of springs between the brakes and their respective links. Such configuration allows the device to store energy when the operator exercises a force against a virtual constraint. The actual energy stored within the springs can be maintained or decreased by controlling the currents driving the brakes, and therefore it is possible to control the direction and magnitude of the output force perceived by the user.

3 A spring-brake actuation approach

While particle brakes do offer a safe alternative for actuating haptic devices, there remain some significant limitations in the way constraints and forces can be programmed to the device. In the real world, a person may interact with an object by moving it, grasping it, or even deforming it. The latter occurs for instance when grasping a rubber ball (see Fig. 6). When an elastic body deforms, potential energy is stored internally and is released when the external forces or physical constraints disappear. In a scenario where a ball is grasped by a hand, the energy necessary to deform the object is provided entirely by the person manipulating the ball and not by the surrounding environment. Unfortunately with a simple brake actuation approach, it is impossible to store any potential energy which could be released at a later time when the operator opens his or her hand.

To overcome these limitations we extended the brake mechanism described in section 2 by inserting a spring between the actuator and its respective link. A secondary position sensor was also mounted onto the brake in order to precisely estimate the energy stored by the spring. An example of a two-degree-of-freedom interface using springs and brakes is presented in Fig. 7.

When both brakes are disabled (no electrical excitation) the handle moves freely throughout the entire workspace of the device. When one or more brakes are enabled the user can still move the end-effector freely, but as soon as he or she moves the handle away from the position where one or more brakes were engaged, a reaction force proportional to the deformation of the springs is perceived at the end-effector. The actual forces generated by the springs can be measured precisely by monitoring the difference between the primary and secondary encoder values and by knowing the physical stiffness of the springs. The actual energy stored by the springs can be maintained or reduced by controlling the current driving the coils of the respective brakes. By releasing the energy stored by the springs it is possible, and within boundaries defined by the actual energy stored by the springs at a given time, to modify the direction and magnitude of the force perceived by the operator.

If we consider the previous example where we modeled an elastic sphere, we realize that the brake controlling the vertical axis simply needs to be engaged when the tool reaches the surface of the object. The virtual tool can then compress the object by moving the handle, and as a consequence, energy is stored inside the spring provoking a reaction force which is sensed by the operator. When the user moves away from the object, energy is released from the springs and the force is gradually reduced to zero without any discontinuities.

While this approach greatly improves haptic-rendering performances compared to previous passive actuated devices, there remain some important limitations regarding the range of stiffnesses which can be rendered. The ideal case occurs when the stiffness of the virtual environment is equal to the stiffness of the springs. The upper limit is directly imposed by the physical characteristics of the springs; in other words, it is impossible to simulate an object which feels harder than the actual physical stiffness of the springs. Finally there remains the case when the stiffness of the virtual environment is much lower than that of the springs; in such a situation the springs are of little use and the behavior of the system is similar to a device composed of brakes only. Thus it is important to select an appropriate stiffness for the springs that is very similar to the stiffness of the simulated environment.

It is also noted that the perceived stiffness depends on the kinematics model of the device and therefore it's magnitude may vary directionally (non-isotropic) and also according to the position of the end-effector within the workspace. The actual perceived stiffness K_p is expressed by the following equation, where J(q) describes the Jacobian at the end-effector for a given configuration q (joint positions) and where K_s represents the torsional stiffness of the spring.

Eq. 1: $K_p = J^T(q) \cdot J(q) \cdot K_s$

4 A hybrid actuation approach

In order to overcome the limitations presented above, we extended our spring-brake mechanism by mounting small mini-motors on each link of the device. The concept is illustrated in Fig. 8. Under this new configuration, the forces applied at the end-effector are the combined contributions of both the springs and the mini-motors. While the springs can store and release energy when the operator is interacting with the virtual environment, they also act as low pass filters and therefore the force spectrum is decoupled into two regions where the low frequencies are handled primarily by the springs and brakes, and where the high frequencies are operated by the mini motors.

The controller of the device takes as an input command a desired force F_d which is applied to the end-effector of the haptic device. The desired torque Γ_d for each actuated link of the device is computed by Eq. 2. Based on the desired torque values for each link, the controller computes the respective torque commands Γ_b and Γ_m which are then sent to the brakes and the motors. The torque commands for the brakes and motors are computed in the following way.

Eq. 2: $\Gamma_d = J^T(q) \cdot F_d$

In a first stage we estimate the torques Γ_s applied by the torsion springs. Each torque value is computed by measuring the torsional angle of each spring and by multiplying its value by the torsional spring stiffness K_s. This relation is expressed by Eq. 3 where the torsional angle is measured by comparing the values of both encoders which are mounted on each side of the spring. If a brake is disabled, or in other words when no current is traversing the coils of the actuator, the measured torque will remain near zero.

Eq 3. $$\Gamma_s = K_s \cdot \Delta_{torsionangle}$$

In a second stage we perform a sign comparison between the values of the desired torque Γ_d and the sensed torque Γ_s. Two situations can occur. (1) In the first case both signs coincide, or in other words the values of Γ_d and Γ_s are either both positive or both negative. In such situation a torque command of magnitude Γ_d is sent to the brake and a command corresponding to the difference between the desired torque Γ_d and the sensed torque Γ_s is sent to the motor. Physically, this situation corresponds to the ideal case where most of the desired force is produced by the loaded spring and where only a fraction of it is generated by the motor. (2) The second case occurs when the signs of both torques Γ_d and Γ_s differ. This situation happens when the desired force is opposed in direction to the force currently exerted by the torsion spring at a given time. This situation requires to release all the energy stored in the spring and therefore the brake command Γ_b is set zero and the motor command Γ_m is set to the desired value Γ_d. This situation corresponds to the worst case since the desired force is now entirely generated by the motor without any contribution coming from the spring.

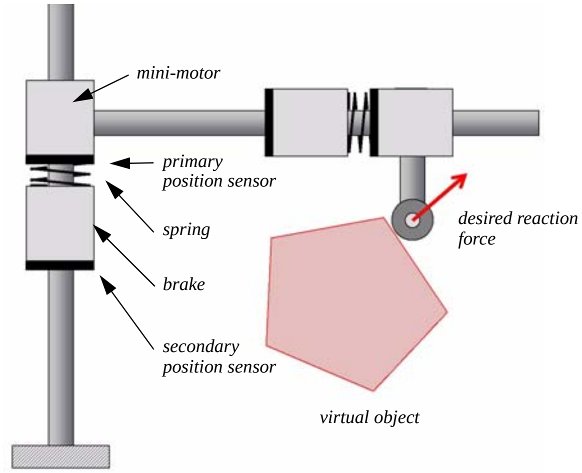

Fig. 8 - The limitations of the spring-brake device which is illustrated in Fig. 7 are addressed by adding small mini actuators on each link.

5 Results and conclusion

In order to evaluate both actuation approaches presented above, we modified a 3 DOF Phantom Haptic Device by replacing the original motors with three hybrid actuation modules, each composed of a particle brake, a torsion spring and a motor (see Fig. 10). Two position sensors (optical encoders) were mounted onto the shaft of the brake and the motor to evaluate the actual torque applied by the torsion spring. To measure the capabilities of the new actuators, we coupled the device to the virtual simulation framework CHAI 3D [17] to simulate interactions between a virtual tool and various types of rigid and deformable bodies.

When the brakes and springs were used alone (without the use of the mini-motors) and when the stiffness of the environment matched that of the springs, the operator was able to naturally interact with all types of objects without encountering any important haptic artifacts. As predicted by the kinematics model of the device, we did notice some stiffness limitations when the end-effector moved towards the edges of the physical workspace of the device or near singularities. The overall performances diminished gradually as the stiffness of the objects would be reduced to levels lower than the actual stiffness of the springs. In certain situations when the operator would move along a curved surface and when the exact desired forces could not be matched by the springs, tangential friction forces corresponding to the error between the desired and the actual projected force were noticeable when sliding along the surface of the object.

These limitations disappeared completely as soon as the mini-motors were engaged. By combining the brakes, springs and motors together we also measured an important reduction in energy consumption. More specifically, in the situation where the brakes were disabled and therefore no energy could be stored by the springs, the device would require at least five times more electrical energy to power the motors in order to generate interaction forces with the same desired direction and magnitude. The following table presents the performances obtained for the maximum continuous force, maximum stiffness and measured electrical energy power required when the maximum forces were being applied. The update rate of the haptic simulation loop was running at 1.0 Khz.

Table 1: Measured performances for a 3 DOF haptic device

	Brakes only	Motors only	Motors and Brakes
Max. Force (N)	14.0 N	7.5 N	21.5
Max. Stiffness (N/m)	350 N/m	2200 N/m	2200 N/m
Max Power (W)	2.8 W	30.3 W	8.8 W

Fig. 9 - Overview of the Stanford Hybrid Haptic Device. which is powered by three hybrid actuator modules that are illustrated in Fig. 10. The device is compensated for gravity by using several counterweights which are positioned along each link.

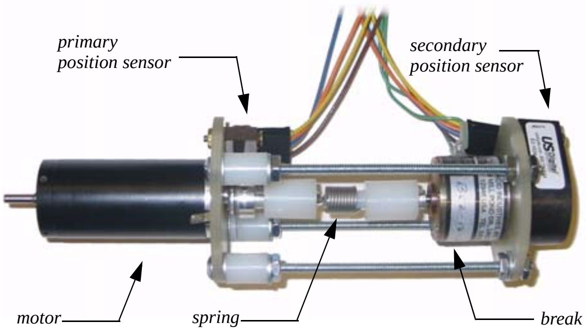

Fig. 10 - Overview of the hybrid actuator which is composed of a brake, a spring and a motor. Two encoders are used to measure the energy stored by the spring.

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